A thermo-bio-architectural framework (ThBA) for finding inspiration in nature

Biomimetic energy efficient building design

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To the love of my life Iman, this thesis is dedicated to you. I fall short of words when it comes to thanking you because what you mean to me is without a price.

To my amazing parents, Ebrahim and Shohreh, and my beloved sister Nazanin. You are my everything. I would not be the person who I am today without you.

Abstract

Design inspired by nature has been known as biomimicry or biomimetic design that is believed to transform human technologies into a sustainable status through translation of biological models, systems, and processes.

Considering energy efficiency as one of the aspects of sustainability in the concept of bio-inspired building design, the problem was how to access the solutions best matched to the design problem. Various tools for finding existing knowledge from a different domain are described but as yet there appears to be no tool for allowing building designers to access the efficient ways found in nature of producing energy, using energy, and recycling resources.

What the research investigated was to find if it is possible to develop a generalised thermo-bio-architectural (ThBA) framework by use of which architects would be able to improve the energy performance of buildings in a wide range of climates, by following a systematic process that methodically connects design thermal challenges to thermal adaptation principles used in nature.

The ThBA was developed by studying biology to find how thermal regulation strategies used by living organisms can be classified and generalised. The proposed ThBA was confirmed and evaluated before it was used for the rest of the research. The biological part of the ThBA was assessed by biological experts within a focus group session. Having the ThBA confirmed, the research also investigated how the heat transfer principles in buildings can be articulated to be linked to the generalised thermal adaptation strategies in nature. For this, a series of case studies were selected and for each an energy simulation was run to analyse its thermal performance and identify its thermal challenges.

Then, the ThBA was used to introduce innovative solutions for improving the thermal performance of the case studies with big energy use to reveal unexpected techniques or technologies. This, however, necessitated its reconfiguration so as to be useful for architects.

Testing the ThBA for two extreme climates in New Zealand, highlighted the fact that the simple translation of the majority of biological thermal adaptation principles are being used by architects, although for some, the architectural equivalents did not function in exactly in the same way as biological thermoregulation strategies. The

differences were seen either in the central thermoregulatory principles or the broader properties within which the key principles fitted. Apart from that, for both architectural and biological thermoregulatory strategies the heat transfer parameter and methods were the same. Given that, in a context where biomimicry is understood as the imitation of complicated thermoregulatory solutions in nature for which innovation is evolutionary achieved, the term biomimetics seems to not have a place in the context of bio-inspired energy efficient design considering the current state of technology. The ThBA, however, suggested a few strategies that might address opportunities for designing a new generation of buildings in the future. This implies that the ThBA is more useful for researchers than architects.

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Glossary

AHU	Air Handling Unit
AN	AskNature
AOX	Alternative Oxidase
ASHRAE	American Society of Heating, Refrigerating and Air-conditioning Engineers
BEES	Building Energy End-Use Study
BID	Bio-Inspired Design
BKE	Bio-Inspired Kinetic Envelope
BLAST	Building Loads Analysis and Systems Thermodynamics
BTF	Biomimicry Theoretical Framework
CAQDAS	Computer Qualitative Data Analysis Software
CEHL	Cutaneous Evaporative Heat Loss
CF	Critical Functions
CIB	Conseil International du Bâtiment
CV(RMSE)	Coefficient of Variation of The Root Mean Squared Error
DANE	Design by Analogy to Nature Engine
D-APPS	Design By Analogy Performance Parameter System
DBA	Design-By-Analogy
DOE-2	Department of Energy
EC	Energy Consumption
EE	Embodied Energy
EEDP	Energy Efficiency Design Parallels
ESD	Ecologically Sustainable Development
ETE	Environmental Theories of Ecosystems
EUI	Energy Use Intensity
HB	Honeybee
HBM	Heat Balance Method
HCI	Human-Computer Interaction
HSR	Heat Shock Response
HVAC	Heating Ventilation and Air Conditioning
IEA	International Energy Agency
IEQ	Indoor Environmental Quality
IUPS	The International Union of Physiological Sciences
LB	Ladybug
LFD	Laundry Folding Device
MBE	Mean Bias Error
NIWA	National Institute of Water and Atmospheric Research
OE	Operational Energy
PBD	Performance-Based Design
PMV	Fanger's Predicted Mean Vote
PPD	Fanger's Draught Model
PV/T	Photovoltaic/Thermal
R.H.	Relative Humidity
SAPPhIRE	State-Action-Part-Phenomenon-Input-Organ-Effect

SBF	Structure, Behaviour, Function
SD	Sustainable Development
SI	Swarm Intelligence
SMP	Shape Memory Polymer
SOHO	Self-Organising Hierarchical Open Systems
TARP	Thermal Analysis Research Program
TCV	Thermal Conductive Venting
ThBA	Thermo-Bio-Architectural Framework
TRNSYS	TRaNsient SYstem Simulation
TTR	TeToki a Rata
USA	United State of America
VSM	Vector Space Model

1 Introduction

1.1 Introduction

This introductory chapter provides the contextual background, scope, problem, significance, and hypothesis of the research. It starts by positioning the research in the broader context of climate change and its possible effects on the performance of future buildings through imposing substantial changes in their patterns of energy use. It continues with introducing biomimicry as one of the emerging frontiers of architectural design that has promised ecologically sustainable development and technological innovation by suggesting solutions for improving energy efficiency. The chapter concludes with the necessity for the proposed research by outlining the research problem. This chapter also provides a visual summary of the contents of individual chapters in the thesis.

1.2 Climate change and building performance

The recent growing concern about climate change has been raised in different disciplines. The evidence shows that the pace of global warming will shortly exceed that behind the worst case scenarios predicted for 2003 and 2005 (Roaf et al., 2009, p. 2). The effect of human-induced global warming has even contributed to recent heavy precipitation events (Min et al., 2011). Given that greenhouse gas emissions are one of the factors that affect the future of climate change (Carter et al., 2015), and considering buildings as huge consumers of energy (Stojiljković et al., 2015) and thus one of the largest contributors to the increase in greenhouse gas emissions, designing energy efficient buildings should make a substantial difference in climate change mitigation.

Climate change is known as one of the planetary boundaries which seems to have been crossed. The concept of planetary boundaries was proposed by environmental scientists in 2009, focusing on conceptualising the relationship between humanity and nature, and this links to the concept of the Anthropocene, defined as the period in which human activities have been the main drivers of global change. The debates around the pace of environmental change have meant the possible benefits of sustainable development have become the centre of attention (K. Brown, 2017). Increasing the energy efficiency of buildings is one strategy suggested for climate change mitigation (Newman et al., 2009, p. 64).

Research shows that global warming will continue growing if measures and policies are not passed by authoritative organisations or met by influential industries (Y. Chen, 2015). Many countries have set out policies and initiated research for controlling and mitigating the potentially excruciating effects of climate change on human lives.

The increased attention being given to the concept of a low carbon future seems to be behind national-scale programs such as *CarbonWatchNZ* in New Zealand that focuses on the whole country carbon balance through measuring greenhouse gasses in the atmosphere (NIWA, 2019). The temperature increase is expected to affect several aspects of building performance and this will happen through change in the patterns of energy consumption.

1.3 Building performance from the standpoint of energy use

The raising of environmental awareness has been described as the primary reason for developing the concept of building performance-based design (PBD) (Hens, 2016). The concept of performance was first introduced by Blachere (1965) and led to its introduction in building (1972) defined by the International Council for Building Research Studies and Documentation (CIB) Commission (Foster, 1972).

Building performance can be evaluated from the three perspectives of 1) the requirements of the occupants, 2) economic sense, and 3) environmental performance (Leaman et al., 2010). The latter explains and evaluates the characteristics of buildings with regards to their environmental impact and from the perspective of energy and material flows (Lützkendorf et al., 2005). Therefore, one of the approaches to improving the environmental performance of a building is to reduce its energy use. Reduction in energy consumption seems to be a significant requirement for future building design as buildings consume 40% of total global energy consumption (Sustainable Buildings and Climate Initiative (SBCI), 2009).

From another point of view, building performance relies on climatic conditions and building physics (Y. Chen, 2015). Regarding the latter, greater disassociation between indoor and outdoor conditions necessitates more rigorous building performance requirements as it leads to consuming a great deal of energy to keep the internal environment comfortable. This shows the importance of building physics as a means of reducing whole building energy consumption.

Bearing in mind the climate change effect on building performance, the notion emerges that "*Building physics—and its potential to quantify related performance requirements—is at the forefront of building innovation*" (Hens, 2016, Preface). The idea that innovation is essential for achieving sustainability (Duncan, 2000), presents a new perspective on investigating innovative solutions for designing energy efficient buildings, improving their environmental performance, and ultimately mitigating climate change disasters.

1.4 Nature offers innovative solutions for energy efficient building design

Technological innovations can increase the energy efficiency of energy-consuming systems (Herring & Roy, 2007). In the same context, biomimicry has been recognised as an innovative design approach for improving energy efficient design (Lurie-Luke, 2014; Radwan & Osama, 2016, pp. 45-46; Pedersen Zari, 2018, p. 45). As Angela Nahikian of Steelcase stated:

"*Nature is constantly innovating, endlessly experimenting and ever reinventing itself in the face of new challenges. From materials and products to business models, biomimicry offers a fresh lens for all the dreamers and doers remaking the man-made world.*" (The Biomimicry Institute, 2019).

One of the benefits of adopting biomimicry principles in the construction industry is the potential reduction in global warming. It seems that nature uses low energy processes (Oguntona & Aigbavboa, 2018) and this suggests the presence of numerous examples of biological organisms which could be explored for the energy efficient processes they use to inform innovative solutions for solving human design problems. It has also been suggested that Biomimetic design might provide opportunities for creating a shift in the conventional ways of design (Vincent et al., 2005).

1.5 The importance of access to relevant biological information

Several tools and methods have been developed to enable design-by-analogy in different disciplines. Designing such tools for translating data is significant as between any two distinctive fields of knowledge, the distance from analogy, modality of representation, and expertise affects the outcomes of bio-inspired design (Fu et al., 2014).

The points mentioned in 1.2, 1.3 and 1.4 highlight the benefits of providing access to biological information. Considering biomimetic design as a cutting edge field of innovative technology that promises sustainability and energy efficiency for the built environment, investigating the possibility of developing a system for connecting architecture and biology that would suggest innovative biologically based energy efficient solutions for improving the energy efficiency of buildings, seems important.

The usefulness of the system also needs to be evaluated as *"For the last thirty years, in much of the English-speaking world … when asking ourselves whether we support a proposal or initiative, we have not asked, is it good or bad? Instead we inquire: Is it efficient? Is it productive?"* (Judt, 2009).

1.6 Problem statement and hypothesis

While there is evidence that shows biomimicry can improve the energy efficiency of buildings, there is no system for connecting biology and architecture. Accepting the fact that transition of knowledge from one field to another needs a procedure, in the design of bio-inspired energy efficient buildings there seems to be a need for a system to link the two different fields of knowledge.

The design approach taken in existing bio-inspired energy efficient buildings is metaphoric and non-methodological. Considering technological innovation and sustainability as the two main promises of biomimicry, bridging the gap between architecture and biology could improve the energy consumption of future buildings and thus be part of constructing a low carbon future.

Given this situation, this research sets out to investigate the possibility of developing a systematic process for designing bio-inspired energy efficient buildings. The aim is to improve the current state of the bio-inspired design approach from a non-systematic, random-based selection of biological solutions that seems to be built on the pre-existing knowledge of biology, to a system for methodologically identifying relevant biological energy efficient strategies, based on the thermal challenges identified through the evaluation of the energy use patterns of a particular building.

1.7 Thesis structure

This thesis starts by highlighting the problem in accessing biological information, which seems to be significant for designing bio-inspired energy efficient buildings. Addressing the problem, **Chapter 2** provides an introduction to biomimicry. **Chapters**

3 and 4 continue the literature review by investigating the contribution of biology to the embodied and operational energy of buildings. Reviewing the literature reveals the current gap which is explained in detail in **Chapter 5**. **Chapter 6** describes the research design, methods, the main research questions and the necessary steps that should be taken to answer the research questions. **Chapter 7** deals with investigating the thermal challenges in five case study office buildings in New Zealand. These thermal issues then feed into a framework known as the thermo-bio-architectural framework (ThBA), which is developed by conducting a comprehensive literature review on biological thermal adaptation strategies in **Chapter 8**. The ThBA is then evaluated and confirmed by experts in biology as it needs to be reliable in order to be used for designing energy efficient bio-inspired buildings. The assessment of the ThBA and how this was achieved is explained in **Chapter 9**. **Chapter 10** describes how the thermal issues found in **Chapter 7** can be used as inputs to the ThBA to connect them systematically to relevant thermal adaptation strategies in nature. It also describes the level of innovative solutions the ThBA suggests. **Chapter 11** concludes the research and addresses the research questions and future research areas. The structure of the thesis is shown in Figure 1-1.

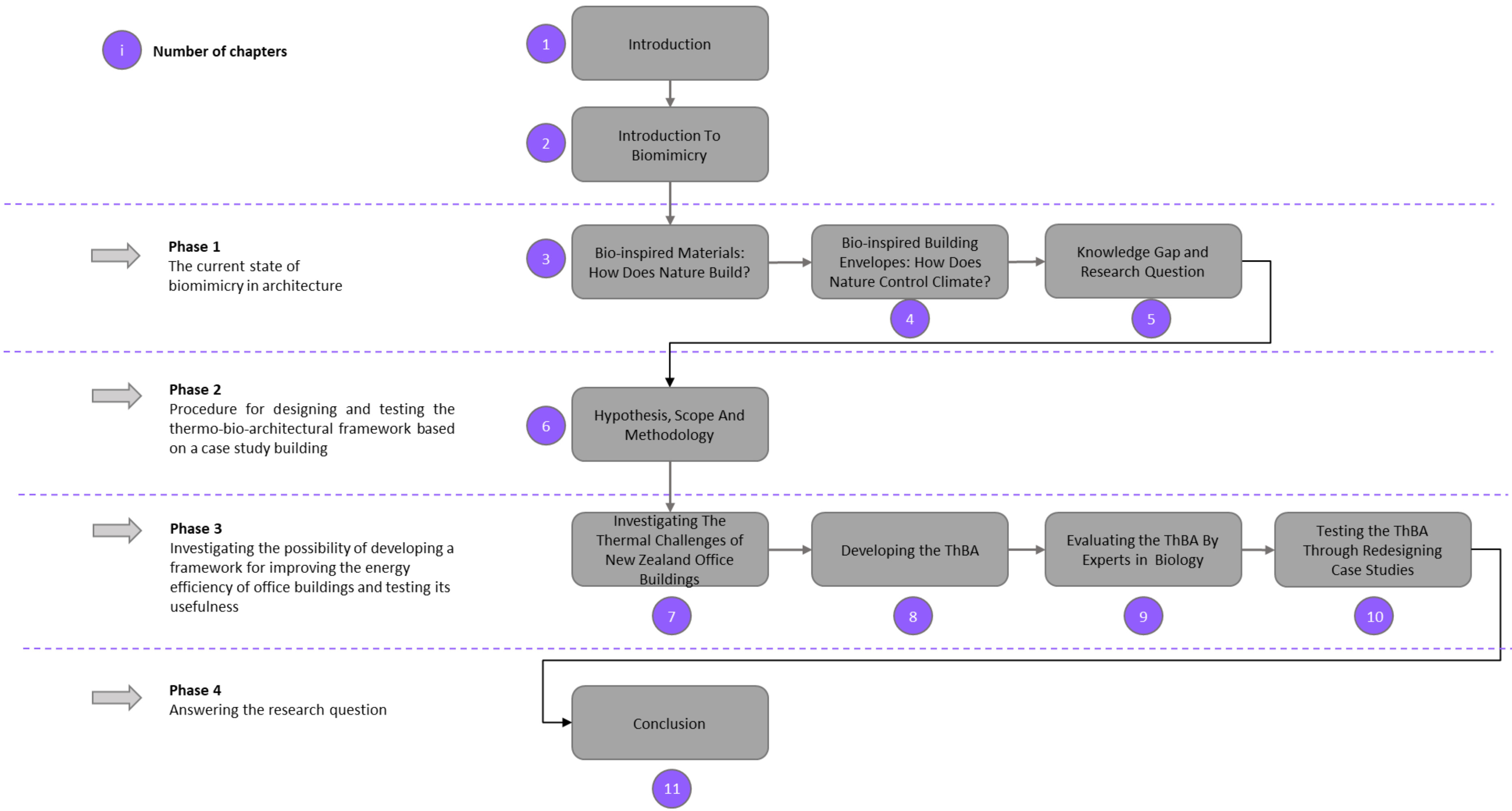

Figure 1-1 Thesis structure

2 Introduction to Biomimicry

2.1 Bio-inspired design: its origins and background

Design inspired by nature or biology is often referred to as biomimicry. The word biomimicry is the combination of biology and mimicry. Mimicry is derived from the Greek word *mimesis* which relates to the concept of *mimos* and refers to *"the act or the ability to simulate the appearance of someone or something else"* (Marshall & Lozeva, 2009). The Ancient concept *mimos* literally means '*actor*' or something or someone representing life. However, in the context of architectural design it tends to mean copying aspects of natural organisms.

The term biomimicry was first coined by Janine Benyus (1997) in her book *Biomimicry: Innovation Inspired by Nature*. Since then in research, the terms Biomimicry, Bionics, and Biomimetic, have been used interchangeably. Biomimetic is involved with artificial mechanisms created to produce materials similar to ones that exist in nature (Reap, 2009), and is thus different from bionic design, which consists of taking control of nature (Wahl, 2006) and which seeks to resolve engineering problems using data related to biological functions (Reap, 2009). Much earlier and before the term biomimicry appeared Papanek (1974) argued that bionics is related to *cybernetics* and Vogel (1998) claimed that it focuses on artificial intelligence. In contrast, biomimicry is primarily focused on aspects of built environment sustainability (Wahl, 2006) and imitating nature's efficiency (Reap, 2009).

Janine Benyus argues that looking at nature and imitating its existing models, systems, and processes could solve design problems in a sustainable manner (Benyus, 1997, p. 40). Pawlyn (2011) suggests biological organisms can be considered as embodying technologies that offer sustainable solutions. She also recommends focusing on the functional aspects of biomimicry rather than morphological imitations of biological samples. Technological innovations and sustainability criteria are also seen as interrelated aspects of biomimicry as Rao (2014) explains: "*biomimicry uses an ecological standard to judge the sustainability of our innovations*". Biomimicry has been argued to serve two main purposes: innovation and sustainability (Pedersen Zari, 2012). Bar-Cohen (2005) stated that biological processes have also been acknowledged as being "*far superior*" to human innovations.

Biomimicry is not a new design approach. The origin of biomimicry or biologically inspired design can be traced back to Leonardo Da Vinci's flying machine inspired by birds (Pohl

& Nachtigall, 2015), and later the bio-inspired style of Art Nouveau (1890-1910) was manifested in both architecture and the visual arts (Harris, 2012, p. 213). Looking at these former examples of bio-inspired design, it seems both were mainly focused on the formal aspects of nature, with little attention being paid to imitating the functional principles of natural organisms (Pohl & Nachtigall, 2015). This issue was addressed by Nachtigall (2010) in his book "*Bionik als Wissenschaft*" (Bionics as Science). As later suggested by Pohl and Nachtigall (2015), this was the book in which the technological applications of natural principles were probably taken into account for the first time, and where the fundamental idea of Biomimetics also took shape.

The principal focus of this chapter is to investigate the philosophical approach of biomimicry to determine whether it could help in finding new techniques in nature for use in buildings.

2.2 The philosophy of biomimicry

Biomimicry is a design philosophy that has already been applied to architectural design. A small number of researchers have discussed the philosophy of biomimicry (Bensaude-Vincent et al., 2002; Mathews, 2011; Blok, 2016; Blok & Gremmen, 2016; Dicks, 2016). Mathews (2011) was one of the first authors to try to provide a philosophical basis for biomimicry. He also believes biomimicry could produce a second industrial revolution. Despite the dominant role of biomimicry in the industrial sector, its philosophical aspects have remained underdeveloped and descriptive, leaving the ethical approach to biomimicry unexplored (Mathews, 2011). Other philosophers such as Blok and Gremmen (2016) have conceptualised biomimicry as an ecological form of technological innovation. The ethical and ecological approaches to biomimicry are not examined further here as they are not fundamental to the goal of this research. Instead, the technological approach to biomimicry is discussed as it is the motivation for the biomimicry approach in this study.

Benyus (1997) defined a set of dimensions for biomimicry through which key aspects of the human relationship with nature are shaped: nature as model, nature as measure, and nature as mentor. These are summarised below.

> **1) Nature as Model:** "Biomimicry is a new science that studies nature's models and then imitates or takes inspiration from these designs and processes to solve human problems, e.g., a solar cell inspired by a leaf."

2) Nature as Measure: "Biomimicry uses an ecological standard to judge the 'rightness' of our innovations. After 3.8 million years of evolution, nature has learned: What works? What is appropriate? What lasts?"

3) Nature as Mentor: "Biomimicry is a new way of viewing and valuing nature. It introduces an era based not on what we can extract from the natural world, but on what we can learn from it." (Benyus, 1997, Front matter)

Some researchers believe these three dimensions form the basis for classifying the different approaches to biomimicry (P. A. Reed, 2003; McGregor, 2013), although others have critiqued them (Mathews, 2011; Dicks, 2016) as they believe the three dimensions stated by Benyus are more related to the concept of nature as physics and that the philosophical aspects of biomimicry have not been adequately developed by these three dimensions. Dicks (2016) refers to nature as model, nature as measure, and nature as mentor as being the poetic, ethical, and epistemological principles of biomimicry respectively, but he also argues that the philosophy of biomimicry includes another dimension that is more about questioning the meaning of nature in a deeper philosophical approach.

As discussed by Mathews (2011), this dimension does not seem to be addressed by Benyus' second set of principles, which contains nine statements. These seem to be more about the descriptive aspects of biomimicry rather than discussing what nature truly is. Benyus (1997, p. 7) refers to these statements as strategies and laws. These principles are:

- Nature runs on sunlight;
- Nature uses the energy it needs;
- Nature feeds form to function;
- Nature recycles everything;
- Nature rewards cooperation;
- Nature banks on diversity;
- Nature demands local expertise;
- Nature curbs excess from within and;
- Nature taps the power of limits; (Benyus, 1997, p. 7)

Coming back to the three main dimensions of biomimicry suggested by Benyus, in recent years 'nature as model' appears to be the approach most often followed by scientists. Pedersen Zari (2012) suggests most biomimetic designs are motivated by technology and build upon the 'nature as model' definition of biomimicry of Benyus *("a new science that imitates or takes inspiration from designs and processes to solve human problems e.g. a* *solar cell inspired by a leaf"*). This type of approach to biomimicry fails to consider improving performance through innovative design based on ecological principles (Reap et al., 2005; Wahl, 2006), as in the examples below.

- Designing undetectable cameras based on eyes of insects (Toko, 2000; Duparré et al., 2005)
- Emulating DNA to create industrial Nano-machines (Lerner, 2004; Böcking & Gooding, 2007)
- Designing space craft inspired by worms (Thakoor et al., 1999; Ayre, 2004)
- Developing military technology based on studying animals and plants (Amoroso, 1985)

However, in the examples above the technological approach to biomimicry does not address integration with the natural world. Given the relevance of the theory of biomimicry to the technological approach, Myers (2014) states that biomimicry might be more acceptable to architects if it avoids exact imitation of nature's technologies and instead follows a more cooperative and incorporative approach towards engaging natural principles. Wahl (2006) and Wilber (2010) also assert the importance of the human and nature relationship.

Noting that this research aims to concentrate on employing biomimicry as a means to technical innovation, understanding the philosophy of technology is also required. Mathews (2011) believes this understanding, which has been focused on ethical issues, is growing gradually. This suggests biomimicry has not been adequately theorised, and as a result it has remained difficult to distinguish the difference between other approaches to innovation inspired by nature, such as bionic, bio-inspiration, and biomimetic innovation (B. L. Zhou, 2000; Vincent, 2009). Even though the theory of biomimicry and its approaches has not been completely formalised (Marshall & Lozeva, 2009) the literature displays an ongoing attempt towards framing biomimicry into a design method. Researchers have defined biomimicry as a design method using Benyus' principles. For example, Hargroves and Smith (2006) say that interpreting nature as model, mentor, and measure has formed the foundation of biomimetic design, and has provided an opportunity for researchers to take advantage of this knowledge. Others have discussed biomimicry more generally. For instance, Koelman (2004) refers to biomimicry as a new pathway for design and construction.

From this brief overview of the concept of biomimicry, its theory, and approaches, it seems there is not yet an agreed inclusive and fixed classification for these. Nevertheless, worthwhile steps have been taken towards classifying biomimicry approaches. These classifications are not necessarily interrelated and have been shaped based on a varied understanding and interpretation of biomimicry.

2.3 Motivations behind biomimetic design

It seems that biomimicry serves the two main purposes of innovation and sustainability. Pawlyn (2011) states biological organisms can be considered as embodying technologies that might offer sustainable solutions. As discussed above, Benyus as a biologist, author, and innovation consultant, has introduced biomimicry as both an environmental theory and a design approach, and as a path to solving design problems sustainably (Benyus, 1997). Based on her claim, Aziz and El sherif (2016) believe the most important aim of biomimicry is sustainability. Pedersen Zari (2010) has a similar opinion of biomimicry and has explored the potential of applying ecological strategies to the built environment. She follows a system-based regenerative design approach (B. Reed, 2007) in which buildings are considered as small parts of a large system (their environment). The relationship between buildings and their environment resembles the relationship between organisms and their ecosystems.

There are different opinions regarding the fundamental means by which the basis of a sustainable approach to biomimicry takes shape. These foundational levels have been referred to as the form, process, and function of organisms (Gamage & Hyde, 2012; Kennedy et al., 2015). From another point of view, these can be described as:

- imitation of an organism's feature(s)
- imitation of an organism-community relationship, and
- imitation of an organism-environment relationship (El-Zeiny, 2012)

Technological innovations and sustainability criteria could be interrelated aspects of biomimicry as Rao (2014) explains: *"Biomimicry uses an ecological standard to judge the sustainability of our innovations"*. Other researchers such as Elmeligy (2016) consider there should be a third motivation for biomimetic design, this being an increase in human wellbeing based on understanding the living world. This is referred to as *bio-philia*. Marshall and Lozeva (2009) have introduced another approach to biomimicry, which they term *Ecomimicry*, whereby design values are more focused on ecological issues. In relation to the ecological approach to biomimicry, Blok and Gremmen (2016) have stated that biomimicry can be conceptualised as an ecological form of innovation. To sum up, considering nature as model, measure, and mentor leads to technological/innovative, sustainable/ecological, and epistemological approaches respectively.

As a new approach to design, biomimicry has both its opponents and proponents. Table 2-1 compares the ideas of a number of these opponents and proponents. Even though, the former believe the technological applications of biomimicry have not proved to be sustainable and that biomimetic design is still premature, many recent studies show that bio-inspired building design can lead to sustainable solutions (Tachouali & Taleb, 2014; Alkhateeb & Taleb, 2015; Y. Han et al., 2015; Kim & Torres, 2015; Nessim, 2015; Al Amin & Taleb, 2016), thus highlighting the usefulness of bio-inspired designs. Table 2-1 covers the theoretical arguments rather than those proved by practical building design.

Table 2-1 Opponents and proponents of biomimicry

Opponents	Proponents	Main argument
(Papanek, 1974)		Designers' viewpoints towards nature are '*clouded by a romantic longing*'. Designers interested in biomimicry should not lose their critical view of what is useful, as if they do, biomimicry is overshooting its goal.
	(Benyus, 1997)	"*Doing things the natural way*", makes technological improvements more naturally embedded. This also harmonises man-made systems with natural ecosystems
(Vogel, 1998)		Biomimicry is naive Translating the exact technology found in nature into design without any adjustments is not possible The majority of designs are unsuccessful
	(Hawken et al., 1999)	Similar to arguments of Benyus (1997)
	(McDonough & Braungart, 2002)	Similar to arguments of Benyus (1997)
(Bensaude-Vincent et al., 2002)		Biomimetic seems more like a slogan made by chemists who seek to dominate sustainability issues in the context of chemistry. Sceptical that being biomimetic is a real revolution
(Reap et al., 2005)		*"A biomimetic design approach does not necessarily mean the resulting product or material will be more sustainable than a conventional equivalent when analysed from a life cycle perspective."*
(Kaplinsky, 2006)		Biomimicry is more like technological innovation rather than ecological evolution Biomimicry does not guarantee nature-given solutions are better than man-made ones
Baumeister cited in (Pedersen Zari, 2007)		Some designers consider moving towards sustainability when they employ a biomimetic approach, while others only use it as a source of innovation
(Mathews, 2011)		Biomimetic implications are not developed in a philosophical way
	Schuknecht cited in (Abrahms, 2012)	No disadvantages
(Volstad & Boks, 2012)		Many past bio-inspired projects have remained at a conceptual level and are never launched
(Buraczynski, 2013)		There is a chance of endangering humans if biomimetic architecture fails Humans mimic nature simplistically Biomimicry is still premature
(Blok & Gremmen, 2016)		Biomimicry is ambiguous when it discusses "*technology versus nature, discovery versus intervention, (technological) exploitation versus (ecological) exploration, and so on*"

2.4 Application of biomimetic approaches to architecture

The application of biomimicry in architecture could emulate the process and function of natural organisms instead of imitating morphological aspects of biological samples, but this accessing and understanding these functions could be harder than just imitating natural forms.

From a different perspective, biomimicry can be placed into the two categories of direct and indirect approaches (Panchuk, 2006; Vincent et al., 2006). In the direct approach, biological strategies, behavioural patterns, or ecosystem functions are replicated exactly and while the indirect approach involves abstracting ideas found in nature and using these as design principles.

2.4.1 Problem-based and Solution-based Approaches

Another pairing of approaches consists of bottom-up (solution-based) and top-down (problem-based). Solution-based and problem-based approaches have also been called '*biology push*' and '*technology pull*' respectively (Pohl & Nachtigall, 2015). These two approaches were distinguished for the first time by Vattam et al. (2008). Problem-based and solution-based approaches have also been called '*challenge to biology*' and '*biology to design*' respectively (Badarnah & Kadri, 2015). Pedersen Zari and Storey (2007) defined the problem-based approach as '*design looking to biology*'. In other research Helms et al. (2009) and Goel et al. (2011) focused on Biologically Inspired Design (BID) processes and getting students to use these to design bio-inspired models. Their observation of the usage of biological analogies by students assisted them in confirming these two distinctive approaches to bio-inspired design.

In the problem-based approach, real-world problems are identified by designers who look to nature and use the assistance of biologists to solve the problem. Taking the same stance, El-Zeiny (2012) developed a framework with the purpose of assisting architects to find an appropriate approach for applying biomimicry to design. Badarnah and Kadri (2015) studied the strategies of five problem-based approaches to biomimetic design:

1) *Biomimicry 3.8* led by Benyus
2) *BioTriz* led by Julian Vincent (Vincent et al., 2005)
3) '*Biomimetic for Innovation and Design Laboratory*' led by Li Shu (Mak & Shu, 2004)
4) 'Design & Intelligence Laboratory' led by Goel, and
5) '*Plants Biomimetic group*' led by Thomas Speck (Speck et al., 2008).

The common threads behind the bio-inspired design process in all five approaches include the following:

- Definition: the problem is defined or the function and the context are identified;
- Abstraction: functions are changed to key verbs, the question is reframed and a conflict is formulated;

- Exploration and investigation: this involves research in databases and biological textbooks, and collaboration with biologists;
- Classification: the biological information is evaluated and classified;
- Final stage: this includes identification of principles, designing concepts, emulating the principles and finally evaluating the results (Badarnah & Kadri, 2015)

A methodology for the problem-based BID approach was also developed by Badarnah and Kadri (2015) called *BioGen*. This is claimed to be useful for generating biomimetic design solutions based on studying the methodologies offered by the five approaches (Figure 2-1).

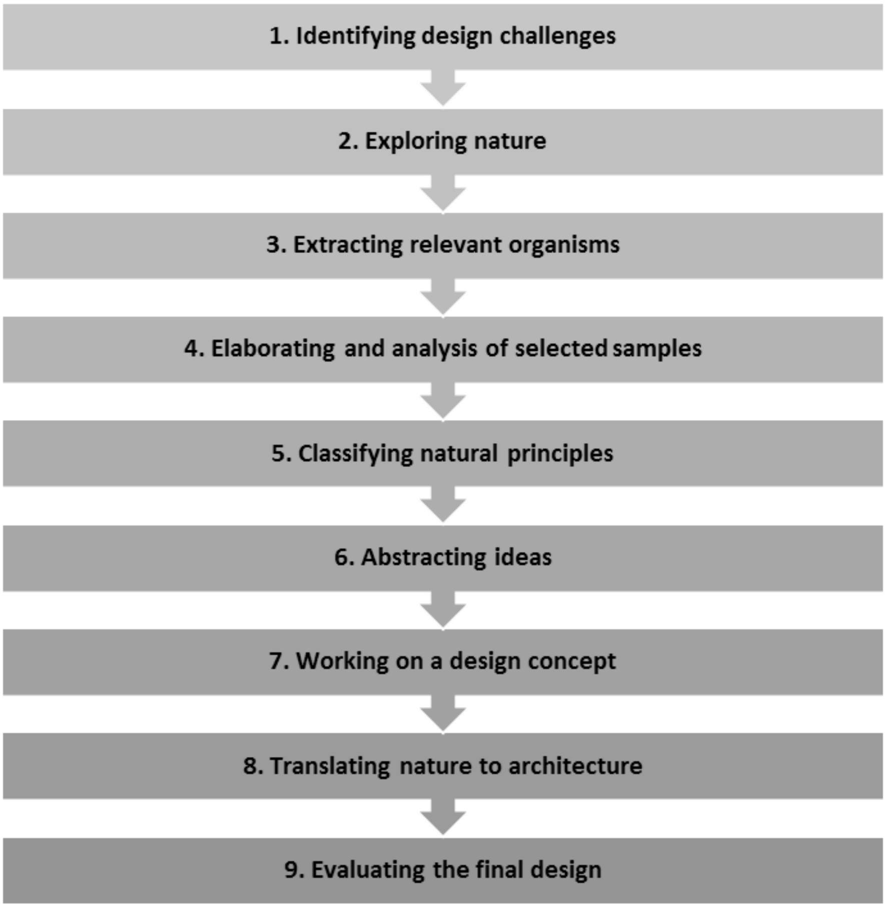

Figure 2-1 BioGen methodology adapted from Badarnah and Kadri (2015)

Although these methodologies sound useful they all suffer from a lack of clarification in the exploration and investigation stage, as although the purpose is to find relevant biological samples, there is no explanation of how this search should be conducted. This is a missing link that will form the focus of this research.

In the solution-based approach, specific knowledge of biology leads to solutions which are not necessarily predetermined. In this approach, designers know how to design because they have the biological knowledge to give them the solution at the outset (Vincent et al., 2005).

2.4.1.1 Earlier frameworks for problem-based bio-inspired design

Because biology and architecture are two different knowledge domains that have no obvious overlap in education, for BID to be successful there needs to be a way for designers to find the relevant analogies in biology and subsequently translate these into architectural design principles. To this end, a number of tools and frameworks have already been developed by researchers to support the bio-inspired design approach.

State-Action-Part-Phenomenon-Input-oRgan-Effect (SAPPhIRE) is a model developed by Chakrabarti et al. (2005) that contains several levels of abstraction of function through which the function of any biological system can be described. This is a modelling framework which provides information about previously used biomimetic samples, and considers the structural, behavioural, and functional aspects of these. In this software, textual representation of organisms is used as nouns, verbs, and adjectives to describe engineering design problems. Biological engineering design is then achieved by matching the texts to the database. Mechanical engineers work with *SAPPhIRE* (Helms et al., 2009). This model has been further examined by Sartori et al. (2010) by focussing on biological transfer mechanisms, and thus translating biological principles into design principles. Another tool called *IDEA_INSPIRE* has been developed based on *SAPPhIRE* by Chakrabarti et al. (2005).

Other studies have suggested a framework for BID. The Structure, Behaviour, Function (SBF) model developed by Goel et al. (2009) represents biological models through their relationships (function, behaviour, and structure, hence SBF). This model has been reported as working effectively for BID (Helms et al., 2010) and has been extended into a big library of SBF models called Design by Analogy to Nature Engine (DANE) (Vattam et al., 2011). DANE is a thus database built on SBF modelling (Vattam et al., 2011; Wiltgen et al., 2011).

Pawlyn (2011, p. 4) states "*Biomimicry has been defined as mimicking the functional basis of biological forms, process and systems to produce sustainable solutions.*" Thus the BID process would seem to benefit from frameworks such as SBF and *IDEA-INSPIRE*, as all are focused on explaining a system by means of abstracting its functions.

Gamage and Hyde (2012) have suggested a Biomimicry Theoretical Framework (BTF) that could be viewed as holistic approach. They suggest their "*bottom-up*" theory is better than the approaches adopted by others. However, this is totally in contrast to the problem-based bio-inspired design approach discussed above. They claim there is a problem with the whole idea of the application of biomimicry principles and that BTF is a problem solving process. This seems somewhat unreasonable as they have not defined how biomimetic principles can be applied in the architectural design process, whereas defining a framework seems an important, or even the main step, in applying biomimetic design to architecture.

2.4.1.2 Solution seeking and bio-inspired design

The term Design-by-analogy (DBA) has application in different fields of knowledge including engineering, architecture, and computational design and is relatively important in the bio-inspired design approach. As Gentner (1983) stated analogy happens where two situations are connected either through relational or representational establishments.

DBA has been referred to as a method for assisting designers to find solutions or analogies in the field they are looking to for inspiration. Different methods have been developed based on analogy. Moreno et al. (2014) argue these methods can be grouped into three categories based on where the exploration for analogies occurs.

1) Methods that are used to take inspiration from the natural world in a general format.
2) Methods employed in the context of knowledge-based domains such as engineering and architecture to improve biomimetic or bio-inspired design concepts (Mak & Shu, 2008; Helms et al., 2009; Chakrabarti & Shu, 2010; Nagel & Stone, 2011).
3) Methods for developing existing analogous solutions through effective abstraction of functional models and flows (Hirtz et al., 2002; Chakrabarti et al., 2011).

In addition research has also been conducted on improving exploration in the target knowledge domain through the way design problems are presented (Segers et al., 2005; Linsey, Wood, et al., 2008).

The origin of the concept of functional modelling can be found in earlier research focusing on knowledge-based or expert systems, such as *ARGO* (Huhns & Acosta, 1988), that incorporate a series of techniques for facilitating the design-by-analogy process. Functional modelling could almost be considered to be the basis of all data extraction systematic methods (Stone & Wood, 2000) and is aimed at minimising fixation on previous ideas generated by precedents (Vincent et al., 2005; Lucero et al., 2014) by providing access to a large number of analogous examples (G. Pahl, 1996; Otto & Wood, 2000; Chakrabarti & Bligh, 2001). Fixation on what is already known can limit the quality of the final design concept as the researcher is not motivated to investigate the most effective methods for dealing with unfamiliar examples (Ngo, 2014). According to the literature there is evidence that functional modelling has been useful for identifying design solutions and accordingly implementing them into a new design process (Casakin & Goldschmidt, 1999; Ball et al., 2004; Christensen & Schunn, 2007; Chan & Schunn, 2015).

Most of the existing tools for performing functional modelling retrieve the relevant samples from databases by using a verbal abstraction of the design problem and then looking for the best matches through linguistic similarity (Chakrabarti et al., 2005; Vattam et al., 2011; Goel et al., 2015). Thus functional modelling, as a common tool for abstracting ideas (Qian & Gero, 1996; Hirtz et al., 2002; Gerhard Pahl & Beitz, 2013), is manifested in different ways in which the analogous models are represented by a series of keywords that describe their functions.

Functional basis is a generalised taxonomy of all functions (channel, support, connect, branch, provision, control magnitude, convert and signal) (Hirtz et al., 2002). Iterative taking apart of these main functions generates more specific functions. The generalised flow taxonomies are material, energy, and signal. The more functions are fragmented and specified, the more specific flows are generated (Lucero et al., 2016). The functional model is basically an expanded version of the '*black box*' including all sub-functions and flows, as explained below.

A '*black box*' model is a mainly qualitative approach for retrieving analogies through a workflow. This model is used for formulating the overall design function and is composed of three parts: input, function, and output, where inputs are defined as those which enable the function, and functions as items that generate the outputs (Agyemang et al., 2017). This simplified 'black box' functional model can be further expanded into a model that includes sub-functions connected by material, energy, and information flows. Figure 2-2 for instance, shows the '*black box*' and functional models for a *SuperMaxx ball shooter*.

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Figure 2-2 Top) 'Black box' model, Bottom) Functional model (Agyemang et al., 2017)

There are many databases available when using the DBA approach but few tools have been developed to assist designers in extracting relevant data from these. There has been some research focus on testing new methods for extracting relevant examples from the existing databases in a systematic way. *WordTree* is one such method that systematically guides designers through the design process. Using this method different representations of the design problem lead to unexpected innovative analogies (Linsey, 2007). The *WordTree* method has three main steps:

1) The design problem is described by different words that represent the key functions (multiple linguistic representations of the design problem). This problem representation happens through the *WordTree*;
2) Potential analogies and domains are identified and researched, and
3) These analogies and domains are used for generating ideas.

For example if the aim is to design a laundry folding device (LFD), in step 1 the key functions required for this device to work are abstracted and described by using the combination of a) the functional model, b) the '*black box*' model (see 2.4.1.2), c) mission statements, and d) customer needs. The descriptive keywords derived from these four methods should be in the form of single word action verbs.

The '*black box*' model of the LFD represents the inputs needed for the device to work properly and, correspondingly, the consequent outputs of the device. In this case the customer needs can be described by the verb *fold*. Figure 2-3 shows the functional and black box models.

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Figure 2-3 Top: Functional model, Bottom: 'Black box' model (Linsey, Markman, et al., 2008)

In step 2, the key problems identified in step 1 need to be re-represented and arranged using *WordTree*. This enables the designer to recognise the relevant examples (analogies) and analogous domains. All the key functions are hierarchically structured starting from the more general words (hypernyms) to the more specific ones (troponyms), with the main initial word sitting in the middle of the *WordTree* (Figure 2-4). In this step the *WordNet* database is also used to produce additional results as this database supports natural language processing and provides users with additional words that are similar to those found in step 1 (Veale, 2006).

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Figure 2-4 Hierarchically structured key functional words adapted from Linsey (2007)

WordTree can be further extended once the additional terms found by *WordNet* are discovered. Figure 2-5 shows the enhanced model of the *WordTree* where unfamiliar words expose previously distant analogies (hypernyms). The discovered analogies are then studied in step 3 as the basis of generating innovative ideas.

Analogous domains can usually be discovered in parallel branches. For example, dousing a sail (lowering quickly) and reefing a sail introduce sailing as an unfamiliar analogue domain that could inspire innovation. However, the research conducted by Linsey (2007) did not go as far as describing the final innovative concepts produced by the design teams that would have shown the effectiveness of this approach.

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Figure 2-5 Extended version of the *WordTree* as adapted from Linsey (2007)

Other analogy-type tools using computational methods have been developed that offer support to the design-by-analogy approach. These methods enable systematic web-based searches through which designers can rapidly find the most relevant analogies in either a general source or in patent databases (Murphy et al., 2014).

Murphy et al. (2014) utilised the functional vector space model (VSM) as an approach to functional-based DBA. Their research had four main steps that were also used later by Fu et al. (2015). The details of all four steps are summarized in Figure 2-6.

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Figure 2-6 Summary of the computational DBA method adapted from Murphy et al. (2014)

The main purpose of developing these solution seeking methods was to enable retrieval of non-obvious analogies. This implies that researchers have always been concerned with the dissimilarity of different knowledge domains and consequently the need to increase the effectiveness of the techniques for concept generation. However, as argued by Blanchette and Dunbar (2000), retrieving analogies from the large number of data repositories, which have been set up for different fields of knowledge, is difficult, and identified analogies are not necessarily exactly matched to specific design problems. For example using the systematic search method suggested by Murphy et al. (2014) the functional model and black box model of an automated window washer is shown in Figure 2-7 and Figure 2-8.

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Figure 2-7 The '*black box*' model of an automated window washer (Murphy et al., 2014)

The functional semantic representations of the simplified functional model are: import, transform, transmit, regulate, couple, support, and remove. In turn some of the fragmented functions of the generalised ones are: channel, branch, convert, control, connect, support.

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Figure 2-8 The functional model of an automated window washer (Murphy et al., 2014)

The query generation tool (Figure 2-9) is used to generate additional similar secondary functions. Using these additional functional key words, the tool provides designers with the most relevant patent documents. Computational methods used in the tool enable retrieval of the analogous patent descriptions, which are ranked based on their relevancy scores. Basically, a previous patent description indexed using the most similar or common functional keywords is distinguished by the tool as the best match to the design problem.

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Figure 2-9 The query generation tool (Murphy et al., 2014)

The research conducted by Fu et al. (2015) built upon the previous research by Murphy et al. (2014) as they developed a method for investigating the extent to which source analogies were similar to each other (Fu, Cagan, et al., 2013; Fu, Chan, et al., 2013). Discovering the relationships between the source analogies allowed for their clustering.

Fu et al. (2015) analysed the functional similarity of all source designs, in this case patent descriptions of the products or existing analogies, in mapping software by developing natural language processing algorithms. They also standardised the language processing of the functional models based on the functional basis approach developed by Stone and Wood (2000) and Hirtz et al. (2002). The research of Fu et al. (2015) comprised four steps, which are similar to those developed by Murphy et al. (2014):

1) Processing knowledge databases using algorithms,
2) Generating functional vocabulary,
3) Retrieving information and clustering data through query generation tool, and
4) Analogical mapping using algorithms.

In the first part, natural language processing algorithms were employed to reduce the documents to their key functional terms. Next, the results were represented by the Vector Space Model (VSM) in which each document was shown by a vector of the retrieved functional words. In step 2 a set of functional words were selected in a manner that would cover all the documents in the databases. Based on the functional words retrieved, in step 3 the documents were indexed again in a new database. This database was created to formulate the query. In step 4 the database was set up, and designers would be able to enter any functional words related to the design problem into the query generator. The query generator tool would then assist designer in identifying the primary and secondary functions related to the design problem. In the final step the database would list the most relevant patent documents in a PDF file as somewhere a designer can look for inspiration. The results showed that using this method, more relevant documents and hence novel ideas were generated.

To illustrate this process, Fu et al. (2015) described the design problem below:

> "*Design a device to collect energy from human motion for use in developing and impoverished rural communities in places like India and many African countries. Our goal is to build a low-cost, easy to manufacture device targeted at individuals and small households to provide energy to be stored in a battery. The energy is intended to be used by small, low power draw electrics, such as a radio or lighting device, hopefully leading to an increase in the quality of life of the communities by increasing productivity, connection to the outside world, etc*."

The primary functional words were: collect, convert, store, low cost, easy to manufacture, and portable. The secondary functional words were: import, convert/transform, transport, move/rotate/oscillate, collect, produce, and export/supply. The second set of keywords was concurrently used in a patent document called "*Wave-operated power apparatus*". This analogous patent could not have been found if the secondary functions/sub-functions had not been generated. Getting inspiration from this find, a floating bridge was designed capable of extracting the energy from people who walked over the bridge to cross the river.

The purpose of this investigation was to see how similar the functional descriptions of the design problems were to those of the design solution examples. Using these algorithms, all the documents in the databases can be reduced to a small number of analogue functional keywords. This enables designers to look for the closest match to their design problem. The results showed that the tool provided designers with the most relevant examples in the literature.

The Design by Analogy Performance Parameter System (D-APPS) (Lucero et al., 2014; Lucero et al., 2016) is another computational tool that retrieves analogies based on the performance parameters of design problems and design solutions. While previous DBA tools had mostly evaluated the linguistic similarity of the functions/SBF, this approach was focused on the performance correlations of those functions. In other words, it was predicted that more analogies would be found if designers could also search for the performance or quantifiable aspects of the design problems. Lucero et al. (2016) also believe certain functions contribute more to the performance. They call these critical functions (CF) and believe that looking for CFs is very important when the designer is looking for analogies in a totally different knowledge domain.

> *"As an example, compare a can opener with a vehicle jack. The primary function of the can opener is to separate a portion of the can to allow access to its contents. The primary function of a vehicle jack is to lift the vehicle. If the design problem were to improve the energy efficiency of the design, both examples would suggest that the convert (energy) function would be the most significant. However, the can opener is only functional if the separate function is also effective, while the vehicle lift is only functional if the stabilise and transfer functions are effective. So, the can opener has two CFs while the vehicle lift has three." (Lucero et al., 2016)*

D-APPS is capable of finding analogies within a repository of functional models which have been populated manually. The results of existing experimental '*design-by-analogy*' studies can also be analysed quantitatively based on the performance metrics of the bio-inspired designs. These results are encoded by the D-APPS tool and will return the best match biological samples to the designer.

2.4.1.3 Methods of biological transfer: analogical reasoning for generating bio-inspired design (BID) concepts

In the context of the BID approach, once the relevant examples are determined by the designer, a series of steps needs to be taken so the existing knowledge can be transferred into the new design domain. This stage can be referred to as '*analogical transfer*' or '*biological translation*' (Helms et al., 2009), with the latter being the term used in this thesis. Previous studies sought to formalise the way in which design knowledge, and specifically cross-domain knowledge, can be represented. There is also evidence showing the BID process can be generalised (Lucero et al., 2014; Lucero et al., 2016). Lucero et al. (2016) also note the importance of biological translation phase in a design by analogy process. As they explain, using the D-APPS method shows how the explorative process of DBA can work much more effectively where the source and target design domains are completely different (see 2.4.1.2). In research conducted by Lucero et al. (2014) and (2016), the Structure-Behaviour-Function (SBF) path (see 2.4.1.1) was used as the basis for the DBA process and representations of the functions of the analogue examples were analysed within a broad range of fields, from industrial and graphical design to architecture and engineering. The results showed that even though the domains are different, representation of the function of examples can be still generalised into specific categories (see 2.4.1.2).

The Design-by-Analogy process borrows the variables from an existing domain (source design) for creative use in a new domain (target concept design). It has always been a question of how the relevant examples, whether these are biological or not, can be used in a way that is appropriate for the target design domain. As stated by Qian and Gero (1996), source design (biological examples) and target concept design (building design principles) can be connected using a process. As described by them this process should contain logical links between a series of elements that represent different attributes of the source design, since once the relevant examples are found, only a well-structured knowledge transfer model has the ability to contribute to the new design domain.

Analogical reasoning/transfer is a substantial part of creative design (Boden, 2004) and is a process through which source and target concepts are compared. Using this process the source concept is abstracted and transferred to the target concept. As stated by Cheong et al. (2014), even though analogical translation plays an important role in creative design, it is not fully understood in the biomimetic design approach. Many factors influence the application of biological solutions in architectural and engineering design ranging from cognitive factors (Mak & Shu, 2004) to the inclinations of designers, and design fixations (Mak & Shu, 2008).

Wilson (2008) proposes analogical translation should follow a systematised transfer process. He suggests there are different scale-based schools of thought (at form, process, and ecosystem levels) for translating biology to the engineering domain. Most are used in industrial design and mechanical engineering, although some systems have architectural applications, such as *BioTRIZ* (Gamage & Hyde, 2011). *TRIZ* is a well-established method used for analogical reasoning. Its foundation is a number of generalised problem-solving principles and the *TRIZ* method uses a contradiction matrix. As argued by Otto and Wood (2000), innovation happens when the designer investigates the existing contradictions between the technical characteristics of a subject. He believes looking for these contradictions leads designers to find the main principles that will generate creative ideas. *TRIZ* was further developed and renamed *BioTRIZ*. This version mainly incorporated biological design principles into design. In other words it was used to draw analogies between nature and engineering science. *BioTRIZ* includes design problems that can be matched to previous biomimetic solution strategies (Vincent et al., 2006).

Wilson (2008) also alludes to the lack of cross-domain knowledge. He states that current translation systems are not efficient at extracting biological mechanisms and strategies, and a systematic process is missing. Shu et al. (2011) suggest developing a generalizable translation system is essential.

Moreno et al. (2015) were interested in evaluating the effect of learning DBA methods on the factors selected by participants (individual, performance, self-perception, and contextual factors), these being the most important items affecting their creativity during the design idea generation process. Three different tools (*Control*, *WordTree* (see 2.4.1.2, Figure 2-5) and *SCAMPER*) were used to investigate the influence of cognitive factors on creative performance in design, or in other words, the methods used for formalising design by analogy (DBA). Learning DBA appears to affect creative bio-inspired design when the metrics of fluency, novelty, and fixation have been used to evaluate the generation of creative ideas. This has been proved (Moreno et al., 2015) based on a two-phase experiment, of which the second phase contained a training session on how to use the tool to generate ideas.

Reviewing the literature, most architectural translations are morphological (Badarnah et al., 2010; Elghawaby, 2010; Ahmar & Fioravanti, 2014b, 2015; Y. Han et al., 2015; Kim & Torres, 2015; Reichert et al., 2015). These solutions start with a biological form and look for where to apply it in a building (mostly on facades).

The textual description of biological phenomena known as "*causal relations*" describes how biological functions are achieved through the behaviour of organisms. Causal relation template is a method for formulating analogies to help designer to retrieve the relations between the target and the source knowledge domains (Cheong et al., 2010). This has been proved as beneficial for generating a better concept when it comes to design problems. Studies have investigated the possibility of developing a framework for the concept generation phase of biologically inspired design (Vattam et al., 2008). The aim was to find whether a better textual description of existing BID models could improve problem solving.

The literature suggests analogical translation is more developed in cases where the interaction between computers and designers is important. However, the outline of such a process could be used in the bio-inspired design (BID) approach, which by its nature is a design-by-analogy concept. For example, as suggested by Qian and Gero (1996), the Structure-Behaviour-Function (SBF) framework could be used to describe any source design such as biological examples, by their function, behaviour, and structure. They add that the design process can be developed and shaped through these three aspects (Qian & Gero, 1996). They also claim the SBF framework has been shown to work well, although Maher et al. (1988) suggest that providing only non-abstracted descriptions of the source design (biological examples) is not useful for creative design by analogy.

Generation of creative ideas is not only dependent on the nature of the design problem but also the illustration of the design solutions.

In the context of BID, how the biological examples are presented in terms of the textual description of the selected samples or the graphical illustrations of the solutions they encompass, has been shown to influence the diversity of the final design concepts. This seems to be more crucial where design problems are more technical and hence, where the designers need to be well-informed about the strategies biological examples use to survive. Consequently, such a visual exemplification should provide a better understanding of the natural principles found in the biological solutions that organisms use to overcome the challenges of their environment, and this, therefore, could contribute to a successful BID process. This has been proved by Vandevenne et al. (2016) who measured the impact of the *AskNature* (AN) tool (Figure 2-10).

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Figure 2-10 Biomimicry taxonomy library of *AskNature* adapted from Lucero et al. (2016)

AskNature (AN) is a biomimicry taxonomy library where users can find relevant biological examples by choosing one of the main three groups suggested by AN. These three functions are each branched into three to four subgroups. The last level of narrowing down to the design solution(s) is achieved by selecting one of the functions of these subgroups. This tool was developed to enable a systematic bio-inspired design process for generating creative design concepts. Three conditions were set for comparison: design without AN, design with AN but with textual description, and design with AN by graphical illustration.

Analysis of the concept of analogical reasoning in the context of biomimetic design has been undertaken both through qualitative (observations such as in workshops for BID) and quantitative approaches (numerical representation of similarities between the source and target models).

Overall, in the context of analogical reasoning, the similarity between the source and the target concepts can be represented at both the superficial and relational levels. In biomimetic design the superficial level is related to the attributes of the biological examples while the relational refers to their function (Cheong et al., 2014). Moreover, the relational level is claimed as useful in analogical transfer (Cheong et al., 2014) where designers need to abstract causal relationships (structure, function, behaviour) from the corresponding processes of the biological examples (Goel, 1997).

2.5 Biomimicry and buildings

As a broad concept sustainability has recently become one of the main aspects of building design. Sustainable design is considered to be a leading architectural concept by which the quality of life can potentially be improved in the three (social, economic, and environmental) dimensions (Ortiz et al., 2009). These dimensions are argued to have synergistic relationships.

As part of being environmentally sustainable, a building needs to minimise the fossil fuel energy used for its construction, operation, and maintenance. It also needs to minimise the land needed to supply its material resources, whether these be timber, masonry materials, metals or plastics. This means an environmentally sustainable building is expected to have low or zero environmental impacts. In light of the three dimensions of sustainability, sustainable building design should consider resource conservation, cost efficiency, and human adaptation strategies. Resource conservation can be categorised into energy, material, water, and land conservation, of which energy conservation has been regarded as the most important issue affecting the environment (Akadiri et al., 2012).

Globally buildings, or rather what people do in buildings, are huge consumers of energy. As reported by The International Energy Agency (IEA) (2019), buildings make up around one third of world energy consumption. Hence, energy efficiency improvements in building design and construction could make a significant contribution in reducing global energy needs. While acknowledging that energy reduction is not the only issue in making a sustainable building, it will form the focus of this research. The two main approaches to reducing total building energy consumption are:

1) Minimising the energy used for extracting, processing, transportation and installation of building materials and equipment for using renewable sources of energy (EE); and
2) Minimising the energy used for building operation and using renewable sources of energy (OE)

The former is generally referred to as Embodied Energy (EE) and is an indicator in evaluating the overall environmental impact of a building. EE has been reported to play a critical role in buildings total energy use as the energy used in building material industry accounts for around 20% of the world's fuel consumption (Dixit et al., 2010). However EE varies between 12.55 and 18.50% of a conventional building operational energy (Dimoudi & Tompa, 2008). The embodied energy of renewable energy equipment also needs to be taken into consideration.

Building operation is defined as the activities that are necessary for a building to perform as designed. In order for a conventional building to operate well energy is normally spent for heating, cooling, ventilation, lighting and operating equipment. In other words the operational energy is the energy a building consumes to maintain an acceptable inside environment for the occupants.

Even if efforts are made to reduce the embodied energy, a building might not be seen as energy efficient if considerable energy is needed to make the interior environment liveable once the building is constructed (Dimoudi & Tompa, 2008). Conversely, reducing operational energy through use of appropriate levels of mass, glass and insulation (Donn et al., 2001) may lead to increased embodied energy. The question for this thesis is how biomimicry might be used to investigate how to reduce energy use in buildings while also looking at how an acceptable indoor environment can be achieved with a minimum use of energy.

Based on this, there is a need to investigate the different approaches through which architects, researchers and engineers have incorporated biomimicry in building design to achieve energy efficiency. The next two chapters are accordingly focused on reviewing the literature to discover how being inspired by nature has resulted in innovative sustainable buildings that are energy efficient in terms of both embodied energy and operational energy.

2.6 Chapter summary

This chapter provides an overview of biomimicry including its origins and background, terminological definition, and discussion of related philosophical aspects. Different types of biomimetic design approaches and the main motivations behind biomimicry are explained. As discussed in section 2.3, biomimicry could be considered as a method through which technological innovations and sustainability principles can be achieved. Approaching sustainability and creating technological innovations emerge as the main purposes of biomimicry based on its three main dimensions as defined by Benyus. This implies that considering nature as a model and a measure can be attributed respectively to the innovative and sustainable aspects of biomimicry.

In the context of architecture and building design and bearing in mind the dual promises of biomimicry (technological innovations and sustainable outcomes), designers could potentially find inspiration in nature for solving building design problems, especially by the 'sustainable' solutions species use to survive. The problem is how to access the solutions best matched to the design problem. Various tools for finding existing knowledge from a different domain are described but as yet there appears to be no tool for allowing building designers to access the efficient ways found in nature of producing energy, using energy, and recycling resources.

The next chapter is a literature review of bio-inspired building materials that have contributed to decreasing energy use in buildings.

3 Bio-inspired Materials: How Does Nature Build?

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Declaration of co-authorship in publication

The content of this chapter fits in my thesis as is a literature review conducted to investigate examples of bio-inspired materials contributed to increasing the energy efficiency of buildings either during or after the construction process. Considering the subject of this research, the literature review upon which the whole research needed to be built up was aimed at covering two main aspects regarding the energy efficiency of buildings. To this end, this research was published to cover the first aspect mainly focused on the contribution of bio-inspired materials to the environmental energy use of buildings. This chapter was co-authored by my supervisor Professor Michael Donn, and a PhD student, Zahra Balador.

I was the key author of this research and performed the dominant role in conceptualizing the main idea, doing all the research, preparing the manuscript, analysing and interpreting the data, and ultimately writing, editing, and producing relevant tables and diagrams.

The contribution of my supervisor was offering useful comments on the writing as well as helping me in shaping the overall theme. The contribution of my second co-author was limited to a number discussions we had on the content as at a time, we were working on another chapter for the same book in which she was the key author.

I am aware of the Victoria University of Wellington Policy on authorship and I certify that I have properly acknowledged the contribution of other researchers to my thesis, and have obtained written permission from each of the co-authors to include the above material in my thesis.

Michael Donn	Zahra Balador
Signature	Signature

3.1 Abstract

This chapter systematically analyses the existing literature on bio-inspired materials used in architecture, construction, and building design. Imitating nature accounts for an effective strategy for designing innovative buildings. Integrating this biomimicry strategy into the design process generates benefits for both designers and the natural environment, as bio-inspired designs can contribute to sustainability. Mimicking nature, various biomimetic approaches have produced environmentally friendly, innovative, smart, or intelligent materials for buildings. This literature review demonstrates that researchers and designers are significantly inspired by animals', plants', or microorganisms' innovative biological systems (functions, structures, and processes) in order to design bio-inspired materials for increasing energy efficiency of the buildings. However, the range of innovative bio-inspired materials is not broad, and most of the published research seems to be about one-off cases. The chapter first introduces the systematic literature research methodology used for analysing the current knowledge of architectural bio-inspired materials. Current research on bio-inspired materials used in architectural and building science is reviewed, and a new classification scheme for clustering relevant data is presented. These innovative materials serve different functions in buildings. This classification scheme enables a new synthesis of existing knowledge based on the multi-functionality of currently developed bioinspired building. The chapter concludes by substantiating the argument that "there is no systematic and general workflow for data mining innovative building design/construction concepts from biological processes." Overall, then, this research suggests that there is a need for a bio-architectural workflow assisting scientists and designers to find the relevant organisms in nature as the source of inspiration for innovative design.

3.2 Introduction

Biomimicry has been proposed as a means of merging environment into design projects in order to achieve principles of sustainability (Wahl, 2006) and innovation. The labels bionic, biomimetic, and biomimicry have been used interchangeably in recent research. However, there is a fine line between bionic, biomimetic, and biomimicry. Biomimetic (and its associated noun biomimicry) is proposed as a descriptor for artificial mechanisms to produce materials with performance similar to materials that exist in nature (Reap et al., 2005), while bionic is more related to "cybernetics" and artificial intelligence (Vogel, 1998; Reap et al., 2005). Biotechnology as a term refers to a form of biomimicry using biological systems for industrial processes or using any type of biological organisms to benefit human or human surroundings (Pele & Cimpeanu, 2012); in other words, natural solutions are applied in technological practice to solve human problems (Benyus, 1997). In this chapter, biomimicry or biomimetic as general terms refers to any type of bio-inspired design approaches which imitate nature's approach (Reap et al., 2005).

Some authors state that biomimicry promises improvement in the environmental conditions in buildings (Pedersen Zari, 2010; Pawlyn, 2011; Badarnah, 2012; Gamage & Hyde, 2012; Mazzoleni, 2013). Construction technology has experienced a dramatic development in the use of bio-inspired materials. Around 0.25% of all known natural organisms have a current application in the industry (Peters, 2011). Mimicking structural, behavioural, functional, and morphological aspects of natural organisms can lead to numerous types of bio-inspired materials all introducing new methods for structural design, thermal insulation, waterproofing, etc. Albani et al. (2010) suggest that multicellular organisms have been able to adapt themselves to the environmental conditions and threats for over 2.1 billion years. A part of biomimetic science focuses on finding ways organisms have found to survive. From these, biomimicry promises lessons learned about energy efficiency that can be applied to buildings. Some of these lessons suggest materials with high thermal performance. For example, buildings' façades play a significant role in exchanging and storing energy as a filter moderating energy flows between the internal and external environment. Great improvement in thermal performance of buildings is achieved by imitating nature and considering building façades as like the skins on living organisms. Even though conventional façade technologies have partly fulfilled energy exchange mechanisms, the contemporary biomimetic approach has opened new avenues for creating innovative materials which effectively contribute to thermal comfort. Likewise, conventional materials such as concrete and glass are being replaced by bio-inspired materials. Natural patterns such as honeycomb's and soap bubble's structural configurations have recently inspired the creation of construction membranes described by Peters as "innovative textile membranes" (Peters, 2011).

Basically, the energy performance motivation behind most bio-inspired materials is to either reduce the energy consumption spent on the whole material production process and recycling systems or to improve buildings' energy performance. The manufacturing process of artificial materials such as mining, refining, and coating – described by Janine Benyus as *"heat, beat, and treat"* (Benyus, 1997) – consumes a significant amount of energy.

The contribution of biomimetic innovation to sustainability can be broadly classified as following two different strategies: bottom-up and top-down. The first strategy studies a biological mechanism and then forms a technological solution. This bottom-up approach is described by Gruber et al. as "solution-oriented" or "biomimetics by induction" (Gruber et al., 2011). The second strategy identifies a technical inquiry in a specific area of knowledge. Gruber et al. describes this as "problem-oriented" or "biomimetics by analogy" (Gruber et al., 2011). Investigating a biological solution for this inquiry necessitates data mining process in biological science.

This chapter addresses two issues: it examines a catalogue of bio-inspired materials identifying their strengths, potentials, and limitations and it also investigates whether the top-down strategy might be formulated into a general framework for mining biological science for building design inspiration.

3.3 Method

Using a systematic literature review (SLR) process, this chapter looks to establish whether there are examples of the application of biomimetic principles in architectural/building design. In this chapter, the process is used to examine the potential for mining the biological sciences for bio-inspired principles that can be transformed into architectural principles for the purpose of innovation. To accomplish the SLR, a formalized search process is used that derives conclusions which can be considered trustworthy (Evans & Benefield, 2001). The required steps in this process are documented below:

3.3.1 Search process

The following literature databases have been recognized useful by recent studies and were searched in the preparation of the base material for this systematic review:

- **ProQuest:** ". . . *is recognized as one of the three major databases used by academic institutions*" (Blessinger & Olle, 2004).
- **Emerald:** covers the major computer science subjects (Lombard & Jones, 2007) and covers the portfolio of around 300 journals.
- **Scopus:** is known as the most extensive database on science and technology (Chadegani et al., 2013).
- **PubMed:** has the capability to interlink all databases containing biotechnology information (Gasparyan et al., 2013).
- **Google Scholar (GS):** covers a large number of sources, including some of the "grey" literature.

- **IEEE Xplore:** allows for a more precise search using efficient search filters.
- **Wiley, Springer Link, and Taylor and Francis (T & F)** databases were also searched; apparently only around 68% of Springer link's content (X. Chen, 2010), one third of Wiley's documents, and one-fifth of Taylor and Francis' published articles are covered by Google Scholar (Walters, 2007).

The search was keyword based. Keywords were sought in the full text, and the search took place between 1st and 5th of October 2017. In each database, search terms were made consistent to focus the search process on the research scope. The databases were scanned three times with five different sets of keywords since bioinspired materials in architectural science are also referred to as "eco materials", "biomaterials" or "smart materials."

In addition to these separate synonyms which were the "Main keywords" the keywords searched for were:

A: Main keywords + building,

B: Main keywords + building + biomimicry

C: Main keywords + building + biomimetic

D: Main keywords + building + biomimicry NOT Robot NOT Aircraft NOT Medicine NOT Polymer NOT Protein NOT Medical NOT Organ NOT Pharmaceutics NOT Drug NOT "Tissue Engineering"

E: Main keywords + building + biomimetic NOT Robot NOT Aircraft NOT Medicine NOT Polymer NOT Protein NOT Medical NOT Organ NOT Pharmaceutics NOT Drug NOT "Tissue Engineering"

Only items D and E in this keyword search list focus on the topic of this chapter. As can be seen in Table 3-1, without the terms that exclude references not related to buildings, the main keywords identify many irrelevant references.

Table 3-1 Search terms within the databases (date of last search: 1-5 October 2017)

	Biomaterials					Eco materials					Smart materials					Bio-inspired materials					Materials				
	A	B	C	D	E	A	B	C	D	E	A	B	C	D	E	A	B	C	D	E	A	B	C	D	E
Birkhauser	532	6	121	0	4	0	0	0	0	0	191	5	24	0	0	15	1	6	0	10	60K	53	327		34
Emerald	144	1	8			3	0	0			98	1	4			0	0	0			87 K	31	67		
GS	660 k	3K	96.4K		422	1.7k	38	90			38k	629	6.9K	15	103	2.5K	222	1.5K	6	18		9.6K	113K	56	477
IEEE	1.9K	20	224		2	13					2.1K	6	219		5	113	4				363K	143	2.1K	1	0
ProQuest	25.8K	349	4.5K	4	21	815	10	8			5.8K	96	627	6	8	328	38	170		17				438	582
PubMed	1.16K	9	111	0	6	4					28						17					11	422		113
SAGE	1.07K	6	106			7					518	2	28			5						80	364		20
Scopus	31K	386	6.2K	4	64	275	1	7			11K	38	852		43	448	31	283		4		942	16K	215	1.4K
T & F	4K	19	309		3	35					525	12	45			27						230	889	79	38
Wiley	18K	168	2.8K	1	25	60					2.5K	26	299		6	211			7	90				82	649
Springer	18K	103	1.6K	103	1.6K	100					2.5K	34	281		8	133			11	62				153	320

3.3.2 Selection criteria

Very few publications focused precisely on bio-inspired materials in architecture. Most articles published on the subject of biomimicry and architecture include only a considerably small section in which materials of biological origins are introduced.

Most of these focus on the following topics, so biomaterials are not core to their content: flow of material through industrial society for the aim of implementing sustainability in construction and manufacturing, social sustainability and the conservation economy, high-quality recycling of construction and demolition, sustainable cities, urban metabolism, creativity in education, life cycle analysis, and biomimicry in landscape and infrastructure.

Biomaterial is a popular word in the following disciplines: biomedical engineering, medicine, tissue engineering, cell biology, polymer science, dentistry, biochemistry, pharmacology, and microbiology. “Smart materials” are widely used in aerodynamics, robotic, and medical applications. Consequently, the searches D and E applied a filtration process which removed “polymer, protein, tissue engineering, drug, pharmaceutics, medical, organ, robot, aircraft, and medicine” from the search process. The grey cells in Table 3-1 show the selected articles.

3.3.3 Summary of papers selected: The “Pearl” method of expanding the search

The references section of all papers has also been checked for finding the most relevant articles. This is an application of the “pearl method”: ensuring that when relevant references are found, they form the “pearl” around which other references accrete.

The integrated results for five sets of keywords (consisting of a total of 1730 papers) were initially screened by looking at the title, abstract, and author-generated keywords to ensure relevance. This was to exclude irrelevant papers or duplicates. Nine hundred articles were removed from the list at the first step. The remaining 830 articles were reviewed in more depth leaving only 200 papers for detailed examination. On review, only 50% of these were excluded for the following reasons (Figure 3-1):

- There is no line between material and structure in nature as the essence of any material (e.g., bone, collagen, wood) is the microscopic structure and it is almost impossible to differentiate “structure” and “material” in natural organisms (Gorb & Gorb, 2016). Considering this fact, innovative bio-inspired building envelopes can also be regarded as bio-inspired material but of course in a very large scale called “textile membrane” (Pawlyn, 2011). This type of bio-inspiration is not included in this chapter. Even novel architectural membranes inspired by biological construction process (e.g., underwater reinforced web construction of water spider) or structural properties of natural composite materials (e.g., fibre orientation in insect cuticle) are not included (Gorb & Gorb, 2016).
- Materials in nature are used efficiently in complicated forms. Imitating this process, rapid prototyping (RP) in architecture emulates the layer by layer deposition of materials in a hierarchical structure to improve materials’ efficiency. Variable property modelling (VPM) as a bio-inspired fabrication approach for designing building components is introduced by Oxman (2010, 2011). Created surfaces using RP manufacturing technology, however, can also be regarded as bio-inspired materials – in the form of a *“textile membrane”* – but are not included in this chapter as the materials used for prototyping are artificial (e.g., plastics).

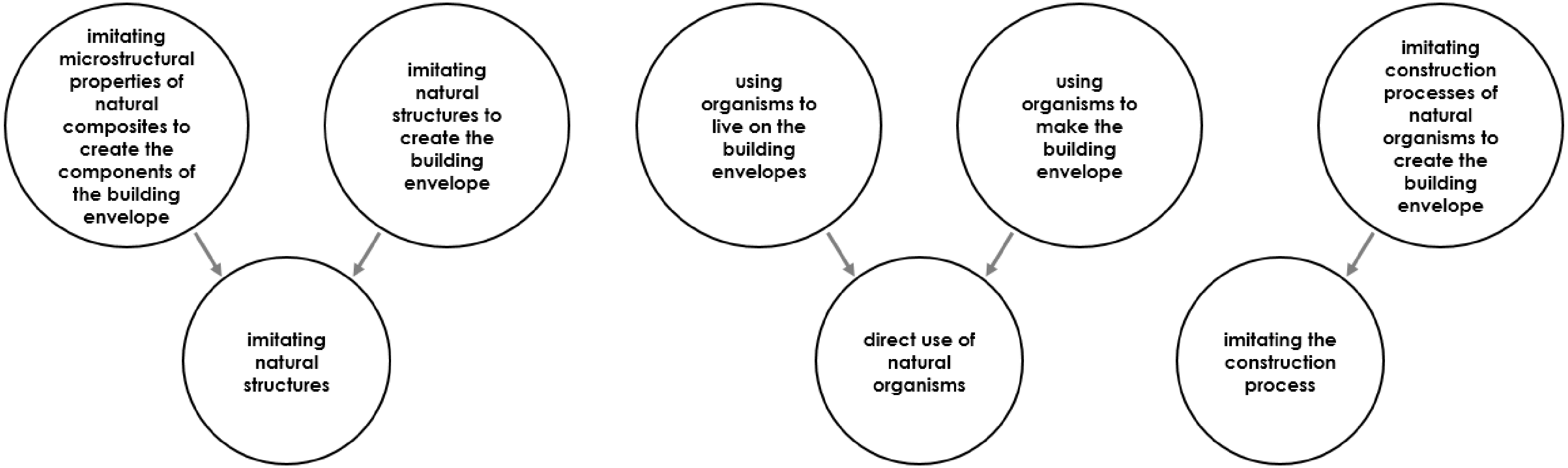

Figure 3-1 Different types of bio-inspired building envelopes (not considered in this research)

- Sometimes natural organisms are utilized in building envelopes without being even combined with other materials including perhaps artificial polymers during the manufacturing process. For example, in some biological building envelopes, natural materials improve the filtration/extraction process through which pollutant and volatile compounds are sucked out leaving the interior spaces with purified air (Xing et al., 2017). The direct use of natural materials also contributes to thermal insulation. For example, Spinifex grasses are a biological material well known for their resilient leaves (Memmott et al., 2009). From an architectural point of view, this type of grass is used for cladding timber frame shade structures and is used also as an adhesive material in plugging water vessels. Even though the innovative use of such biological materials shows an efficient climatic response to the rain, wind, and high temperature, they are not considered as innovative bio-inspired materials in this chapter.
- In very rare cases, natural organisms themselves are responsible for making the "textile membrane" in architectural design. For example, in Silk Pavilion (Oxman et al., 2013), a 3D printer has been used to fabricate a lightweight scaffold. By controlling the environmental factors, silkworms are guided to fabricate the whole structure – similar to their cocoon – in terms of fibre arrangements and silk deposition. These types of bio-inspired materials are also omitted from this research.

Omitting above four types of bio-inspired materials – as they could be considered more related to bio-inspired building envelopes – the literature review suggests that bio-inspired materials used in buildings can fall into four major categories: (1) using natural materials in the manufacturing process for better recycling as well as mimicking (2) structural properties, (3) functions, and (4) biological processes of natural organisms. Each individual approach yields innovative sustainable outcomes (Figure 3-2). More importantly not even one study explained a process by which researchers found the source of inspiration in nature in order to develop an innovative building material which means there is no generalised and systematised procedure for mining bio-databases.

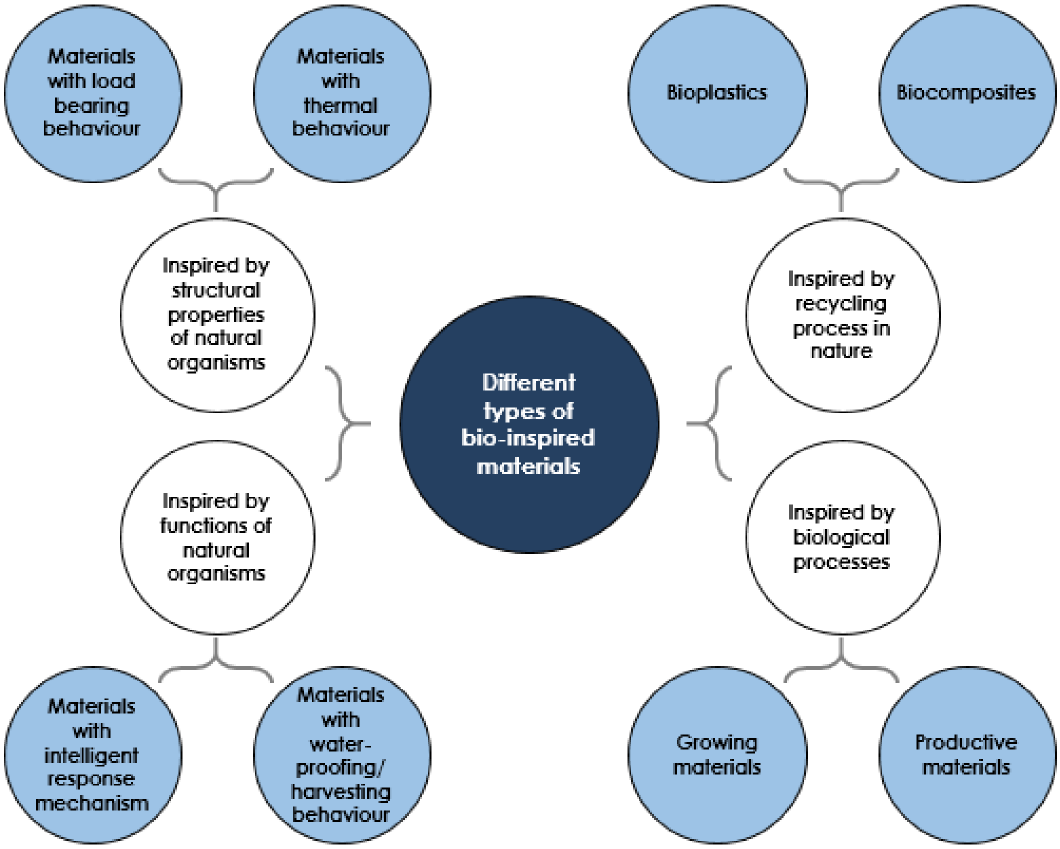

Figure 3-2 Classification of bio-inspired materials

3.4 Classification of bio-inspired materials based on biological characteristics

Bio-inspired materials for recycling can be classified into two major groups: (1) bioplastics and (2) biocomposites. Bio-inspired materials which imitate organisms' micro/macrostructure or patterns show either (1) load-bearing behaviour or (2) thermal behaviour. Imitating organisms' function has inspired materials with (1) intelligent response mechanism known as smart materials mainly used for enabling movement or thermal regulation, self-cleaning and self-healing, and vibration resistance and (2) waterproofing or water harvesting mechanism. Bio-inspired materials which imitate biological process can be divided into two interrelated and almost similar categories: (1) growing and (2) reproductive materials.

Researchers in biomaterials study nature following a scale-based approach. Either macro-, micro-, or nano-scales of imitation ultimately contribute to the energy efficiency of buildings. These types of approaches result in energy efficient and environmental-friendly construction.

Biomimicry (imitating organisms' functions, structures, and processes) mainly focuses at the micro- and macroscale levels of imitation. Nanotechnology can also be considered as a type of biomimetic design method focusing at nanoscale level of imitation. Bio-inspired nanostructured materials are founded as nanocomposites (a mixture of conventional materials with nanomaterials) or as nano-engineered materials both structurally modified at nanoscale level (Altun & Örgülü, 2014). For example, imitating crystallization of natural materials such as mineralized skeleton, researchers have designed bio-inspired concrete in which physical and chemical properties of concrete nanostructure are optimized (Hu, 2016). Nanotechnology in architecture essentially contributes to improving the functionality of conventional materials and turns them into more efficient products such as self-cleaning windows, UV-resistant timber frames, or dirt-repellent coatings.

3.4.1 Bio-inspired materials for natural recycling

Most bio-inspired materials in this category (macroscale) are considered as biodegradable materials. McDonough and Braungart (2002) classify two different cycles which if improved or understood contribute to waste reduction: *"biological"* and *"technical"*. While the former benefits from adding natural fibres into the material mixture (bio-based materials), the latter intends to assure everlasting durability of metals and minerals once they enter the manufacturing process.

Recently used synthetic plant-based materials – in which plants as raw materials are dispersed in the polymer matrix – are called "*bio-aggregate*"-based building materials (Amziane & Collet, 2017). Materials introduced in this category can also be considered as "*eco materials*" as the whole life cycle (starting from production to disposal stage) of products is considered to be assessed during the design process to reduce the environmental impacts of materials (Montana-Hoyos & Fiorentino, 2016).

In the manufacturing process of these eco/ecological/bio/bio-based/bio-aggregate materials, natural fibres are added to composites to improve the material properties. These materials can be classified into the following basic groups based on their applications in building industry.

3.4.1.1 Bioplastics for natural recycling

Bioplastics have natural origins (plants or microorganisms) and are made, at least in part, from renewable biological raw materials in order to facilitate biodegradation process. This means that polymers can be derived from renewable feedstock or can return to nature

(Mekonnen et al., 2013). Plant-based bioplastics include building blocks such as lignin, vegetable oils, cellulose, thermoplastic starch, polylactic acid, etc. Algae-based bioplastics have flame-resistant properties showing the potential to be used in the building industry. However, the procurement process of changing this fast-growing natural organism into *"alginsulate foam"* materials is costly. The life cycle and convenient disposal of this type of bioplastics make it distinguishable from conventional polystyrene.

3.4.1.2 Biocomposites for natural recycling

One of the main features of biocomposites is their sound-absorbing quality. Their specific structure leads to the active control of noise and vibration inside the building. Biocomposites might have different sources such as plants or animals. Biocomposites can also be made of a combination of plastics with either reinforced natural fibres or wood.

Wood polymer composites (WPC) are plant-based biocomposites with an inorganic manufacturing process. They make a perfect combination of desirable manufacturing properties such as low thermal expansion and moisture resistance. The application of these composites in buildings can be seen in skirting board profiles. As a new technological approach to using bamboo – a traditionally used material for scaffolding in building industry – this natural material has been added to wood-polymer composites (WPC), fibre-reinforced concrete, and bioplastics. Cork polymer biocomposites, as another sample of plant-based materials, are recently produced and used in the building sector (Boussetoua et al., 2017). Thermal and electrical insulation of cork-based composites is achieved through cork's cellular structure (Xing et al., 2017). Cork's water-permeable quality, as well as its thermos-hygro-mechanical properties, makes it a favourable biocomposite for building construction. "Subertres" as a cork-based product is being used for thermal and acoustic isolation purposes in roofs and facades. Due to their specific surface structure, cork-based materials are also used for interior design. Jute-based composites as one of the most types of widely used biopolymers show high tensile strength and are employed in the ceiling, floor, and windows (Asha et al., 2017). Hemp concrete is also a biocomposite material made of hemp and lime which, due to its specific thermal conductivity, can be used for thermal insulation (Aït Oumeziane et al., 2017).

Biocomposites can be referred to as animal-based biocomposites with an organic manufacturing process. While the synthesis of a series of biomaterials takes place in factories, the rapid growth of fungus (a microorganism which is more related to classification of animals) provides a chance for manufacturers to produce hard foams naturally, as fungus sticks to solid surfaces such as wood and soil to colonize (Peters, 2011). The threads of this type of foam which are formed by fungus get dehydrated at a considerably lower temperature than that of required in the manufacturing process.

3.4.1.3 Bio-inspired materials imitating organisms' micro/macrostructure or patterns

Innovative materials in this category can be classified into two distinctive ways by which buildings' technical requirements can be achieved: materials with load-bearing behaviour and materials with thermal behaviour. The effect of these types of bioinspired materials on energy reduction can be also divided into two groups: reducing the energy spent on (1) off-site manufacture such as construction process, transportation, and module fabrication and assembly and (2) decreasing thermal conductivity in buildings. In regard to the first approach, lightweight materials such as self-reinforced thermoplastics and fibre-reinforced structures contribute effectively to lower off-site energy consumption. In the second approach, two interrelated aspects of heat transfer mechanism (thermal insulation and conductivity) get optimized by innovative foam-based materials in which the structure of air chambers is modelled after morphological configuration of natural structures.

3.4.1.4 Materials with load-bearing behaviour: imitating organisms' micro/macrostructure or patterns

The macroscale and microscale structure of natural organisms has inspired researchers to design high load-bearing buildings. For example, in macroscales, the mechanical stability of trees under dynamic loads, and in microscopic scales, the flexible connection of diatoms' cells, has inspired designers to develop elastic materials for dampers to reduce the structural failure in buildings intelligently (Vukusic & Sambles, 2003). Imitating the structure of sea urchin spines, researchers have recently developed a functionally graded concrete with high load-bearing capacity in which the inner structure has different levels of porosity similar to that of the urchin spines (Klang et al., 2017).

Studying kinematic behaviour of plants during the pollination process has recently inspired deployable systems in architecture (Lienhard et al., 2011). Bird-of-paradise flower's pollination mechanism motivated a form-finding process in architectural design resulting in innovative materials used in flexible cantilever and single-span beam design. This biomimetic approach makes the entire building structure capable of elastic deformation without the need for hinges' formation. Lienhard et al. (2009); Lienhard et al. (2011) and

Poppinga et al. (2010) refer to this bending kinematics as a result of the strong relationship between plants' function and morphology.

The mortar-like structure of nacre (mother-of-pearl) and the bone is claimed to be formed by two types of newly discovered proteins both controlling the biomineralization process in nature as biomineralization is the determining factor for producing hard bio-inspired materials. A type of biomimetic composite material made of a hexagonal honeycomb structure filled with fluidics is inspired by bones' structure and used in Japanese buildings as wooden joints (Ota & Enoki, 2010). This composite decentralizes load and absorbs the earthquake shocks as joints in buildings are responsible for absorbing distortions and vibrations.

The high ratio between porous and compact spaces – the efficient use of natural materials – in bone's structure makes it capable of bearing a lot of weight with a low density. Honeycomb structures (frequently constructed by social insects) (Gorb & Gorb, 2016) have also inspired sandwich panels consisting of a comb core (hexagonal lightweight materials) and two covering layers on sides offering a high load-bearing potential for construction. The covering sheet is usually made of reinforcement layers of natural fibres such as cellulose (Peters, 2011). Investigating hierarchical structure of natural materials has also resulted in the production of fracture-resistant man-made materials (Kolednik et al., 2011).

Basically, both toughness and lightness of bone's hexagonal structure have inspired lightweight structures in buildings. Self-healing fibre-reinforced polymer (FRP) composites offer high tensile strength enabling designers to produce complex geometries. These types of composites are designed by copying the damage tolerance and self-repair functions of bones (Trask & Bond, 2010). Copying nacre's microstructure, a multilayer ceramic is designed in which the porous nanostructure interlayer resembles the protein-based layer of nacre's structure.

3.4.1.5 Materials with thermal behaviour: imitating organisms' micro/macrostructure or patterns

Among all bio-inspired approaches to energy efficiency including (1) energy production, (2) energy storage/harvesting, and (3) energy delivery (Honey & Pagani., 2013), mostly the first and the second ones lead to bio-inspired materials. From another perspective, bioinspired engineering of materials for thermal management can also be divided into two categories: bio-inspired materials for thermal insulation and bio-inspired materials for efficient heat transfer in cooling applications (Tao et al., 2015).

In microscale, honeycomb structures, in addition to their high-performance, loadbearing capacity and pressure resistance properties, have inspired plastics and cardboard panels to serve thermoregulatory purposes in buildings. In comparison to conventional solar cells, light harvesting and solar energy absorption have been improved when they are imprinted with the nanostructure of butterfly's wings (W. Zhang et al., 2009; C. Zhang et al., 2016). These bio-inspired solar cells have the capability to harvest a wider range of visible light – between 400 and 500 nm (Liu et al., 2010) – and show a high-quality photocatalytic performance (J. Chen et al., 2012). Diatoms as photosynthetic microorganisms benefit from a specific hierarchical structure in their silica-based cell walls. By imitating this structure, more light can be trapped inside the solar cells to increase the level of electricity generation (H. Zhou et al., 2011).

As another example, some studies have been inspired by the structure of polar bear fur and skin; they have developed artificial furs capable of collecting solar radiation efficiently (Stegmaier et al., 2009; Jia et al., 2017). Fabricated alumina fibres are inspired by the structural and thermal insulating properties of silkworm cocoons (T. Wang et al., 2013). Even the colour-changing properties of *"brittle star"* (a class Ophiuroidea closely related to starfish) which seem to be caused by lens-like protuberances spread on its skin suggest further research for the development

of a colour-changing façade made of optical lenses and capable of gaining more solar energy (Vanaga & Blumberga, 2015). The nanostructural configurations of tapered elements in the compound eyes of Lepidoptera (an order of insects including butterflies and moths) have been inspired antireflective glasses which are highly efficient for incident light absorption (Vukusic & Sambles, 2003; Z. W. Han et al., 2016; Jia et al., 2017). The energy-harvesting structure of fly's eyes can also be used for optical coatings in solar cells (Martin-Palma & Lakhtakia, 2013).

3.4.2 Bio-inspired materials imitating organisms' function

In the context of biomimicry, the roles played by the strategies living systems use to survive extreme environmental conditions have been defined as organisms' functions. A biological function is an adaptation mechanism of the living systems. Biological strategies have inspired human's technologies to function in an innovative way that the living systems use to survive.

3.4.2.1 Materials with intelligent response mechanism imitating organisms' function

Even though nearly all intelligent mechanisms in building design such as self-healing, self-repairing, self-cleaning, self-assembly, and intelligent movement require electrical power for actuation or sensing, the amount of energy consumed for exchanging energy from one form to another as a typical function of smart technologies is often more efficient than conventional technologies (Shaikh et al., 2014).

Natural organisms sense and respond to environmental stimuli. In buildings, smart materials emulate the intelligent response processes in nature (Figure 3-3). For example, shape-changing materials in plants have inspired synthetic materials recently used in sun-harvesting solar panels and reactive textiles. The possible application of "smart materials" in architecture can be seen either in sensors or actuators (Reyssat & Mahadevan, 2009; Randall et al., 2013) or as no-tech/low-tech hydromorphic materials (Holstov et al., 2015).

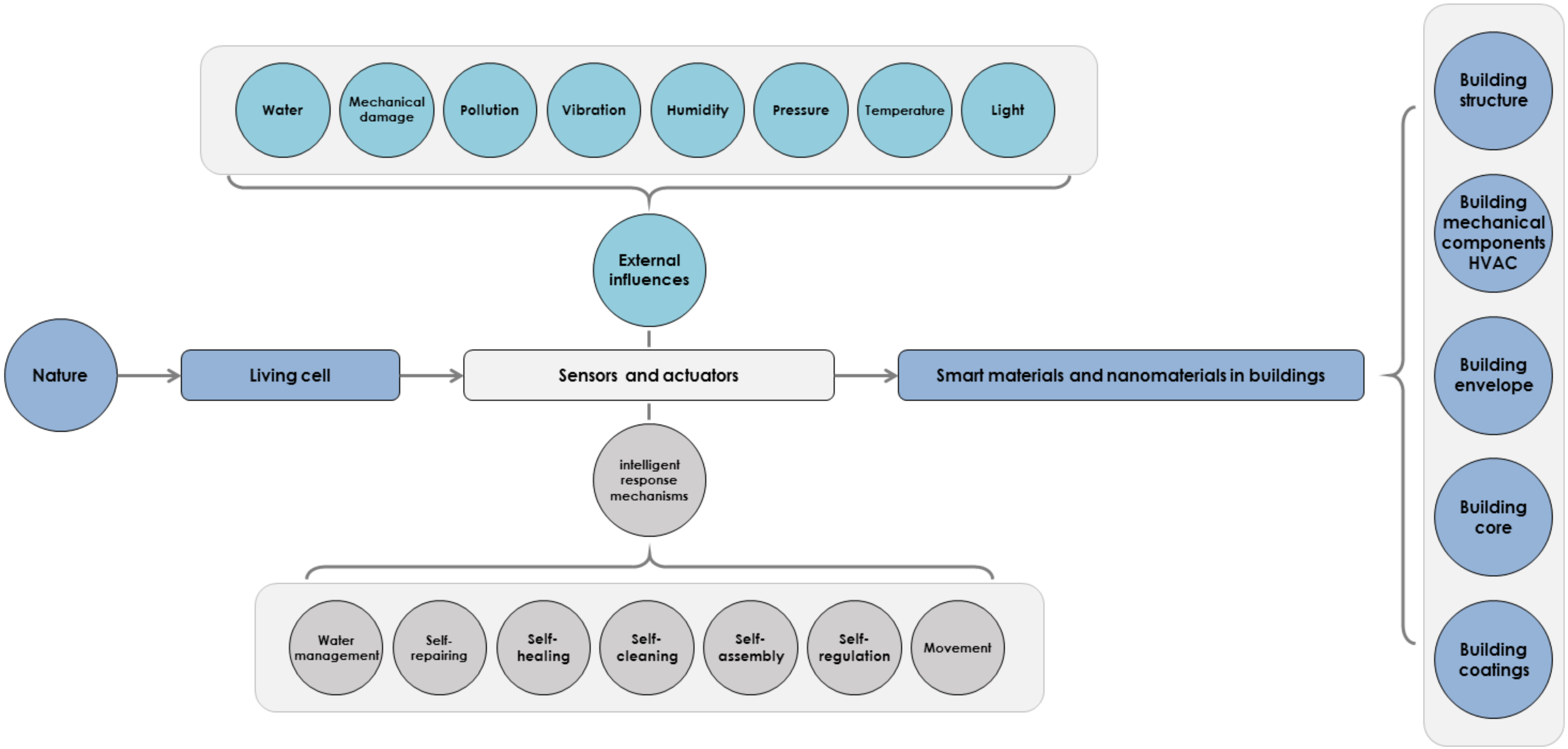

Figure 3-3 Bio-inspired intelligent response mechanisms to environmental stimuli in buildings

The biological membrane of living cells is the basic structural, functional, and biological unit of all known living organisms which responds to environmental stresses through using three main components: a sensor, a controller, and an actuator. Actuators are responsible for producing mechanical effects, while sensors monitor temperatures, humidity, and movement. Most of the intelligent response mechanisms in buildings are achieved through using sensors or actuators in a similar manner so that buildings also are able to respond to environmental stimuli.

Bio-inspired optical fibre sensors do not literally imitate intelligent response of natural systems but, from another perspective, are inspired by animals' echolocation. Echolocation has motivated scientists to design distance measurement optical sensors for the purpose of structural health monitoring in building structures.

Materials in this category are inspired by both biological functions and structural properties of natural organisms as their structural composition is linked with relevant functions. For instance, the microstructure of Bacilli's spore membrane changes over time according to the UV absorption intensity. Imitating this structural deformation and UV resistance mechanism is claimed to be the first step toward developing biosensors (Vukusic & Sambles, 2003). Imitating structural colours, antireflection, and light collection processes in birds, insects, and marine animals has also inspired biosensors capable of reflecting light for improving the performance of optical devices (C. Zhang et al., 2016).

Nano- and micro-electrical mechanical systems' (MEMS) sensors as the results of combining two innovative bio-inspired technologies, smart materials (e.g., piezoelectric ceramics, polymers, or composites) and smart nanomaterials, are promising but still unknown to building construction while they are widely used in medical science. For example, piezoelectric materials inserted in the concrete structure of beams and plates are used as damage detectors and control the building structure (Lim & Soh, 2014; Jayaguru, 2016), while structurally optimized smart nanomaterials show a unique acoustic and lighting performance (Loh et al., 2015).

Actuators have also been developed based on smart materials such as shape memory alloys or electro-magneto-restrictive materials (Jan Knippers et al., 2016), and these have been used in different parts of buildings.

Shape memory alloys also act to demonstrate another smart material function: phase change behaviour. Current research on multiphasic materials is inspired by frost-resistant plants offering unique processes by which heat and mass can flow easily through a porous solid matrix in plant tissues (Eurich et al., 2016).

In addition to bio-inspired materials, some studies report the possibility of developing an innovative kinematic system inspired by the stiffness adaptive hingeless structure of plants. The technical translation of kinematic movements in natural organisms enabled by water-dependent actuation or joint-free flexible systems can be a rod-like structure in buildings using pneumatic cushions for actuation (Betz et al., 2016).

3.4.2.1.1 Smart materials for enabling movement or thermal regulation imitating organisms' function

S.-Y. Chen and Chiu (2007) refer to kinetic responsive architecture or "*smart skins*" as new design strategies which employ smart materials to make buildings more energy efficient compared to static conventional architecture. These approaches benefit either from using natural materials or from imitating the mechanisms that natural organisms employ to perform movement. In the former, smart materials are the kinetic systems (no-tech strategy and low-tech strategy), while in the latter, smart materials act as a generator for the mechanical movements of the kinetic surface (low-tech strategy) (Maragkoudaki, 2013). Electroactive polymers, hydromorphic biocomposites, and thermobimetals belong to the first category of biocomposites which use the no-tech strategy. Kinematic building envelopes which are animated by shape memory alloys belong to the second group (low-tech strategy).

Hydromorphic biocomposites (HBC) are modelled after natural hydromorphic actuators found in a pinecone and wheat awn (Le Duigou et al., 2017). The stems of pinecone scales consist of two different materials showing opposite behaviours to humidity as one shrinks while the other opens up. Imitating this intelligent mechanism, a multilayer artificial textile (veneer-composite system) made of numerous small flaps is developed in which flaps close and open up in response to air humidity (Reichert et al., 2015). This responsive architectural system does not use electronic equipment for sensing, actuation, and control but instead responds to climatic conditions following the biological principles plants employ to actuate organ movement.

Dielectric electroactive polymers (DEAPs) change shape and stiffness when a voltage is applied to the surface of materials which are covered by metal electrodes. Generating dynamic movements using DEAPs has been used for different purposes in building design such as soundproofing and energy saving (Berardi, 2010). Conventional glasses can be replaced by a new type of glass which is covered by DEAP-laminated sheets which bend around the vertical and horizontal axes and effectively regulate the light transmission to mitigate overheating in interior spaces. Thermobimetals are used in building envelopes to improve energy performance by dynamic movement as well as automatically taking control of reflectivity and light transmission through solar shading (Sung, 2016).

The stomatal movements in plants stimulated by humidity, temperature, carbon dioxide concentration, and light intensity have been investigated by measuring the amount of CO_2/H_2O produced within a leaf. Following this approach, active materials for current building façades have been developed which respond to both temperature and humidity (Lopez, Croxford, et al., 2015). Living glass and smart glass perform motions incorporating shape memory alloy technology (Maragkoudaki, 2013). In the smart glass, change colouring and adaptive darkening function are achieved through glass nano-layers by which light transmission is controlled according to the environment (Gebeshuber et al., 2010). One of the smart technological approaches to increasing thermal energy storage (TES), using either passive or active method, incorporates smart phase change nanomaterials (PCM) embedded in different parts of the buildings such as building core, solar facades, suspended ceilings, and HVAC systems.

Some active materials such as carbon dioxide-responsive polymers have been tested in laboratories by calculating the dimensional changes of the surface of the samples. During an experiment, the thermal performance of shape memory polymer has been analysed in a physical model. Shape memory polymer sheets installed in internal windows can bend to allow for airflow according to the inside temperature (Nessim, 2015). Using this type of polymers in windows contributes to reducing energy consumption in buildings in which the building envelope behaves like a living organism to regulate heat. Likewise, researchers refer to the intelligent shape-changing behaviour of red blood cells as a solution to designing a smart energy efficient composite for thermal insulation. A shape-changing material inside composites would increase or decrease the thermal insulation by changing the thickness of interlayers reacting to either humidity or temperature (Vukusic & Sambles, 2003).

Smart windows with water circulated intelligently can reduce heat loss and unwanted heat gain (Gil-Lopez & Gimenez-Molina, 2013). Regulating solar gain which is a smart mechanism in liquid-shielded windows contributes to reducing thermal loads in buildings (Carbonari et al., 2011). In these very last two examples, the façade is itself the "*smart material*".

3.4.2.1.2 Smart materials with self-cleaning and self-healing function imitating organisms' function

Biological membranes are developed by imitating the self-assembling process in nature by which biological structures and polymers arrange their molecular entities in response to environmental stresses. Self-healing materials have the potential to repair themselves without the need to be externally renovated.

For example, exploration of self-repair mechanism in plants has found application in pneumatic constructions. Emulating this process, a type of innovative polymer material which regulates the air pressure and consequently prevents the system breakdown has been developed to be used in a pneumatic structure membrane (Vukusic & Sambles, 2003). The morphing application of this membrane is called "*adaptive stiffness*" in which (again) shape memory materials are responsible for pressurizing honeycomb cell structures (Jan Knippers et al., 2016).

Currently, self-healing processes in cementitious materials are referred to as "*autonomic or autogenic*" (Xu & He, 2017). For instance, in the autonomic approach, the self-repairing mechanism of one type of concrete, in case a rupture takes place, occurs due to the secretion of an adhesive material through a hollow fibre onto the surface layer (Carolyn, 1994; Y. Zhang, 2003). In the autogenic approach, a thermophilic anaerobic microorganism is added to the concrete mixture. The compositional properties of this living concrete allow the microorganisms to grow inside increasing the potential of the concrete to serve different purposes in construction. Similar to autonomic self-healing concrete, this microbial bio-concrete benefits from a highly efficient autogenic self-healing treatment technique for filling the possible cracks in the concrete composition (Seifan et al., 2016) while concrete's durability and strength are also increased (V. R. Kumar et al., 2011) and at the same time the concrete thermal performance gets improved (B. Han et al., 2017). In some studies, SMAs are used to repair the emergency damage in concrete.

Similarly, self-healing metals fall into two main categories in which the healing process is achieved through transportation of either liquid or solid to the damaged area (Nosonovsky & Rohatgi, 2011). However, the translation of the self-repair mechanism of living tissues into bio-inspired self-healing metals and concrete is not even close to what natural organisms are capable of. These examples copy the function but not the mechanisms by which healing occurs in nature.

In addition to the self-repairing mechanism, building skins as advanced "*biological membranes*" might be able to contribute to air filtration as well if bio-inspired materials imitate multiple aspects of living organisms such as self-assembly and metabolism (e.g., photosynthesis) at the same time.

3.4.2.1.3 Smart materials with vibration resistance imitating organisms' function

Bio-inspired structures learn from lightweight constructions in nature which employ an energy dissipation strategy to protect the whole structure from total collapse. This intelligent responsiveness to overload conditions is an integrated functional and structural mechanism.

In buildings, energy dissipation mechanism in seismic dampers happens via either active or passive systems of which the former incorporates smart materials. For instance, residual deformation in buildings after an earthquake can be eliminated or mitigated by modern re-centring devices or products made of smart materials such as super-elastic shape memory alloy (SMA) bolts (Braconi et al., 2012; Seo & Kyoung-Hwan, 2017).

Likewise, dielectric electroactive polymer sensors can be inserted in mortar for the purpose of monitoring building's vibration (Berardi, 2010). Electro- and magnetorheological fluids in vibration dampers can change their viscosity in a magnetic field. Through this mechanism, any fluctuation caused by earthquake load or wind power can be reduced and even controlled. There are cases in which dampers resemble morphological configurations of living things. For example, the proposed structure of a type of damper is modelled after the climber plant in which the viscosity of fluidics in the tendril works as smart material and makes the stem strong (Kaluvan et al., 2016).

3.4.2.1.4 Materials with a waterproofing or water harvesting mechanism imitating organisms' function

The water repellency of the lotus flower has resulted in technically developed dirt-repellent surfaces such as the hydrophobic PTFE-coated fabric. However, zooming more into details of this mechanism, the hierarchical nanostructure of petals is found to be responsible for the ultrahigh adhesion effect (C. Zhang et al., 2016). Water-resistant bio-inspired materials are made of innovative hydrophobic surfaces – by which water changes into droplets – while bio-inspired hydrophilic dirt-repellent coatings make a thin film spread all over the surface (Peters, 2011) and play a more significant role in water harvesting mechanism.

The water collection mechanism in cactus, spiders, desert beetles, birds, butterflies, frogs, and some types of grass has been reported frequently by many researchers. For example, the multifunctional surface of some types of desert insects is capable of storing and harvesting water by preventing water from evaporating and capturing that through the hydrophobic/hydrophilic properties of cuticles (Gorb & Gorb, 2016). Likewise, the water harvesting mechanisms in several lizard species occur through the capillary function of blood vessel networks. This specific type of water transport system (the flow of fluid in channels between scales) proposes opportunities for developing water harvesting materials in climatic regions that experience water scarcity (Ripley & Bhushan, 2016).

3.4.3 Bio-inspired materials imitating biological processes

There seems to be a wide gap between nature-inspired motivations or creative thoughts and the current technological developments used for producing *"living"* bio-inspired materials. For example, imitating growth as a natural process is still held at imagination level and is not even comparable to what is found in nature.

Self-organization in biological systems is a process through which internal components of a system get organized without being controlled by any external forces. The self-arrangement characteristics of living organisms at a preliminary level can be translated into architecture where the organized properties of composite materials (natural fibres and matrix) are interwoven to make a fabric. Biochemistry, however, promises advanced performative living materials for architectural design (Hensel, 2006).

A protocell designed by Armstrong has similar properties to that of a living cell (Armstrong, 2014). Reacting to light, the protocell moves down into the water according to the water level fluctuation and makes a precipitate (artificial reef) to reinforce the timber tiles of Venetian houses. *"Biorock"* is another mineral structure created by the electrodeposition process through which a low-voltage electricity flows through reinforced steel structure changing minerals into crystallized components. This material is considerably stronger than common types of concrete and has the potential to be used in construction (Goreau, 2012).

Vukusic and Sambles (2003) state that Bacilli's sporulation (reproduction) mechanism can be replicated in architectural design. The living spaces (e.g., rooms), similar to Bacilli's reproduction mechanism, can dynamically appear and disappear (be constructed or destroyed) if their boundaries (e.g., walls) are made of an innovative architectural material which shows a shape-shifting behaviour during growth. Currently, in extreme environmental conditions, some interior spaces are left abandoned and unused. Using this material, spaces could be used efficiently according to seasonal changes.

While all natural materials used in construction are fully grown (adding biodegradable materials to the conventional material mixture), a few impressive efforts have resulted in designing literally living materials capable of adaptive self-reinforcement and intelligent response to the environmental stimuli by imitating biological processes such as gradual growth (Deplazes & Huppenbauer, 2009).

3.5 Conclusions and Further Outlook

Energy saving is one significant advantage of using natural materials or imitating either structures, functions, or processes in nature for creating bio-inspired materials. Bio-inspired materials offer a wide range of applications in architecture and building design. Most contribute to increasing the energy performance of buildings (on-site energy saving) or reducing the environmental impacts of buildings as well as saving energy resources (off-site energy saving).

This literature review introduces numerous ingenious bio-inspired materials most created by imitating structural, functional, and behavioural aspects of natural organisms. However, the literature shows a gap in the very first step where designers search nature to find inspirations to improve mechanical or functional aspects of materials. If one reviews all of the literature examined for this chapter, to find a generalized and systematized procedure for mining biological science, rather than the many one-off examples listed above, then there is no such procedure available at present. Except for the common structural characteristics of natural materials (hierarchical structures) which have been almost fully explored by nanotechnology, other functional and behavioural potentials of biological materials seem to be vaguely translated and written about with very specific and limited examples.

To be able to find relevant natural organisms for the purpose of finding innovative solutions, there is a need for a general framework enabling researchers to find specific organisms in accordance with the design challenge. Developing a theoretical bio-architectural framework which addresses current issues of conventional materials and consequently eases the transfer of biological principles to principles of material design is required. Using this framework, innovative materials inspired by biological processes through which natural organisms camouflage, change colour, reproduce, response to external and internal stimuli, replicate and self-assembly, do photosynthesis, inhale and exhale, move, eliminate waste, etc. could be more systematically created.

Even though some researchers made valuable efforts to outline methods for accumulating data related to the conventional and novel bio-inspired materials, these methods do not necessarily lead to more innovative ideas. This is because current biomimetic designs fail to demonstrate a general systematic procedure for finding the next innovation that others might use to replicate the innovative design thinking processes.

4 Bio-inspired Building Envelopes: How Does Nature Control Climate?

4.1 Introduction

Environmental considerations are now generally seen as part of development and as stated by Lélé (1991), this concern earlier evolved into the new term '*sustainable development*' (SD). By 1990 this new paradigm of development had found global support. SD has been interchangeably used in the literature with "*ecologically sustainable development*" or "*environmentally sound development*" (Tolba, 2013), while in a broader context SD has been used to mean "*sustainable growth*" or "*sustainable change*". This means the definition of SD is not clear (Gow, 1992; Qizilbash, 2001) as there is disagreement over how the term should be defined (Sachs, 1993, 2015). As a result, Jabareen (2008) argues the multidisciplinary literature means SD can be put into different categories, each based on an independent view of sustainable development. In his research he focuses on synthesising the literature to shape a framework for the latter. This framework consists of seven main categories with the concept of "*ethical paradox*" (the paradox between the ethical aspects articulated for both sustainability and development) sitting in the middle and surrounded by the following concepts: equity, global agenda, eco-form, utopia, integrative management, and natural capital stock.

The concept of Eco-form seems the most relevant for this research as it is associated with energy efficient human habitats. Accordingly, Eco-form can be described as the ecological design of a built environment through which buildings are expected to function more sustainably when compared to their precedents. Generally, ecologically design-oriented theories appeared in the 1980s, the period in which the concept of SD was raised (Jabareen, 2008).

Ecologically sustainable design (ESD) mainly targets reducing energy consumption (GhaffarianHoseini, 2012). While there are many approaches towards ecologically sustainable design, such as use of alternative building materials, use of renewable energy, and recycling, the need for the built environment (mainly its buildings) to be "*energy efficient*" seems to be the dominant concept as agreed by many scholars (Jabareen, 2008). In other words, the overall aim of all of these approaches is to decrease the negative impacts of buildings on the natural environment and this can be achieved more effectively by improving their energy performance.

Environmental theories have been sought as a basis for building up approaches to sustainable building design in terms of designing buildings that adapt to natural-ecological systems (Gamage & Hyde, 2011). Adebisi et al. (2015) state the effects of buildings on the environment involve a wide variety of ecological systems. Gamage and Hyde (2011) have argued designers have been motivated to study ecosystems and ecological principles because of their concerns over these negative impacts.

The environmental theories of ecosystems (ETE), such as constructal theory (Bejan & Lorente, 2010) systems theory, ecosystem theory, and ecological systems theory have all been a foundation for developing design approaches. They have also shaped a number of ecological models that consider the flows of energy and materials in an ecosystem. For example, Odum's model was developed to incorporate the principles of living systems and was based on embodied energy flow (Odum, 1988). Following this, the bioclimatic approach was formed to describe the relationship between climatology, biology, architecture, and technology (Olgyay, 2015). The concern has always been to understand ecological principles fully in the hope that building design might improve by imitating these. It seems that the Self-organising Hierarchical Open Systems (SOHO) model was developed in response to this need to help designers understand "*ecosystems as complex self-organizing hierarchical open systems that adapt to their environment*" (Kay, 2003). Biomimicry as a design approach has also been introduced to support Virtuous Cycle and to produce design guides (Gamage & Hyde, 2011). The same authors also pointed out that designers would have a better understanding of the design problem, and consequently any innovative sustainable patterns nature suggests, if the entire gamut of sustainable patterns were structured in the form of a framework. Moreover, in the context of ESD, they argued that architectural design has not properly benefited from these innovative patterns, as natural principles have not been exploited in relation to the architectural design process. In fact, there is a need for a methodology to facilitate knowledge exchange when designing highly functional and energy efficient buildings in the context of bio-inspired design, as this has to be a multidisciplinary approach with the aim of bridging between two different fields of scientific knowledge (J. Knippers & Speck, 2012).

As discussed in section 2.5, buildings are expected to maintain a thermally comfortable indoor environment irrespective of the outside environment and external climatic conditions and this generally implies the use of energy. Prior research suggests that designing buildings with respect to climate has a significant impact on building energy consumption (Cheung et al., 2005; M. J. Holmes & Hacker, 2007). To this end, buildings cannot be considered without their surroundings as their internal environment is always susceptible to being affected by the external environment.

Referring back to the definition of ESD, the overarching objective of ESD is to develop strategies by which buildings can adapt to their environments (GhaffarianHoseini, 2012). The extent to which a building needs to be cooled or heated in order to provide a comfortable thermal environment for the inhabitants is highly dependent on the climatic conditions and the geographical location in which the building is constructed. Given these points, in the context of ESD, energy-efficient buildings can be defined as those with a high level of enhanced thermal performance, which is achieved through the adaptation of the building to its environment in order to create a thermally comfortable condition inside it. Similar to a living organism surviving by acclimatising to a harsh climate through thermal regulation mechanisms, a building as a living organism is expected to allow the survival of its occupants. The central issue addressed here is a conceivable analogy in that the innovative sustainable strategies natural organisms use to regulate their body temperature given the surrounding environment can be identified, emulated, and translated to building design principles, with the intention of designing a technologically innovative energy-efficient building.

Aitken (1998) states most buildings do not interact efficiently with the environment. As eco-friendly and energy efficient building design have already led to technological improvements, more recently attempts to decrease the negative impacts of the built environment have been focused on the "*biomimetic approach*", which is also part of sustainable design (see 2.3). There is evidence that biomimetic design could produce improved building performance as the building designer draws inspiration from nature's approach to design challenges, such as adaptation to climate (J. Wang, 2011; Tachouali & Taleb, 2014; Zuazua-Ros et al., 2016).

As discussed in section 2.2, biomimicry investigates nature through three roles (model, mentor, and measure) and as a model helps designers emulate forms, processes, and ecosystems in nature. Biological systems can introduce innovative and efficient methods for minimising consumption of energy and natural resources. Mazzoleni (2013) notes that biomimicry is a way of merging the environment into design projects in order to achieve the principles of sustainability. Some authors state that biomimicry promises improvement in environmental conditions (Pedersen Zari, 2010; Pawlyn, 2011; Badarnah, 2012; Gamage & Hyde, 2012).

Thermoregulation in nature is associated with daylighting, ventilation strategies, and humidity control mechanisms. Natural organisms are capable of adapting their body temperature to the fluctuating temperature in the surrounding environment and this process takes place through behavioural, morphological and physiological adaptation (Angilletta Jr & Angilletta, 2009).

In this respect, a search process was conducted to discover how researchers have been inspired by biological thermal adaptation mechanisms in order to achieve energy efficiency as well as improvement in the thermal performance of buildings. Given that conventional buildings interact with the environment but show a static behaviour which does not lead to energy efficiency (Fernández et al., 2013; Loonen et al., 2017), and bearing in mind the importance of a knowledge transfer bridging framework in the context of building design, the following search process seeks to investigate how thermoregulation strategies in nature, translated and used in biomimetic architecture, have contributed to enhancing the energy performance of buildings in a systematic way.

4.2 Literature review

This section concerns a literature review (Gough et al., 2012) in support of the search for a systematic way of using biomimicry principles to identify possible innovative solutions for improving the thermal performance in buildings. "*Searching the literature involves the formulation of a search strategy, which includes inclusion and exclusion criteria, keywords, sources of evidence, the documentation of the search, and selection of the research reports to be included*" (Ham-Baloyi & Jordan, 2016).

4.2.1 Search process for finding relevant references

The purpose behind this search process can be separated into two interrelated aims.

1) A literature review that investigates examples of the application of biomimetic principles for designing energy efficient buildings which have improved thermal performance.
2) Using the bio-inspired design (BID) approach as a process, a literature review explores how thermal adaptation mechanisms in nature have been systematically found and transformed to architectural principles for enhancing the thermal performance of buildings.

According to Alice (2013), the following research databases are the most trusted and were used for this search:

Google Scholar, *CiteSeer* (includes papers in the field of computer science), *GetCited* (the webpage does not work anymore), *Microsoft Academic Research* (one related paper was found based on filtering biomimetic, engineering and computer-aided design), *Bioline International* (includes papers related to public health), *Directory of Open Access Journals* (no paper was found), *PLOS One* (only includes biological papers, no architectural research is included), *BioOne* (no paper was found), *Science and Technology of Advanced Materials* (material is not the focus of this research), *New Journal of Physics* (not related), and *Science Direct*. *Scopus* is the largest database of peer-reviewed literature which provides a comprehensive source of scientific/technological papers and *Sage* is the world's 5th largest journal publisher.

Four databases that offered the most likelihood of finding a significant number of documents were searched in detail: *Scopus*, *Sage*, *Science Direct* and *Google Scholar*. The basic keywords were biomimicry, architecture, thermo/thermal regulation. Table 4-1 shows the search results.

Table 4-1 Search terms within the databases *Google Scholar*, Sage, *Scopus*, and *Science Direct*: (date of the last search: 28 July 2016)

Database	Keywords	Number of results
Google Scholar	('thermoregulation' AND 'Biomimicry' AND 'architecture')	2350
	(thermal regulation AND Biomimicry AND architecture) NOT ('medical' [All Fields]) NOT ('morphogenesis' [All Fields]) NOT ('material' [All Fields])	177
Sage	All Fields ('thermal regulation' AND 'biomimicry')	11
Scopus	All Fields ('thermal regulation' AND' biomimicry' AND 'architecture')	63
	TITLE-ABS-KEY ('thermal/thermo regulation' AND 'biomimicry')	1
Science Direct	Field of Engineering ('thermal regulation' AND' biomimicry' AND 'architecture')	14

Bibliographies of selected articles were also screened and the useful publications extracted from these can be grouped into four categories:

1) Thermal comfort/standards in buildings/urban environment, including thermal performance of reflective coating, modelling impacts of roof reflectivity, studying the impact of photovoltaic panels or green roof on energy consumption.
2) Biomimicry/biomimetic as a new way of design.
3) Energy simulation of buildings, including considering the impact of occupancy, electronic equipment.
4) Thermal adaptation (heat gain/loss) in organisms.

4.2.2 Inclusion and exclusion criteria

Eligibility for inclusion was determined by reading abstracts and sometimes whole articles. Three key words: "medical", "morphogenesis", and "material" were excluded in the searches since they would identify papers that were irrelevant. Morphogenesis in architecture is the study of biological forms, patterns, and materialisation processes for developing environmentally responsive forms and structures. The mathematical rules governing the biological structures have in turn inspired the design and development of construction materials and structural elements, and the generation of forms. In the form finding process for example, the cellular and molecular organisations of living organisms are imitated to generate and transform forms in architectural design. This is discussed to an extent in Chapter 3 where bio-inspired materials have been developed with the aim of reducing the embodied energy of buildings. However, morphogenesis is excluded from the keywords as the focus of this chapter is on the operational energy.

As the blue cells of the "number of results" column show, 203 papers were finally selected after excluding some key words. Screening these, three duplicates were found out of the 203. At the first stage of the review, 127 papers dropped off based on irrelevant titles and 44 paper abstracts were screened and dropped off, again because those papers did not exactly address the context of the research. Irrelevant papers were related to the following subjects: tissue engineering (medical science), cellular biology, the role of biomimicry in the future of cities (not related because of the scale of the research), principles of organisation of ecological communities (i.e., ecosystems) for creating sustainable human communities, papers focused on computation and genetic algorithms, bio-inspired structure of buildings, and bio-inspired textiles. Finally, 29 papers were left for detailed study.

4.2.3 Selected references

The selected papers include the following key concepts: thermo/thermal regulation in buildings, biomimetic, biomimicry, bio-inspired architecture, bio-inspired design, natural organisms, biological samples, thermal adaptation strategies/mechanisms, energy efficiency, thermal performance, heat balance strategies in nature, and heat regulation mechanisms of plants/humans/animals.

Articles were grouped according to the following steps:

Step 1) Is the article a one-off study with no description of how the biomimetic analogy was found, and no repetition of the analogy in other design situations (Y=Yes, N=No)?

Step 2) "Practical" means the energy efficiency of the case study has been analysed using energy simulation; "theoretical" implies this step is omitted (T=Theoretical, P=Practical).

Step 3) Introduces the software by which the application of biological thermal adaptation strategies is assessed to evaluate the thermal performance of the redesigned/bio-inspired buildings. This was to aid the choice of the most reliable and efficient software for this research.

Step 4) Names the natural organism(s) used as an inspiration for design in three categories (animals, plants, and human anatomy); it is inferred that this suggests the pre-existence of biological systems.

Step 5) Introduces the architectural objectives mentioned by the authors.

Step 6) Identifies the architectural solution(s) or technologies designed and developed in the article to overcome thermal issues.

Step 7) Labels which climate has been considered (NA = Not Available, CC= Cold climate, HC= Hot climate, H&A C= Hot and arid climate, DC= Different climate).

Step 8) Indicates whether there are explicit links to previous data collections or strategies identifying relevant thermal adaptation strategies found in nature (Y=Yes, N=NO).

All these parameters facilitated the process of finding knowledge gap(s) in the literature. The first result was Table 4-2 which summarises research that has linked biomimicry with thermal performance in terms of these 8 steps.

Table 4-2 Summary of research linking biomimicry and thermal performance

References	Steps							
	Step 1	Step 2	Step 3	Step 4	Step 5	Step 6	Step 7	Step 8
(Park & Dave, 2014)	Y	P	Ecotect	Animal eyes	Daylight distribution	Adaptable façade systems	NA	N
(J. Wang & Li, 2010)	Y	T	NA	Butterfly	Adaptive response to solar radiation	Parametric kinetic building envelope	NA	N
(J. Wang, 2011)	Y	T	NA	Butterfly	Climatic temperature responsiveness	Parametric kinetic building envelope	CC	N
(Zare & Falahat, 2013)	Y	T	NA	Reptiles	Introduces a number of thermoregulation strategies beneficial for architectural design	Conceptual smart wall	HC	N
(Tachouali & Taleb, 2014)	Y	P	Ecotect	Flamingo	Indoor space temperature	Suggests strategies for reducing total energy consumption	H &A C	N
(Zuazua-Ros et al., 2016)	Y	P	OpenStudio & EnergyPlus	Tuna	Reducing heating demand of the building	Heat management in building	DC	N
(Al Amin & Taleb, 2016)	Y	P	Ecotect+ ladybug	Desert snail	Enhancing thermal comfort	Reducing energy consumption	HC	N
(Bermejo Busto et al., 2016)	Y	T	NA	Beehives	Better control of the air cavity	Redesigning Peltier cell prototypes	NA	N
(Ahmar & Fioravanti, 2014a)	Y	P	EnergyPlus + DIVA	Termites	Daylight control	Suggests strategies for reducing building energy consumption in a hot climate	H &A C	N
(Worall, 2011)	Y	T	NA	Termites	Energy efficiency and ventilation	Distribution of HVAC systems	NA	N
(Turner & Soar, 2008)	Y	T	NA	Termites	Airflow regulation/adjusting natural ventilation	Suggests a theoretical model for distribution communication & control between HVAC systems	NA	N
(Badarnah & Knaack, 2007)	Y	T	NA	Sea sponge	Regulating the interior microclimate	Conceptual breathing skin	DC	N
(Y. Han et al., 2015)	Y	P	OpenStudio & EnergyPlus	Flower petals	Reducing urban heat island effect	Retro-reflective building envelope	H &A C	N
(Alkhateeb & Taleb, 2015)	Y	P	IES	Tree bark	Thermal insulation	Suggests strategies for reducing total energy consumption	HC	N
(Nanaa & Taleb, 2015)	Y	P	Ecotect	Lotus flower	Use of natural sustainable energy	Suggests strategies for reducing total energy consumption	NA	N
(C. Lee, 2008)	Y	T	NA	Hair	Mitigating heat load	Overcoming thermal issues	NA	N
(Reddi et al., 2012)	Y	T	NA	Plant leaves & Skin	Stabilized earth construction	NA	NA	N
(Lopez, Croxford, et al., 2015)	Y	T	NA	Plant stomata	Adaptive envelope	Suggests active materials for the building envelope	DC	N
(Lopez, Rubio, et al., 2015)	Y	T	NA	Plant stomata	Adaptive envelope	Suggests active materials for the building envelope	NA	N
(Reichert et al., 2015)	Y	T	NA	Plant cones	Investigates the use of hygroscopic material for the building facade	Weather responsive composite	DC	N
(Alston, 2015)	Y	T	NA	Chemical composition of tree surface	Investigates the possibility of developing a material with adaptive real-time performance	Intelligent glass surfaces	NA	N
(Nessim, 2015)	Y	P		Human skin	Airflow performance with adaptive response to temperature without the use of mechanical or electrical means	Responsive material	ANSYS	N
(Scartezzini et al., 2015)	N	T	NA	Animals	Effective control over indoor climatic conditions	Suggests strategies for reducing total energy consumption	H &A C	N
(Badarnah, 2012)	N	T	NA	Organisms	Evaporative cooling system in building envelopes	Design of a building facade	H &A C	N
(Ahmar & Fioravanti, 2014a)	N	P	DIVA	Plants	Improving the thermoregulation of the building skin	Parametric shading screen	H &A C	N
(Ahmar & Fioravanti, 2014b)	N	T	NA	Plants	Cooling in hot climates	Categorization of biomimetic ideas in thermal regulation based on a small database	H &A C	N
(Elghawaby, 2010)	N	T	NA	Flora & fauna	Improving the ventilation system	Conceptual breathing facades	H &A C	N
(Kim & Torres, 2015)	N	P	Design builder/ EnergyPlus	Perforated folded surface of organisms	Exploring an integrated sustainable façade system	Contemporary curtain wall glazing system	NA	N
(Badarnah & Kadri, 2015)	N	T	NA	Random organisms	Creating a biophysical framework for accessing relevant analogies	Provides part of a structured framework of heat regulation processes	H &A	Y

4.2.4 Data extraction

The following briefly summarises research conducted on improving the thermal performance of buildings by applying natural principles in the design process. The literature has been categorised into three parts: one-off examples, varied examples, and flora and fauna.

4.2.4.1 Part 1: One-off examples

Of the 29 studies summarised in Table 4-2 which met the basic search criteria, 22 were one-off examples. Most studies in the literature are therefore describing metaphors.

4.2.4.1.1 Animals/insects

Park and Dave (2014) studied the geometrical and functional characteristics of the compound eyes of shrimps, which are made up of repeating units acting as visual receptors, as a means of designing the openings and material properties of a gymnasium surface by which the amount of light entering it can be controlled. This was a responsive facade system capable of adapting itself to the environment by following the position of the sun. As a result, daylighting was improved and energy consumption dropped, although the proposed architectural system required expensive automatic sensors leading to high maintenance costs. The emulation process is also limited to mimicking the formal configuration of a natural organism.

The bio-inspired kinetic envelope (BKE) suggested by J. Wang and Li (2010) is claimed to be able to respond to the environment by adjusting its spatial, physical, and material aspects among which only the spatial aspect of this claim (honeycomb cells inspired by butterfly wings) is examined. In J. Wang (2011) research, which is a continuation of the previous study, there is no thermal analysis to support the claim for optimization of energy consumption. The translation of biological principles to architectural parameters still follows a morphological approach.

Of the studies examined 17 do not provide enough evidence to prove that biomimicry can effectively enhance thermal regulation in buildings. However, the biomimetic approach of Zare and Falahat (2013) is architectural rather than morphological. They found that reptiles adapt to their environment using one or a multiple of the following methods: water evaporation from the skin, hibernation and aestivation in the cold season, respiratory and excretion system, solar energy absorption, increasing the length of their hands and feet, sheltering in the ground. They consequently suggested a number of architectural solutions such as underground construction and reducing a building's surface to volume ratio to improve the control of ventilation, heat absorption, and humidity through which the energy consumption of buildings can be reduced in a hot and arid climate.

In contrast, eleven studies were found that had tested the energy efficiency of biomimetic design approaches by running energy simulations. Tachouali and Taleb (2014) translated the breathing mechanisms of the flamingo into new methods of ventilation, resulting in thermal comfort in the interior environment, based on an *Ecotect* energy simulation (Table 4-3).

Table 4-3 Biological/architectural analogy adapted from Tachouali and Taleb (2014)

Biological principle	**Architectural principle**
Feathers	Design of louvres for shading
Breathing system	Creating cross ventilation in the space
Food filtering	Creating a buffer zone

Zuazua-Ros et al. (2016) used *OpenStudio* and proved that the heating demand of a work place drops significantly if the space arrangement is designed based on the strategy used by tuna to conserve energy. This was tested for three different climates by manipulating the two variables of different types of floor layout and occupancy level. Based on the findings, the location of meeting rooms or individual offices in the inner area of the office building (analogous to the location of dark muscles in the body of a tuna) had a considerable effect on the energy savings (Figure 4-1).

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Figure 4-1 The Tuna option for the floor plan of offices (Zuazua-Ros et al., 2016).

Al Amin and Taleb (2016) were inspired by the desert snail and their research was robust in terms of providing evidence since by running energy simulations in *Ecotect* they prove that adding bio-inspired architectural strategies can reduce the cooling load. Using thermo-shield coating and improving insulation dropped the simulated cooling load by 19%. This was reduced by another 3% by adding an intermediate zone. In addition to the previous measures, adding a building atrium reduced the cooling load by up to 40% and evaporative cooling significantly increased the average annual percentage of comfort hours by almost 20%.

Other studies remain as a hypothesis and have not been technically developed. For example, they have not assessed the thermal performance of bio-inspired buildings to investigate whether the biomimetic design approach has reduced energy use.

Bermejo Busto et al. (2016) proposed a new HVAC system based on Peltier cells which follow biomimetic principles (Figure 4-2). They noted that the heat shield and stigmergy strategies used by beehives could be translated into architectural principles for designing autonomous buildings. In this innovative HVAC system the equipment was operated based on signals. For example, emulating stigmergy in nature, empty rooms were neither cooled nor heated. Likewise, the Peltier system in the building extracts heat from the interior and passes it to the cavities in the facades in the hot season. This was inspired by the heat shield created between the brood comb and the exterior wall of the beehive (Figure 4-2). Heat-shielding is a temperature regulation behaviour used by bees to insulate the brood from localised heat stress. Siegel et al. (2005) conducted a series of tests to determine the contribution and behaviour of stationary and moving workers on keeping the brood cool. In response to heat stress, they found the number of worker bees increases on both the hive wall and the brood and the movement of those on the hive wall increases to improve the airflow. The research by Bermejo Busto et al. (2016) can be seen as more in-depth biomimetic design.

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Figure 4-2 Thermal behaviour of bees. Left) heat shield; Right) Peltier System and cavity performance in winter and summer (Bermejo Busto et al., 2016)

Of the studies reviewed 10% relate to imitating thermal regulation strategies in termite mounds. For example, Ahmar and Fioravanti (2015) suggest using a porous double skin façade, thus imitating the behaviour of organisms for reducing cooling loads in hot climates. Their study follows a morphological approach as the design goals are achieved by manipulating the geometry of the façade. Basically the latter is a hierarchy of three iterations of a triangular pattern, and by altering a series of attributes such as the fold depth and area of the triangles, the degree of cooling can be changed. The optimisation of this geometry is achieved using the evolutionary algorithms for fitness criterion.

The research conducted by Worall (2011) is more focused on biological than architectural aspects. They suggest mimicking the vascularized and tidal ventilation of termite mounds would lead to improved thermal performance. They claimed mimicking homeostasis as part of the nest structure would be a simple and efficient strategy for improving ventilation in buildings. Another concept they studied was the stigmergy termites employ as an adaptation mechanism, by imitating which a distributed communication and control of building equipment could be improved.

Turner and Soar (2008) have suggested termite mound analogies are not always successful, pointing to temperature regulation in the Eastgate Centre in Harare, Zimbabwe (Figure 4-3), which is achieved by huge fans consuming high amounts of energy in their running. They note that termite mounds do not require forced-air plants to regulate the temperature. Further, they state there are similarities between termite mounds and lungs and a good understanding of termite mounds as human lung functions

(Figure 4-3) could help architects design more sustainable buildings without the need for use of high energy consuming HVAC systems. This comparison between human lungs and termite mounds is shown in Table 4-4.

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Figure 4-3 Left) Natural ventilation in Eastgate Centre (Wikipedia, 2010); Right) Functional organization of a termite mound (Turner & Soar, 2008)

Table 4-4 Functional analogue of lungs and termite mounds for gas exchange for ventilation in buildings

Gas exchange principles	Human Lungs	Termite mounds
Convection	Bronchioles and fine bronchi	Egress tunnels and surface conduits
Natural ventilation	Alveoli	Nest chimney and subterranean tunnels
Pendelluft ventilation	Airflow between alveoli ducts and fine bronchi	Airflow between lower chimney (slow flow) and subterranean tunnels (fast flow)
High-frequency ventilation (HFV)	Respiratory therapy for enhancing diffusion and promoting pendelluft ventilation	High-frequency flow in upper parts Low-frequency flow in lower parts
Discriminatory mass transfer mechanism	Regulating gases in the lung and balancing water in the mouth	Regulating water and gas balance in the termite nest

4.2.4.1.2 Plants

So far only studies inspired by animals and insects have been summarised. This next group in the review has been inspired by plants.

The accumulation of buildings in urban environments leads to the urban heat island effect which in turn increases building energy consumption (Oke, 1973; Imhoff et al., 2010; Loughner et al., 2012). Different from researchers who have only analysed individual building energy performance rather than that of groups of buildings in an urban context, Y. Han et al. (2015) looked for a biomimetic solution to reduce the impact of urban heat islands. They found the flower *Galanthus Nivalis* produces a cooler intrafloral temperature through the retro-reflective surface of its petals. Based on this a folded facade was designed for building envelopes located in eight climatic regions, with the consequence that building cooling demands decreased considerably (Figure 4-4).

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Figure 4-4 Left) The pattern used for designing retro-reflective building façades; Right) Building blocks (Y. Han et al., 2015)

Alkhateeb and Taleb (2015) studied the complex structure of tree bark to find design strategies for a residential villa situated in Dubai. The strategies they extracted were translated into design principles such as shading, cavity walls, and thermal insulation. Using these, energy consumption in the optimal bio-inspired model was reduced by 34% compared to the original case. A similar approach was taken by Nanaa and Taleb (2015) who investigated the strategies used by the lotus to cope with its tropical environment. Both studies suggested double glazed windows and use of a shading system as bio-inspired design strategies, irrespective of their different sources of inspiration.

A number of research studies have taken a different approach towards creating a bio-inspired adaptive building envelope by investigating the direct use of natural/biological materials. These are again theoretical studies that have not involved or tested the bio-inspired building envelope for its energy efficiency.

Lopez, Rubio, et al. (2015) state that while conventional buildings need mechanical systems, biomimetic buildings inspired by stomatal movement would be able to behave like a living organism, by responding to the environment without requiring any sensors or actuators. Prior to designing materials, they investigated the amount of CO_2 and H_2O within a leaf whenever environmental parameters such as humidity, temperature, carbon dioxide concentration, and light intensity changed. Finally, they introduced a number of reactive materials for windows and tested these in a laboratory by monitoring the dimensional changes of the window surfaces. The materials they introduced were heat sensitive plastics, wood, and carbon dioxide responsive polymers, all with the potential to be used in the building envelope. However, they do not support their research with energy simulations or with the testing of real buildings. The same team (Lopez, Croxford, et al., 2015) also studied the adaptive behaviour of stomata in terms of thermal regulation, water management, and air exchange as all are achieved without needing an external source of energy or a mechanical system. They applied their findings to create adaptive building envelopes, while accounting for the different climate zones and demands of users inside the buildings. Ultimately, they suggested the use of hydrogels and thermal polymers as these could produce real-time responses in the envelope to environmental stimuli. However, the suggestions remain to be tested in the field.

In the research conducted by Alston (2015) the intelligent surface of trees was studied as the tree surface is claimed to benefit from a hierarchical structure in its material composition. The surface is capable of regulating solar adsorption. The absorbency and adaptive real-time performance of tree bark was examined in order to design an intelligent glass façade with a vascular pattern similar to that of the tree bark, which acted as an adaptive cooling layer for the building envelope. Thermal adaptation was achieved by the flow of a chemical fluid similar to the fluidics in trees and within the vascular networks of the glass, which were similar to the patterns of tree bark. Sensors were installed in the glass facades to record the temperature fluctuations. The flow of chemical fluid in the glass was manipulated accordingly to enable the façade to receive the maximum energy for absorption. Alston added that this bio-inspired glass façade would reduce the urban heat island effect. They also believed climate recognition would increase the efficiency of the façade since user demands also vary with geographical location. Again this work needs testing at the large scale.

Reichert et al. (2015) suggested another responsive architectural system which does not use electronic equipment for sensing, actuation and control. Insights they drew from the literature revealed that most current approaches to making a building responsive to climatic issues were based on electrical and mechanical systems. Imitating the hygroscopic actuation plants employ to actuate their organ movement would allow for developing a passive, material embedded responsiveness. This led to the design of two responsive materials composed of composite cells called *Hygroscope* and *Hygroskin*. Each cell has two timber layers of which one opens and another closes in response to changes in humidity. This highly adaptive building envelope is limited to one specific type of material (wood) and one environmental variable (moisture). This is yet to be used in a real building.

4.2.4.1.3 Human beings

Human skin has always been a source of inspiration for thermal regulation in buildings. Gruber and Gosztonyi (2010) have aligned the functions of the skin of organisms with analogies in architecture. Other researchers have considered buildings envelopes as analogous to human skin in terms of controlling heat generation and maintaining thermal equilibrium (Badarnah & Knaack, 2007; Reddy et al., 2007; C. Lee, 2008; Nessim, 2015). This observation introduces a third category of studies in this review focused on human anatomy as a source of inspiration for thermal regulation in buildings.

C. Lee (2008) believed building envelopes have similar demands to human skin in terms of controlling heat generation and maintaining thermal equilibrium. The author refers to hair as a medium in human skin that facilitates heat regulation. They studied the function of hair and its morphological adaptation and designed radiant barriers as an architectural equivalent. However, the architectural strategies in this study were not integrated into the design process and the energy efficiency of the proposed system was not evaluated.

Badarnah and Knaack (2007) proposed a new type of exterior wall capable of inhaling and exhaling, and thus adapting to the changing environment. The proposed geometry for this exterior wall deforms to regulate air pressure on the surface of the building. Accordingly, the interior microclimate can be controlled by the amount of air sucked in or expelled through the building façade. The exterior wall is made of repetitive components called chambers that are similar to human lungs. Air pressure inside a chamber can be controlled by wires and valves attached to its expelling surface (Figure 4-5). This mechanism regulates the air flow through the building. The efficiency of such a breathing wall remains unknown, however, as no simulation has been run to evaluate its performance. Moreover, not enough information is provided on the technical implications of this conceptual design.

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Figure 4-5 Left) Repetitive components of the façade that are similar to human lungs (Badarnah & Knaack, 2007); Right) "Breathing wall" (Elghawaby, 2010)(see 4.2.4.3)

In the context of bio-inspired construction, Reddi et al. (2012) looked at heat generation and evaporative heat loss as the thermoregulatory mechanisms of human skin and plant leaves and suggested a series of challenges and opportunities for biomimetic construction. They claimed stabilised earth as an extensively used construction material could be engineered to imitate biological principles to reduce the energy consumption in the indoor environment. As an analogy, the soil capillaries were claimed to be similar to sweat glands through which water distributes in the soil. Similarly, the shrink-swell nature of soil was linked to the vasoconstriction/vasodilation of the blood vessels.

Only one paper in this category proves its energy efficiency by simulation (Nessim, 2015). The researcher in this study analysed the thermal performance of a shape memory polymer (SMP) using a physical model of a building. The air flow through the model building was improved by the 2mm sheet of SMP used in its internal windows. These sheets bent outward to allow for air flow when the temperature inside the model was increased.

4.2.4.2 Part 2: Other relevant examples

There have been studies on multiple biological examples as a means of discussing the idea of bio-inspired thermal regulation in buildings (Badarnah et al., 2010). Scartezzini et al. (2015) also foresee a number of possibilities for future bio-inspired projects ranging from passive design strategies to manipulation of control networks from the study of the thermoregulation strategies of silkworms, honey bees, and tuna. Based on the interpretation of a building as a cold-blooded animal, a number of passive functions are suggested for providing a comfortable situation for the inhabitants. However, none of these ideas are either well explained or developed.

Badarnah et al. (2010) studied human skin, tuna fish, and termite mounds by looking for the features, challenges, strategies, and mechanisms these organisms use for thermal adaptation. Eventually, they proposed the *Stoma Brick* to improve evaporative cooling in building envelopes constructed in hot and arid climate.

Sara and Noureddine (2015) developed a Bio-key tool which was based on biomimetic principles inspired by prairie dogs, spiders, and termite mounds, and that set out to improve the energy consumption of a building by reducing the energy used for improving indoor air quality and cooling and ventilation. However, there is no evidence of whether energy use can be optimised emulating these principles. The proposed Bio-inspired design framework that forms their tool is also not an original methodology as it is based on *BioGen* developed by Badarnah (2015) (see 5.1), and it also requires pre-existing knowledge of natural organisms.

4.2.4.3 Part 3: Flora and fauna

This section looks at research that has investigated the thermal adaptation strategies of animals and plants in general (Elghawaby, 2010; Ahmar & Fioravanti, 2014b, 2014a; Kim & Torres, 2015).

Elghawaby (2010) investigated thermal adaptation methods in flora and fauna as the basis of designing a conceptual three-layer "*breathing wall*" (Figure 4-5). The exterior layer allows the air to pass while also preventing direct sunlight entering the building. The middle layer works as an insulation layer in which air is cooled by a water spraying system outside the skin. The internal layer acts as a control. This is a very rare case where a bio-architectural solution could be generally applicable to all buildings and has the potential to be further technologically developed. However, the energy efficiency of the proposed system remains unknown.

As Ahmar and Fioravanti (2014b) have pointed out, the thermoregulation strategies of botanical examples (tree bark, leaves and succulents) can be analysed and categorized into four groups each representing a specific type of heat transfer method that could be used for inspiring architectural features. They also explained how the size, shape, orientation, and ventilation system of the surface of the leaf affects thermoregulation. What has been provided is a small database of three botanical examples. Ahmar and Fioravanti (2015) continued their research by examining the energy efficiency of a parametric shading system to be used in two buildings located in hot climate for reducing the cooling load.

An integrated façade system for a multi-story office building was designed to reduce heat loss in cold seasons and increase it in hot seasons by optimising the daylight entering through it throughout the year (Kim & Torres, 2015). The folded perforated skin consisted of aluminium components which followed the movement of the sun. Based on the simulation results, the total energy consumption of the baseline building façade was 30% more than that of the integrated façade.

4.3 Discussion

Table 4-5 summarises the examples outlined in this chapter and their relationship to architecture. These examples are not the result of a systematic search for possible strategies found in nature that might have architectural applications. Only one research study concerned a framework for conducting such a search and given its importance for this thesis is discussed in depth in Chapter 5.

4.4 Chapter summary

This chapter began by explaining ecologically sustainable design and the environmental theories of ecosystems. It made reference to the operation of buildings as a significant consumer of energy, to the overarching objectives of ESD as developing strategies for building adaptation to the environment, to the significant energy spent on improving indoor environmental conditions through cooling and heating, and to biomimicry as an approach to sustainable and energy efficient building design.

Table 4-5 Summary of examples

Biological example	Nature	Strategy	Architecture	Strategy
Termite mounds	Capped chimneys	Air refreshing process Water evaporation Respiratory gases exchange	A row of tall stacks	Cooling mechanism
	Open-chimney mounds	Stack effect mechanism	Flow of heat	Cooling mechanism
	Damping temperature & fan-driven ventilation	Thermal capacity of the soil	Low/high capacity fans	Cooling mechanism
Tree bark	Protection	Tree bark double layer	Multi-layer skin building envelope	Cooling/heating mechanism
	Self-shading	Peeling crusts, deep cracks	Shading	Cooling mechanism
	Insulation	A waxy thick layer of cork prevents water loss in plants	Thermal insulation materials	Cooling/heating system
	Material conductivity	Inner bark responsible for transporting sugars	High-performance glazed units	Cooling/heating mechanism
Lotus flower	Light control	Mechanism of opening and closing depending on daylight level	Shading louvres	Cooling mechanism
	Self-shading	The higher leaves provide shading for the flower	Double roof	Cooling mechanism
	Nourishment	Flower nourishes itself by turning water in it into glucose	PV cells	Protection from heat gain
Flower petals	Evaporation/self-shading	Special directional reflective property of flower petals	Retro-reflective building envelope	Cooling mechanism
Desert snail	Withdrawal inside the shell		Cool roof/thermo-shield	Insulation
	Shell reflectivity		Reflective surfaces	Reduction in heat gain
	Shade	Low temperature of the soil surface under the snail	Intermediate zones	Insulation
	Air as insulation	Withdrawal of snail inside the shell	Extending the roof	Shading
	Evaporative cooling	The weight of a snail changes from day to night	Night purging of building atrium	Cooling mechanism
Fish	Preventing glare	Polarization of light	Glass material	Light distribution
Moth	Glare reduction	Anti-reflective by a protrusion on the surface of the cornea	Glass material	Light distribution
Lobster	Glare reduction	Square tubes	Glass material	Light distribution
Black stork	Glare reduction	The relative angle between water surface, and beak	Glass material	Light distribution
Fly	Glare reduction	Absorbing light by red colouring	Glass material	Light intensity
Meerkat	Glare reduction	Absorption of light by black fur surrounding their eyes	Glass material	Light intensity

This chapter investigated how researchers have been inspired by biological thermal adaptation mechanisms in nature in order to improve thermal performance of buildings. The search process for finding relevant references is described, and the energy efficient bio-inspired design approaches are explained. Papers are then categorised into three groups based on their source of inspiration. The literature review revealed that only one research study used a framework for designing bio-inspired high-performance buildings. Considering the importance of the non-metaphoric application of biomimicry, the next chapter focuses on that paper and will investigate the process it uses for finding inspiration in nature.

5 Knowledge Gap and Research Question

5.1 Introduction

Biomimicry has been proven to increase the energy efficiency of buildings (Tachouali & Taleb, 2014; Y. Han et al., 2015) (see 4.2.3, Table 4-2). Reviewing the literature found many examples that showed that imitating thermal adaptation processes in nature has the potential to contribute to sustainable building design. To do this designers have translated the biological strategies they found into architectural design principles.

What prior research has also suggested is that most researchers do not follow a well-developed bio-inspired design (BID) process when it comes to finding relevant solutions in nature for overcoming thermal challenges buildings. As argued in section 2.4.1, the BID approach has been given multiple names such as *Problem-based*, *challenge to biology*, and *technology pull*, all referring to a bio-inspired design approach that begins with a design challenge and then explores nature to find solutions. The underlying concept, as discussed in Chapter 2 (see 2.4.1) is the importance of having a framework that allows innovative ideas to be found and translated into design. In the context of energy efficient biomimetic building design inspired by thermoregulation processes in nature, only one researcher has introduced a framework for the BID process (see 4.2.4.2). Given the focus of this research is developing and testing a systematic approach to mining biological databases, this chapter explains the *BioGen* framework developed by Badarnah (2012) in more detail.

5.1.1 An existing bio-inspired design framework for thermal regulation of buildings

In her thesis, Badarnah (2012) addresses the need for a framework by which architects can generate design concepts. This is based on her belief that drawing on the innovative adaptation mechanisms employed by natural organisms will result in building envelopes that are capable of adapting themselves to the environment by regulating the four main environmental aspects of heat, water, light, and wind.

Her research also addressed a series of sub-themes as set out below:

1) It investigated the environmental criteria that affect the building envelope and subsequently, the indoor climatic conditions.
2) It sought out relevant adaptation strategies in nature that can be implemented in building envelopes.

3) It explored a method for representing the strategies nature offers.
4) It developed a method for generating design concepts based on the lessons suggested by the relevant organisms.

It seems these sub-themes were developed in order to achieve the main objective of the research, which was how the design principles, methods, and strategies in identified natural organisms can be abstracted and transformed into design concepts for environmentally regulating building envelopes. The research was thus aimed at providing a thermally comfortable condition inside buildings.

As repeatedly emphasized by Badarnah (2012, p. 5), to reduce the research down to a manageable level, only a small number of relevant natural organisms were represented in the methodology. Correspondingly, the functional aspects of the thermal adaptation methods she used for establishing *BioGen*—a biomimetic framework for the design concept generation—are very limited compared to the huge gamut of survival strategies found in nature.

In terms of assuring the generalisability of *BioGen*, Badarnah (2012) notes the proposed design concept generation framework should be tested for the four different environmental principles of temperature, light, wind, and air. Through regulating these the internal environments of buildings should maintain Homeostasis similar to that achieved by organisms.

The purpose of her research was to provide a method for generating architectural design concepts, thus enabling designers to go beyond merely imitating the morphology of organisms and move biomimetic architectural design towards a more functional-oriented approach. This she refers to as successful biomimetic design for building envelopes.

The following challenges were encountered in her research:

1) How to search for and select adaptation strategies
2) The applicability of strategies to design as some might work in only one of the three chosen scales (macro, micro, and nano). The three scales refer to the levels in which thermal adaptation takes place as thermal regulation can be achieved either at cellular, molecular, or organismal level (see 9.4.2.6.6).
3) The conflict between the different solutions a design concept might need in different parts.

The *BioGen* framework consists of two main steps, which Badarnah (2012) refers to as the preliminary design phase and the emulation phase, although she stated the second phase was not considered in her thesis. Figure 5-1 shows the sub-phases developed for *BioGen*, where the blue and green rectangles introduce the sub-phases developed for the preliminary design (blue) and emulation phases (green) respectively. The different shades of blue represent the three main steps of the bio-inspired building envelope methodology. Dark blue is the exploration phase medium blue is the pinnacle analysis (pinnacle is the term use for the biological example identified) and abstraction phase, and light blue the determination phase.

Figure 5-1 Outline of the design methodology map developed by Badarnah adapted from Badarnah (2012)

The sub-phases in Figure 5-1 are carried out to fulfil the following requirements:

1) The function(s) of the building challenge (e.g. heat gain, water gain, and air exchange) are identified by designers, based on the expectations of the occupants and the environmental context.
2) Relevant biological challenges similar to those identified by the designers are explored and investigated; these are explained by factors, processes, and pinnacles (Figure 5-2).
3) A number of organisms (pinnacles) are chosen for further elaboration.
4) These pinnacles are analysed so as to be better understood by the designer as they distinguish the strategies, mechanisms, main principles, and main features of pinnacles.
5) This is achieved by categorising the analysed data into specific groups.
6) The extracted data is abstracted and “imaginary pinnacles” are identified.
7) A design matrix is generated to produce design concepts.

Badarnah (2012) also developed a series of design tools to assist designers in the preliminary design phase. These are the 1) exploration model, 2) pinnacle analysis model, 3) pinnacle analysis matrix, and 4) design path matrix. A brief explanation of each is provided below.

The *exploration model* is a hierarchical representation of biological knowledge and was developed as an example of a data mapping structure. This would then be used by designers to narrow down their search from a general challenge to more specific aspects such as function, process, and factors, so as to end with the relevant organism(s) (Figure 5-2). The final biological examples are termed *pinnacles*. The main challenges Badarnah (2012) established in her research were to do with light, heat, water, and natural air conditioning in buildings.

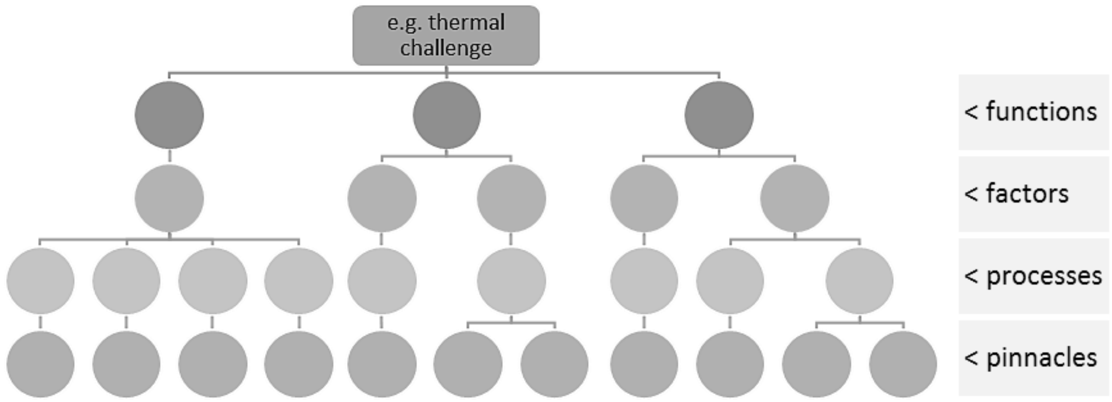

Figure 5-2 Hierarchical representation of the exploration model adapted from (Badarnah, 2012)

What this process inherently means is that generation of the final design concept is directly affected by the exploration phase. This was noted by Badarnah (2012).

> *"The current work provides a selection of representative processes and factors based on the analysis of a rather modest number of pinnacles, negligible compared to the sample size nature provides. In order to create a reliable generalized database, one needs to carry out extensive research on organisms and natural systems, which requires various resources and collaboration of professionals from numerous disciplines. Consideration of a wider number of pinnacles should result in a refined selection of optimized processes and factors. However, the sample size to be considered and the number of features/processes and their categorization remain a great challenge at this stage.*

Even when an extendable database becomes available, with the refined processes and factors, there would still be a need of a continuous investigation and update for such a database, since nature is continuously developing and updating." (Badarnah, 2012, p. 196).

The developed pinnacle analysis model is based on a series of steps following which the main feature(s) of the performance of the pinnacle can be understood. This model analyses the pinnacle by investigating the strategy, the mechanism, the main principle, and the main features of the thermoregulation carried out by organisms. For example Figure 5-3 shows the analysis of termite mounds.

Strategy	Mechanism	Main principles	Main features
The inhabitants of the mound modify it in accordance to the environmental changes for homeostasis	e.g. Structural features to retain or dissipate heat: variations in wall thicknesses, surface pattern, projecting structures, orientation, chimneys, air passages, porosity	Natural convection	Chimneys and air passages

Figure 5-3 The Structure of the pinnacle analysis model adapted from (Badarnah, 2012)

The pinnacle analysis matrix is built on the pinnacle analysis model and is aimed at representing pinnacles by classifying the relevant data as analysed in the previous step in a manner such that the proposed categories contain a potential analogy for the building envelope. These categories present the pinnacles by describing a set of thermal adaptation characteristics. These are the processes, flows (passive or active), different types of adaptations (physiological, morphological, and behavioural), scales (nano, micro, and macro), climatic classifications (e.g. arid or polar), morphological features, and material features (Figure 5-4).

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Figure 5-4 Pinnacle analysis matrix (Badarnah, 2012)

The pinnacle analysis matrix was developed to reduce the complexity of the solutions a designer might face in the case where multiple relevant pinnacles are found and accordingly multiple strategies, mechanisms, principles, and features are identified. Hence, for each function, an imaginary pinnacle is introduced that holds the dominant or common feature of every individual category. Once the imaginary pinnacles are recognised, the design path matrix is created to highlight the dominant features and thus facilitate the generation of design concepts (Figure 5-5).

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Figure 5-5 Design Path Matrix (Badarnah, 2012)

Even though Badarnah (2012) has referred to *BioGen* as a systematic design methodology by which relevant biological principles can be 1) found, and 2) abstracted in order to be 3) applied in the generation of a concept, the first step (finding relevant strategies in nature regarding thermal issues) is not fully explored. This is because only a small number of organisms were investigated for creating the exploration model, which she then developed as a design tool for use in the preliminary biomimetic design phase. For this reason, the proposed biomimetic methodology cannot be said to have been generalised based on exploring all thermal adaptation strategies in nature. Her research is mainly focused on the transformation of strategies available in nature into technical solutions for building envelopes.

The design path matrix is the end stage of the preliminary design phase and the point at which the emulation phase starts. For each environmental challenge, and based on the dominant features, a design concept is developed and its energy performance then evaluated to ensure the energy efficiency of the bio-inspired design of the building envelope.

Badarnah and Kadri (2015) refer to this method as a *biophysical framework* that can be used for generating design concepts for the building envelope. They state the database of natural organisms provided for the proposed framework is not comprehensive in terms of introducing a generalised list of processes, factors, and hence, pinnacles, which in turn implies the need for future exploration and elaboration.

5.1.1.1 Discussion

The examples from the literature review on bio-inspired materials in chapter three and bioinspired buildings in chapter four reveal the increased attention given by engineers and scientists to biomimetic design. It is also clear that biomimicry is an applied science that derives inspiration from the natural world and that can open avenues for technological and sustainable design. As researchers delve more into nature, more sustainable solutions in terms of efficient processes, functions, systems, and materials are being explored.

As seen in Chapter 2, from a general point of view, much research has been conducted with the aim of systematising a process for bio-inspired design with the focus on exploring and transferring biological principles to the engineering domain. However, looking at the examples presented in Chapter 3 on materials and hence embodied energy (EE) the following emerges.

There is no systematic process for developing bio-inspired materials. It seems that the design of bio-inspired materials developed for energy efficiency does not follow a systematic process by imitating which designers would be able to look for the infinite, potential solutions nature offers in order to achieve the desired material characteristics.

There is no specific database focused on biological thermoregulation mechanisms. Even though there are databases for assisting architects and engineers with biomimetic design, none contribute directly to thermal issues by using thermal adaptation strategies in nature. For example, even though *AskNature* to some degree supports a systematic search, it is a framework with a general purpose. This means the functional categories from which exploration of the biological database begin are not directly associated with thermal adaptation principles. *BioTRIZ* connects design problems to previous biomimetic solutions. Likewise, *SAPPhIRE* and *IDEA-INSPIRE* are data banks of previous biomimetic research and are mostly used by mechanical engineers.

Like other fields of knowledge, architectural design has benefited from biomimicry and the literature shows that the performance of some buildings has been enhanced by applying bio-inspired thermal adaptation strategies to building design. Subsequently, the literature review in Chapter 4 related to operational energy (OE) showed:

Most papers have imitated morphological aspects of natural organisms. Most studies in this area were metaphors and thermoregulation was achieved by imitation of the patterns, structures, or functions of natural organisms, leading to geometrical manipulation of building facades (J. Wang & Li, 2010; J. Wang, 2011; Park & Dave, 2014).

There has been an evolution in design approaches. Designing a building skin based on bio-inspired principles has evolved from a simple imitation of patterns and geometries found in nature and applying these to a façade, to designing specific types of wall system or creating advanced materials (Alston, 2015; Reichert et al., 2015).

Most papers found were one-off examples. Of the 29 references found (see 4.2.3, Table 4-2), 65% were focused on only one organism and its relevant thermoregulation strategies. This demonstrates no comprehensive research has yet been conducted in terms of generalizing biological principles.

Current knowledge about natural principles is scattered. Biological thermal adaptation principles are not documented as a generalised dataset that would enable designers to connect existing thermal challenges to the relevant biological solutions.

There is some evidence to show improved energy performance. Energy performance of buildings has been enhanced by applying bio-inspired thermal adaptation strategies to building design (Tachouali & Taleb, 2014; Al Amin & Taleb, 2016; Zuazua-Ros et al., 2016).

The focus of recent literature is on the building envelope/façade for improving energy efficiency. None of the papers has considered the whole building as a living organism.

Most papers focus on hot climates. Where energy efficient examples have been found, most report on biomimetic solutions for hot and arid climates. The fact that more research has been conducted in hot climates suggests four possibilities: 1) there is insufficient information about thermal issues in cold climates; 2) adaptation strategies for organisms in cold climates have not yet been investigated; 3) thermal issues in cold climates are not of concern for architectural designers; or 4) hot climates are simpler examples because the one dimensional need to be cool is a simple problem, whereas cooler climates need a more complex, orientation and time-dependent solution.

Only one paper supports Biomimetic design without a pre-existing knowledge of biology. Using natural systems to overcome thermal issues in buildings necessitates a systematic biomimetic design approach. Almost all research based on pre-existing knowledge about biological examples fails to refer to any specific process by which relevant information (thermal regulation strategies in nature) can been found. Only the one study examined in this chapter has made a notable effort to develop a systematic design approach (Badarnah, 2012).

The exploration model proposed in Badarnah (2012)'s research is a worthwhile attempt since it follows a systematic approach towards biomimetic design. As stated by the author, the developed design tools are flexible in their input and firm in their output. This implies the more various the challenges, and subsequently the functions, processes, factors, and pinnacles are, the more dominant features are found and hence, more imaginary pinnacles are extracted.

As Badarnah (2012) states, despite the availability of myriad biological sources, finding pinnacles and abstracting their principles remains a big challenge for bio-inspired design and designers. She also points out the difficulty of managing a huge exploration model with a large quantity of pinnacles, as she believes the newly generated dominant features of one solution path might affect the others.

5.1.1.2 Knowledge gap

The following paragraphs introduce the existing knowledge gap in the literature.

The practice of biomimicry has for decades transformed human technologies into more sustainable, innovative techniques. However, what is not addressed by most research into bio-inspired buildings is the process by which the source of bio-inspiration was identified. This implies most research seems to be built upon pre-existing knowledge of biology.

In addition the fact that there is a need to break away from the metaphorical morphological approaches to a more systematic means of finding suitable biomimetic design inspiration has been identified.

Furthermore, previous studies have highlighted the importance of a systematic process or a generalised framework with a focus on the thermal adaptation strategies that biological organisms use to regulate their body temperature. In this respect, only Badarnah (2012)'s research has suggested a systematic process, called the exploration model, by which the thermal challenges of a building could be systematically connected to the relevant biological thermal adaptation strategies. However, as mentioned earlier, this model is built on a rather modest number of pinnacles and therefore, an incomplete and non-comprehensive list of functions, factors, and processes are generalised. Above all, to be able to develop a generalised database, Badarnah (2012) has emphasized the need to consult biologists and also conduct an extensive literature review on organisms.

The exploration model seems to have been created following a bottom-up approach, as the relative processes and factors were extracted as Badarnah (2012) studied a series of pinnacles in more depth once they were found in the literature.

Given the significance of energy efficient buildings and the possibility of improving building energy performance, and sustainability through BID, it seems there is currently no generalised framework of thermal adaptation strategies. This is important as imitating thermal adaptation principles found in nature has proven to overcome existing thermal issues in buildings. Moreover, most bio-inspired buildings are in hot regions, whereas a successful generalised framework would be expected to operate in various climates. This raises the question of whether there could be a general approach to searching for relevant thermal adaptation strategies in nature for the purpose of improving the energy performance of buildings by assisting researchers to connect the thermal issues to the relevant organisms systematically.

In light of these comments, what seems to be required is a generalised bio-architectural framework with the potential of connecting the thermal challenges to analogous thermal principles used by a specific species or families systematically. With this it should be possible to design innovative, energy efficient buildings to the benefit of both the occupants and the environment.

The research question was developed based on the points outlined above, especially the shortcomings of the currently available frameworks for generating biomimetic design concepts focused on thermoregulation in nature.

5.1.1.2.1 Research question

> "How could a generalised thermo-bio-architectural framework be developed as an aid to making energy efficient buildings through a systematic process of connecting thermal problems to relevant thermoregulatory solutions in nature?"

This generated the following sub-research questions.

- In the context of a building's simulated thermal performance, how can the heat transfer principles of its thermal behaviour be articulated so as to create a useful link to the generalised thermoregulatory principles, and how can the energy simulation process narrow the results to the main thermal challenges in a building?
- How can a generalised categorisation of biological thermal adaptation strategies be created?
- How can biological thermal adaptation mechanisms can be connected to their architectural parallels?
- To what extent can the biology side of the framework be trusted and does the ThBA has include all biological thermal adaptation mechanisms in an acceptable classification scheme with an appropriate order?
- To what extent is the ThBA useful for bio-inspired energy efficient building design in terms of suggesting relevant and innovative thermoregulatory solutions based on the thermal challenges identified for the office buildings?

5.2 Summary

This chapter described the framework developed by Badarnah (2012) that enables designers to identify the thermal adaptation solutions provided for a limited number of examples in nature, based on assumed thermal challenges in buildings. The chapter also reviews the main points to emerge from the literature review in chapters 2, 3, 4, and 5, and ends with the research question. This leads on to the discussion of the methods to be used in this research, and these are presented in Chapter 6.

6 Research Design and Methodology

6.1 Introduction

This chapter outlines the research aim and objectives, scope and limitations, as well as introducing the methods that will be used to test the hypotheses. Figure 6-1 shows the position of the current chapter within the thesis structure, between the literature review and before the data collection procedure.

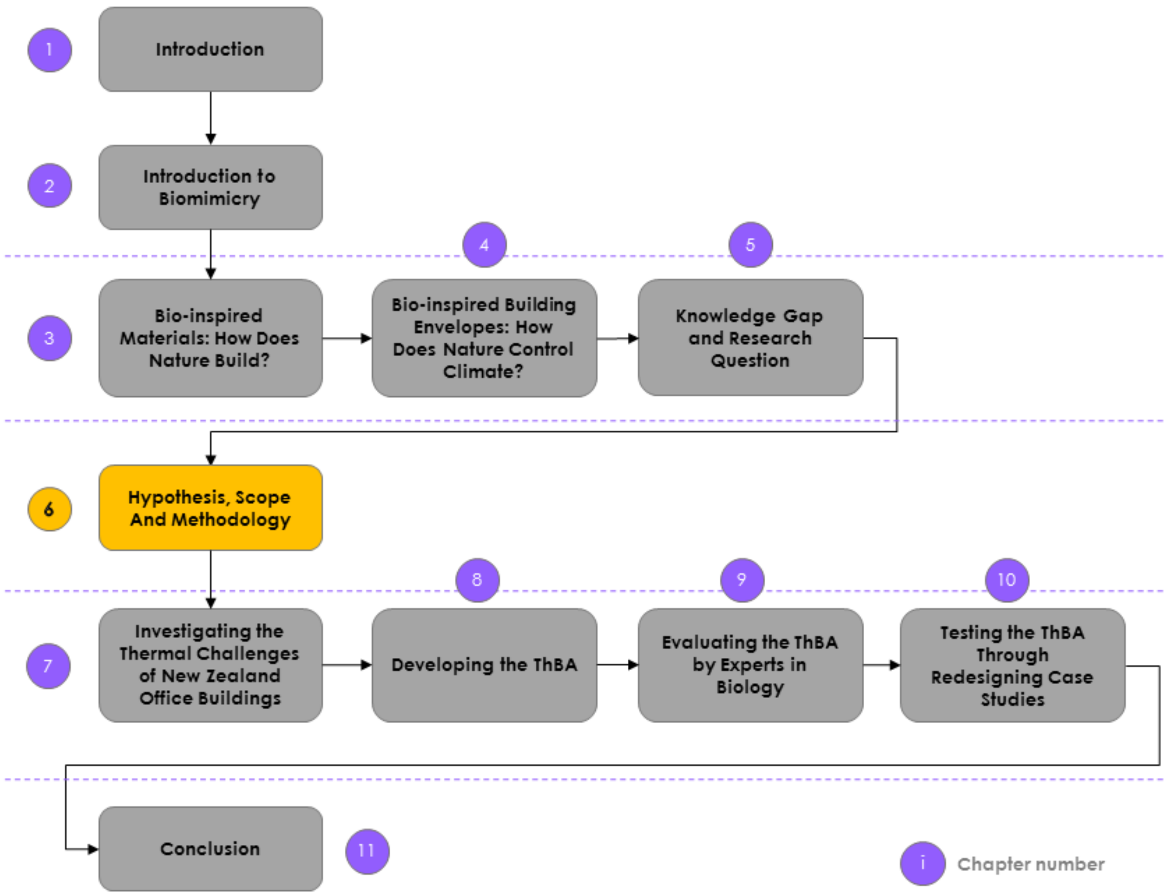


Figure 6-1 The position of the current chapter within the thesis structure

Chapter 2 detailed the philosophical aspects, motivations behind, and architectural applications of biomimicry. Considering the technological and sustainable outcomes of biomimicry, bio-inspired building materials (embodied energy) and design (operational energy) and their contributions to energy efficiency were reviewed in Chapter 3 and 4 respectively. The need to review EE and OE was because of the significance of these in the context of ecologically sustainable development (ESD). ESD (Harding, 2006) has both economic and environmental aspects (Gamage & Hyde, 2012). Of these the environmental aspects address the negative impacts of human activities. Architectural institutes in Australia and the USA work with various environmental policies, some of which include environmental technology initiatives that discuss the thermal performance of buildings.

The literature review in Chapter 3 and 4 suggested there is only one existing framework developed for the generation of bio-inspired design concepts. This was discussed in detail in Chapter 5. The literature review revealed there was no existing tool that could bridge between biological thermal adaptation solutions and building thermal issues to allow architects to access the efficient solutions organisms use to produce and consume energy and recycle resources. These issues together shaped the research question. Figure 6-2 shows the areas of knowledge and the contents covered in chapters 2, 3, 4, and 5.

6.2 Research aim, objectives, and questions

Given the significance of recent energy efficient buildings designed by imitating the thermal adaptation mechanisms of biological organisms, and bearing in mind the lack of a systematic process for fulfilling the requirements highlighted in section 5.1.1.1, there seems to be a need for developing a thermo-bio-architectural framework (ThBA) that will not only assure the generalization of all thermal adaptation mechanisms but that will also systematically connect thermal problems to relevant biological solution(s).

6.2.1 Research aim

The research seeks to test whether it is possible to develop a thermo-bio-architectural framework by which architects can follow a systematic process and take a series of steps in order to find relevant biological organism(s) and the corresponding thermal adaptation mechanisms with the potential to be analogically used in building design.

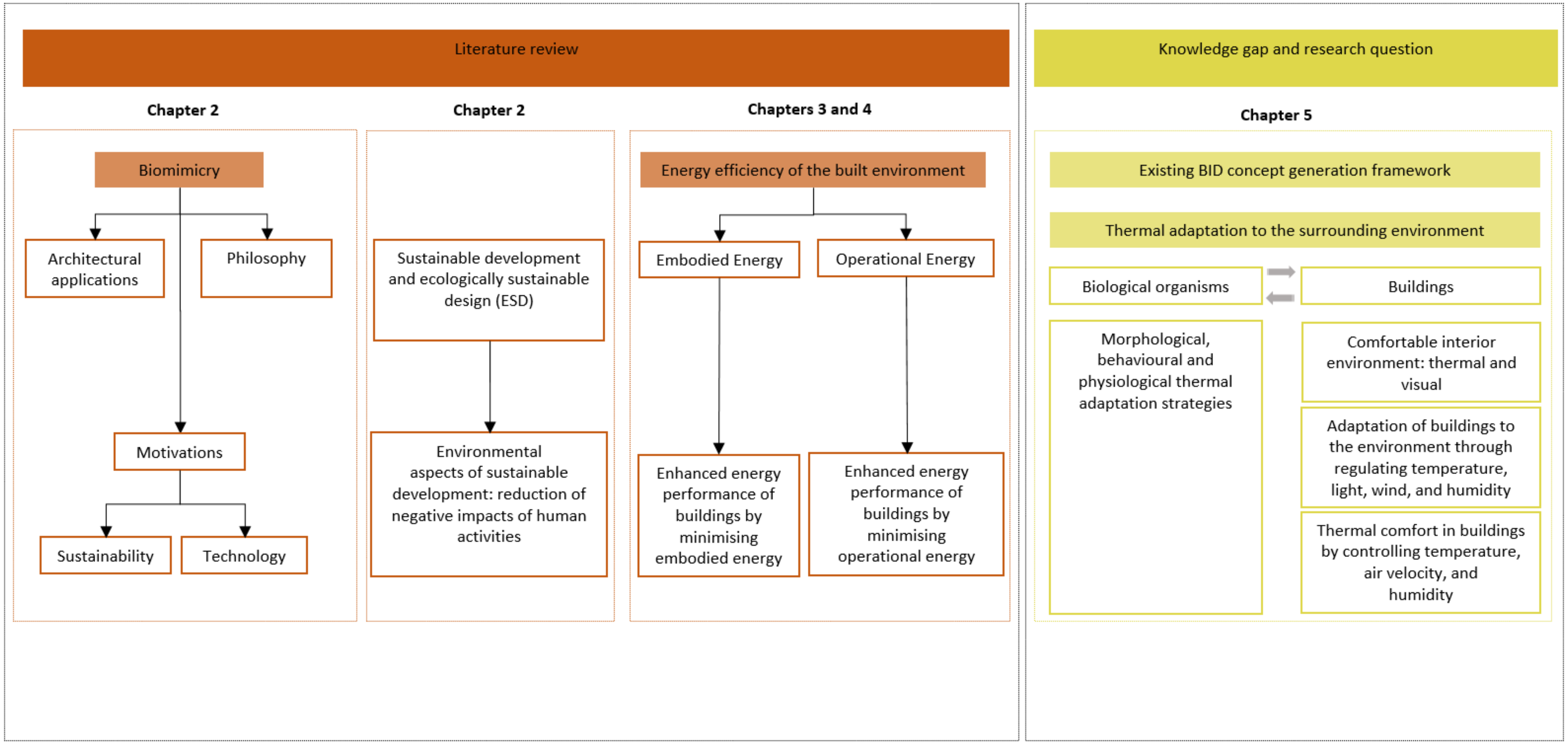


Figure 6-2 The areas of knowledge and the contents covered in Chapters 2, 3, 4, and 5

As there is no evidence of the existence of such a framework that at the same time is generalised in terms of this specific area of biological knowledge and that could systematically lead architects to the relevant adaptation principles to meet the thermal challenges, this research attempts to test the feasibility of developing a thermo-bio-architectural (ThBA) framework to fill this knowledge gap.

On a broader scale, this research aims to seek whether this ThBA framework can achieve improved energy efficiency, through the design of innovative and climatic adaptive buildings that not only impose less impact on the environment but also provide a comfortable interior environment for the occupants.

6.2.2 Research objectives

The following research objectives are shaped in a manner that links to the overarching aim of this research. These objectives can be categorised into four groups (A, B, C, and D):

A. Existing knowledge/data collection

1. Investigation of the existing thermal challenges in New Zealand case study office buildings.
2. Investigation of relevant thermal adaptation principles in animals, plants and human beings either revealed with the help of biologists from different disciplines or mined from relevant databases.

B. Creation

3. Creating a thermo-bio-architectural framework that includes generalised thermal adaptation strategies, by using which the existing thermal challenges of buildings in different climates can be systematically connected to potentially relevant thermoregulation principles in nature.

C. Testing

4. Translating the biological principles found through the ThBA into architectural design principles for the purpose of enhancing the thermal performance of office buildings.

D. Analysis

5. Exploring the energy efficiency of the redesigned office buildings and comparing their thermal performances.

6.2.3 Research question

> "How could a generalised thermo-bio-architectural framework be developed as an aid to making energy efficient buildings through a systematic process of connecting thermal problems to relevant thermoregulatory solutions in nature?"

6.2.4 Research scope

In regards to the interdisciplinary nature of this study, research boundaries need to be set for the fields of both biology and architecture. Given that building type and function strongly affect the design, there is a need to focus on one type of building and confine the design solutions to its specific building attributes.

Regarding the biological aspects, while most studies have tried to collect numerous biological adaption mechanisms, this research investigates those that might elevate the thermal performance of buildings in a specific climate. Hence, the focus of this research is primarily on the strategies organisms use to adapt their body temperature to the environment, while noting the regulation of temperature achieved by these strategies can be associated with light, air, or water regulation mechanisms.

Moreover, the energy performance of buildings can be improved by balancing multiple factors of which this research only focuses on the energy needed for space conditioning, in other words, the energy required to ensure thermal comfort in the building. In addition to the temperature, humidity control is also connected to thermoregulation in buildings and correspondingly the thermal comfort in the interior environment. Of all primary thermal comfort variables, this study mainly focuses on regulating temperature, however, in case thermal adaptation mechanisms in nature offer interrelated mechanisms through which air, light, and water are used as mediums to balance heat, the translation phase of this study could regulate other factors in buildings that are comparable to those used by organisms.

Looking from an architectural perspective to adaptive building design, it seems "*Nearly all forms of adaptations apply to the case of residential buildings*" (Peeters et al., 2009), and most literature has considered thermal comfort in residential buildings (Zain et al., 2007; Peeters et al., 2009; Peng, 2010; Prajongsan & Sharples, 2012; Djamila et al., 2013; Ioannou & Itard, 2015; Adunola & Ajibola, 2016). In contrast, limited research has looked office buildings (Jaakkola et al., 1989; Wagner et al., 2007) from conceptual design parameters, such as shading systems, area or orientation of the building, surface characteristics, and position of the windows, to more detailed parameters such as wall, roof, and floor composition and materials.

Furthermore, in designing thermally adaptive office buildings, climate alone does not determine the need for heating or cooling. While the main environmental factors generally affect the interior climate of a building like an office with its varying occupancy levels over the day, other personal factors such as activity and clothing levels affect thermal comfort. For example, a densely occupied building in a cold climate may have a high cooling demand because of the heat generation related to occupancy level (Cory, 2016). More specifically, in terms of thermal comfort, in many office buildings, people have no choice of sitting place, or the only control they have is over local cooling or heating devices such as fans or personal electric heaters.

Therefore, this research is limited to office buildings. In terms of the biological and architectural scope of the research problem, this is case study research within the biomimetic design context with the following aspects:

1) It looks for thermal adaptation principles, not all possible ways biomimicry might benefit a building design.
2) It looks at a particular use pattern of buildings (offices) because these are typically used for part of the day and year, and so are more challenging than housing in continuous use.
3) The focus of the research in the translation phase, where identified biological principles need to be transformed into architectural design principles, will be on improving the energy performance of the case studies mainly through regulating the temperature inside the building. Hence, regulating humidity is not the primary focus of this research. However, imitating thermal adaptation strategies that are associated with light, air, and water regulation mechanisms might suggest indirect design strategies of regulating light, air, and humidity as a means of regulating the internal temperature.

6.2.5 Research limitations

As the spectrum of biological species is broad, the research does not aim to investigate all species that employ thermal adaptation mechanisms, but rather a comprehensive and representative set of thermal adaptation principles. In other words, this research is aimed at accumulating scattered, unorganised, and varied thermal adaptation strategies.

The research is confined to one building type across a limited range of climates. An exploration of the applicability of the ThBA to this building type is a sufficient first test of the validity of the approach, although it will eventually be necessary to evaluate the approach for other building types.

6.3 Theoretical framework

"*…without a theory there is nothing to research. So, the theory provides a footing for considering the world, separate from, yet about, that world. In this way, the theory provides both a framework for critically understanding phenomena and a basis for considering how what is unknown might be known.*" (Silverman, 2013, p. 112)

This thesis uses the case study approach to test whether access to examples in nature can help designers make more energy efficient buildings. As the research is part of the theory of biomimicry but it will also challenge the usefulness of that theory, in the case that building a tool that gives architects access the thermal regulatory principles in nature may not prove helpful for the design of energy efficient buildings. The research seeks to develop a generalised thermo-bio-architectural framework to systematically connect the thermal challenges of office buildings to relevant thermal adaptation solutions in nature, but recognises that if this is successfully developed it might or might not prove useful. This will add to the theory of biomimicry.

6.4 Research philosophy/paradigms

This research is built on the theory of biomimicry and its philosophical approaches to innovative and sustainable building design (see 2.2). It aims to determine whether a thermo-bio-architectural (ThBA) framework can be developed to help in finding relevant thermal adaptation strategies in nature for use in buildings.

This research uses multiple case studies to test the developed ThBA. Case studies will be redesigned based on the relevant data the ThBA suggests for energy efficient building design. This study uses documents (BEES reports) as evidence to investigate the design of case studies (Gillham, 2000; Yin, 2009, p. 123).

6.5 Research method

Finding the knowledge gap in the literature, the research methodology is established to test the research hypothesis through a case study approach.

Developing the ThBA requires studying biology to find how thermal regulation strategies used by living organisms can be classified and generalised. This research also needs to investigate how the heat transfer principles in buildings can be articulated to be linked to the generalised thermal adaptation strategies in nature. For this, a series of case studies are selected and for each an energy simulation has been run to analyse its thermal performance and identify its thermal challenges.

These two parts together (the literature review on biology and the energy simulations of case studies) are part of the ThBA generation and testing. Considering the nature of the research question and the need for employing both qualitative (literature review on biology) and quantitative methods (analysis of the energy performance of the case studies) for approving or rejecting the hypothesis, this study needs to use a mixed methods approach to narrow the purpose statement. The integration of qualitative and quantitative data allows for a more synergistic data collection and analysis process (Creswell, 2014, p. 217). The mixed methods approach is a convergent parallel method, as qualitative and quantitative data collection and analysis are not sequential and one does not follow or build on another. The two stages take place separately but will be related to each other at the end of the research (Creswell, 2014, p. 220).

Furthermore, the proposed ThBA needs to be confirmed and evaluated before it can be used for the rest of the research. The biological part of the ThBA needs to be assessed by biological experts within a focus group session. The research will use a well-established qualitative technique for the focus group analysis.

Having the ThBA confirmed, the research will investigate if the ThBA can introduce innovative solutions for improving the thermal performance of buildings through revealing unexpected techniques or technologies. The selected building case studies with their thermal challenges will be used in this step. The implementation of innovative solutions suggested by the ThBA will be carried out through a redesigning stage where the relevant biological solutions will be transferred to architectural solutions. The analysis of the energy results at this stage would be quantitative.

This research does not use any explicit theory for quantitative data collection and analysis but applies thematic analysis for the qualitative study (focus group). The inductive or bottom-up, and deductive or top-down processes of thematic analysis allow for investigating emergent and a priori themes (Symon & Cassell, 2012, p. 430; Judger, 2016). The results of both the qualitative study and the earlier quantitative study (energy analysis of original and redesigned case studies), will be brought together to test the research hypothesis at the end of the research.

6.6 Research design

This research looks for patterns, hypotheses or ideas that might contribute to further research. It also suggests how future studies might take place in terms of designing more energy efficient office buildings based on lessons from nature. Figure 6-3 shows the workflow of the research, which is different from the ThBA testing workflow. The latter is illustrated in Figure 6-5.

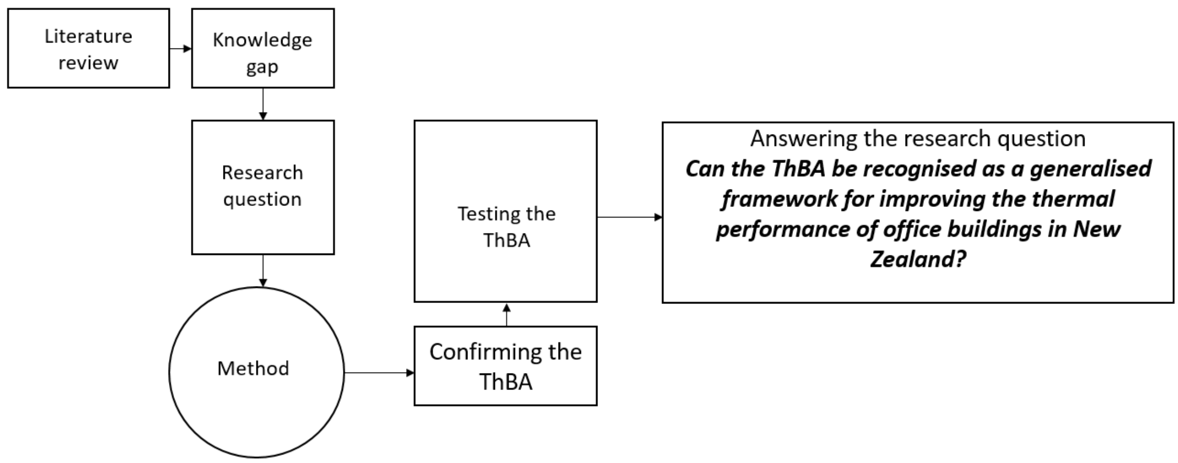


Figure 6-3 Research workflow

6.7 Research Diagram

This research is comprised of five main stages (Figure 6-4) as set out below:

1) Existing knowledge
2) Knowledge gap and research question
3) Data collection and data analysis
4) Testing the ThBA
5) Conclusion and generalisation

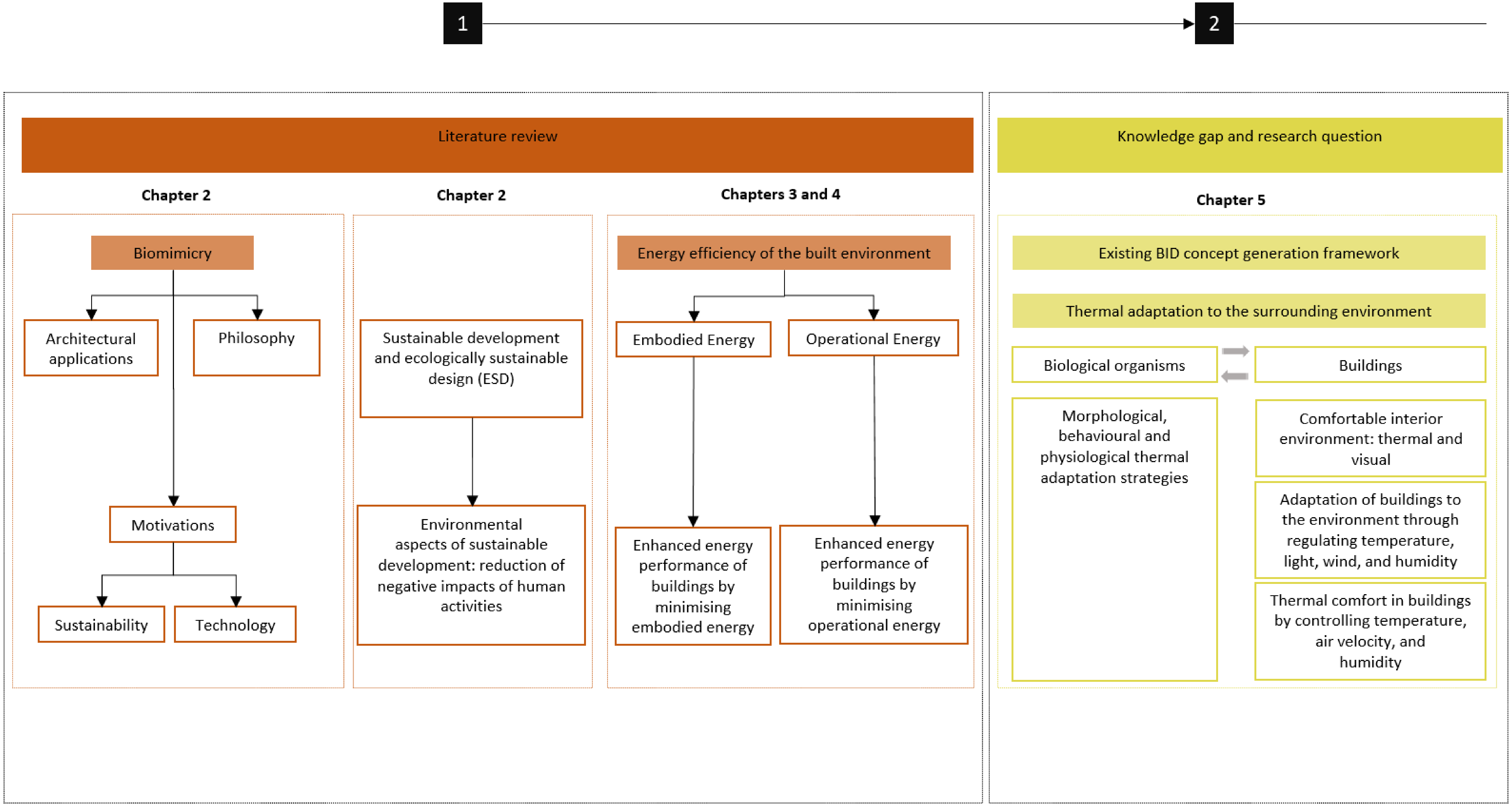
In this research, one challenging case study and two climates are selected for testing the ThBA framework in two main steps (Weisman, 1983). Referring to the case study redesign process happening at stage 4.a (Figure 6-4), as soon as the design of the first case study is accomplished, the results are evaluated and the outcome will inform the efforts required for the second case study design step. Final generated concepts in each design step need to respond optimally to all of the criteria initially set for the design.

In addition, in this study, a prototype workflow for testing the ThBA (Stage 4 of Figure 6-4, and Figure 6-5) will be developed. This is a search system for improving a building's energy performance.

For the five case studies selected initially, energy simulations will be run in Auckland. The analysis of the results of these energy simulations will determine the case studies with thermal challenges. Investigation of case studies with thermal challenge(s) in Auckland and Dunedin will generate options to be used for testing the ThBA using the prototype workflow.

The possibility of improving energy efficiency according to generalised natural principles takes place twice in the redesign phase (Figure 6-5). The ThBA will be tested in the following order:

1) The simplest case study from the previously generated options will be taken through the stages required for redesigning it using the ThBA (Chapter 10). In this context, simplest is the case study with the least thermal challenges.
2) The process will be repeated for the same building in a different climate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Literature review
Knowledge gap and research question
Chapter 2
Chapter 2
Chapters 3 and 4
Chapter 5
Biomimicry
Architectural applications
Philosophy
Motivations
Sustainability
Technology
Sustainable development and ecologically sustainable design (ESD)
Environmental aspects of sustainable development: reduction of negative impacts of human activities
Energy efficiency of the built environment
Embodied Energy
Operational Energy
Enhanced energy performance of buildings by minimising embodied energy
Enhanced energy performance of buildings by minimising operational energy
Existing BID concept generation framework
Thermal adaptation to the surrounding environment
Biological organisms
Buildings
Morphological, behavioural and physiological thermal adaptation strategies
Comfortable interior environment: thermal and visual
Adaptation of buildings to the environment through regulating temperature, light, wind, and humidity
Thermal comfort in buildings by controlling temperature, air velocity, and humidity

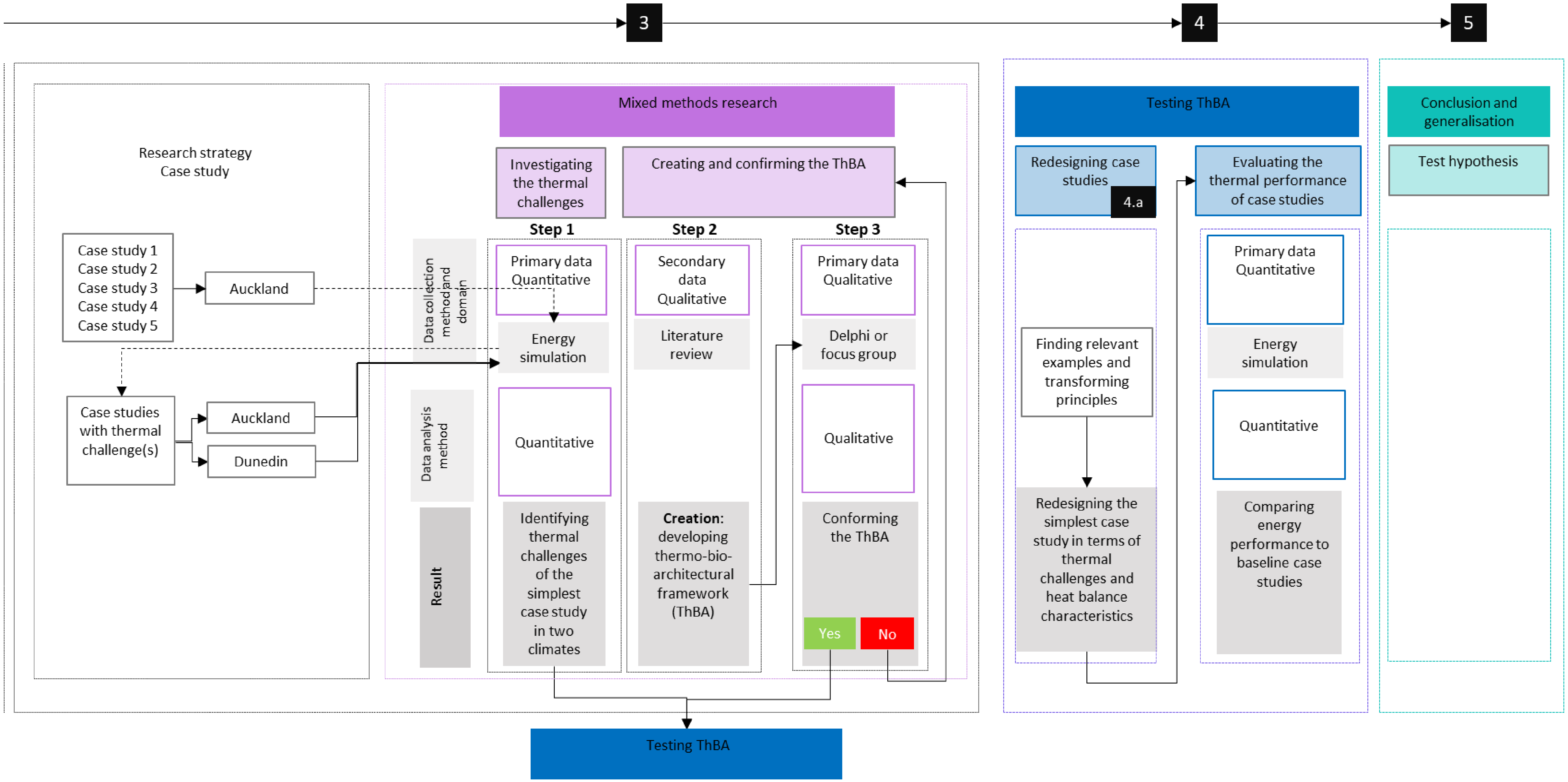


Figure 6-4 Research diagram including research stages

For testing the ThBA, the following stages need to be undertaken:

Stage 1: Selecting the simplest case study

Stage 2: Finding the relevant solutions in nature according to the thermal challenges identified

Stage 3: Transforming biological principles to architectural principles for redesigning the case studies

Stage 4: Evaluation and analysis

Stage 5: The simplest building in a different climate

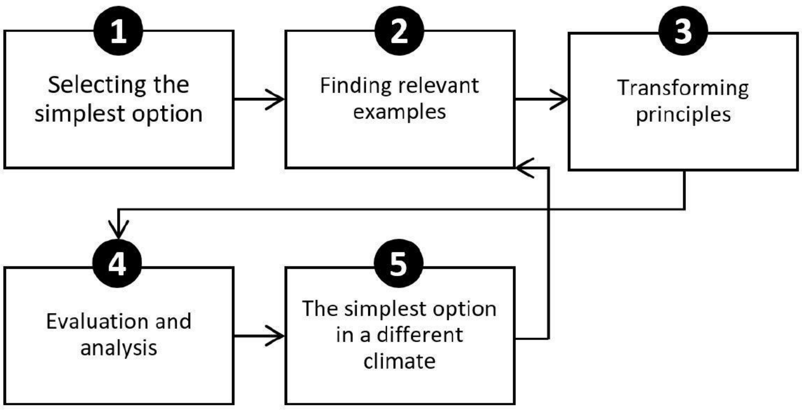


Figure 6-5 The five stages of prototype workflow for testing the ThBA

6.8 Diagram of the iterative process of energy simulation

Figure 6-6 shows the energy simulation iterative process. In the first round of energy simulation, a climate (Auckland) and five case studies (one from five different sized office building types) will be selected. Weather data and other inputs to the energy simulation software (*EnergyPlus*) will be set and the first round of energy simulation for the selected energy models will be run (Chapter 7). In order to identify two thermally challenging buildings, the energy simulation will be run for all case studies in Auckland (the dashed lines in Figure 6-6). The output of the energy simulations for the selected challenging case studies become the thermal challenges that will be fed into the next round of energy simulations.

The second round of energy simulation will be run to assess the energy performance of the redesigned case studies (Chapter 10) developed using the ThBA, assuming this has been confirmed beforehand by biologists as a reliable generalised framework ready to be used by architects (see 9.4.2.5). This happens when the retrieved biological principles identified by the ThBA framework have been translated into a series of design principles.

The result of the second round of energy analysis will determine whether the redesigned building shows an improvement in energy consumption. Energy simulations in this round will be run in parallel to provide the opportunity to reveal the more influential design parameters in improving the energy performance of buildings (see 10.4.2 and 10.5).

The second round of energy simulation will be run twice to assure the efficacy of the ThBA framework. So, once the one simplest option is redesigned in the first climate, the prototype workflow will be examined for the same building in another climate.

Testing the ThBA twice (one case study in two climates) should reveal how robust the process is in different climates. Basically, if at the end of the testing process, a set of generalised search terms appears to work efficiently, then it could be concluded that this framework can be used by other researchers in further studies, allowing that some alterations might be required to match the ThBA to specific building types and climates.

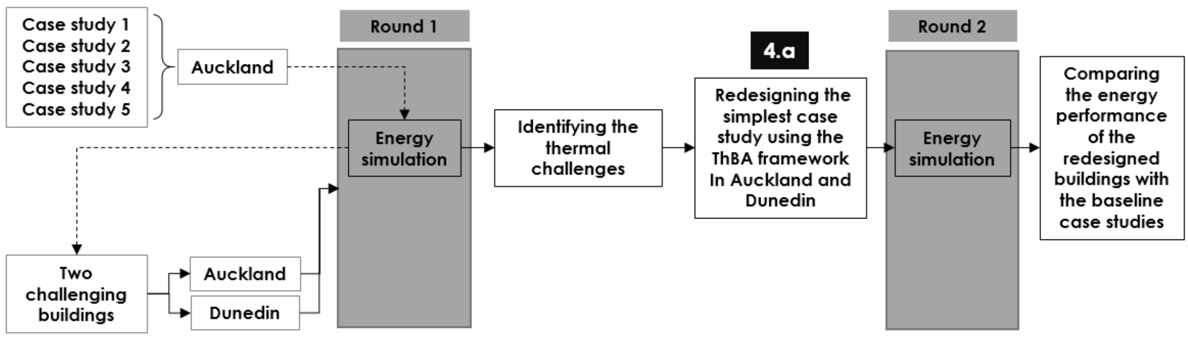


Figure 6-6 Diagram of the iterative process of energy simulation

6.9 Data collection (primary and secondary)

This stage (Stage 3 of the research process, Figure 6-4) includes the three main steps that together will allow for the creation of the thermo-bio-architectural (ThBA) framework.

6.9.1 Identifying thermal challenges

The first step will be focused on finding the existing thermal challenges in the case study office buildings. The outcome of this stage will feed into the next part in which the ThBA will be tested to look for the relevant thermal adaptation principles in nature. The ThBA framework will connect the thermal challenges to search terms. Search terms represent the thermal adaptation strategies but will be framed in the form of basic biological terminologies on the heat transfer mechanisms to enable the more effective mining of biological databases. This will be done to facilitate the connection between two distinct fields of knowledge.

To determine the existing thermal challenges, there is a need to run energy simulations. This consequently necessitates the selection of appropriate modelling and energy simulation software. To run the energy simulation, there is a need for a series of inputs to be first set in the software. All these items are explained as below:

6.9.1.1 Case studies

6.9.1.1.1 Size and sampling

Cory (2016) has modelled and then calibrated the results for 48 case study buildings out of 28,000 buildings reported by the Building Energy End-Use Study (BEES) project. He describes the process by which these were drawn at random from the pool of 28000 buildings and states these represent the whole New Zealand commercial building stock (Cory, 2016, p. 45). He has split the buildings into five different size groups (Strata 1-5) (Table 6-1) and three building types (Table 6-2), each representing around 20% of the total commercial floor area in New Zealand.

This research uses Cory (2016)'s calibrated energy models (marked CEM in tables in chapter 7), with appropriate selection of five archetypal case studies across all existing commercial buildings.

Table 6-1Bees five building size split adapted from Cory (2016, p. 46)

Size Groups	Size group 1	Size group 2	Size group 3	Size group 4	Size group 5
Floor area size range	5-649 m^2	650-1499 m^2	1500-3499 m^2	3500-8999 m^2	Over 9000 m^2
Total floor area in New Zealand (m^2)	5,855,000 m^2	4,489,000 m^2	4,230,000 m^2	4,641,000 m^2	5,927,000 m^2

Table 6-2 Three building type archetypes adapted from Cory (2016)

Commercial Office	Office-type use
Commercial Retail	Retailing use, Motor vehicle sales and services, Liquor outlets including taverns, Service stations, Tourist-type attractions
Commercial Mixed	Buildings with a mixture of commercial uses on one site

Figure 6-7 shows the average Energy Performance Indicator based on the different building characteristics, revealing offices are the largest commercial building energy consumers in New Zealand. The characteristics of commercial buildings in Table 6-3 have the potential to suggest appropriate case studies for this research. This research will also pick office buildings located in an urban area since these consume more energy that those located in rural areas. As reported by BEES, the 2-3 storey building consumes much more energy than other building sizes.

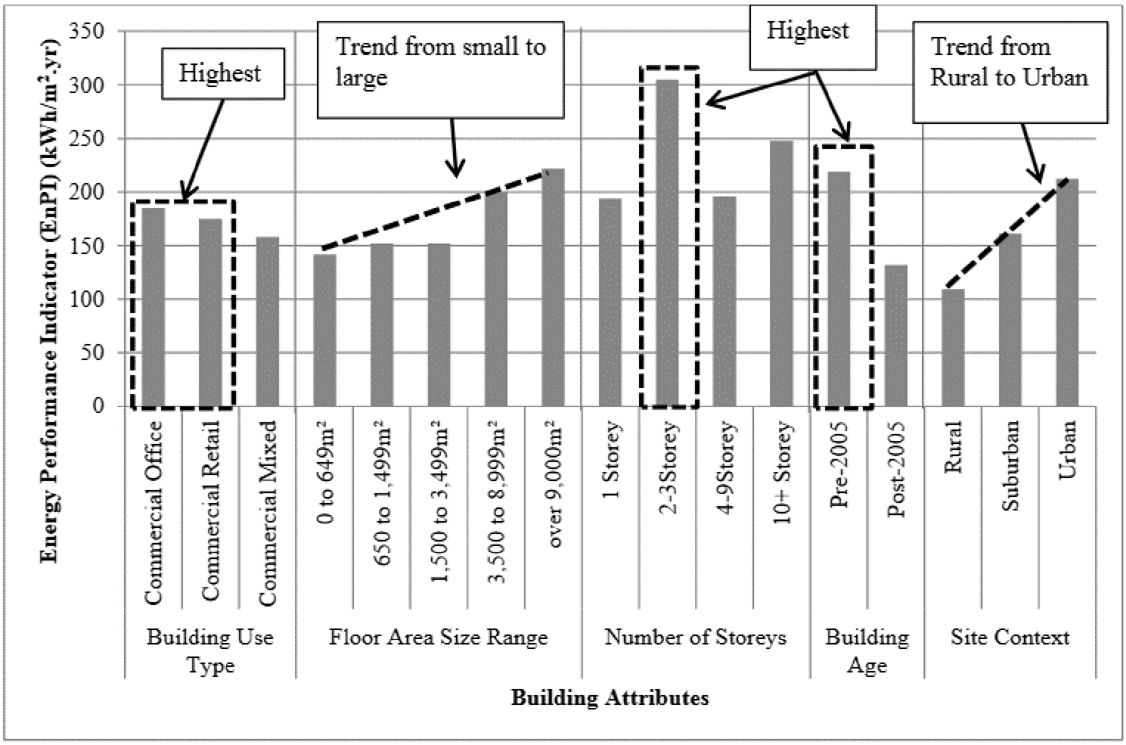


Figure 6-7 Average annual energy use for different commercial buildings characteristics (Cory, 2016)

Each individual building type includes on average 16 buildings that have been randomly selected. Accordingly, the case studies selected for this research are distributed as in the column labelled 'office' in Table 6-3. One office building located in an urban area will be selected from each size category (see 7.2.1).

Table 6-3 Distribution of 10 buildings in each size group adopted from Cory (2016)

Building Type		Office	Retail	Mixed	All
Size Group	1	3	5	2	10
	2	2	5	3	10
	3	3	4	3	10
	4	5	2	3	10
	5	4	1	3	8
Total		**17**	**17**	**14**	**48**

The second criterion for selecting buildings in cities is the population. Having more people increases the demand for new construction and this seems a reasonable criterian for choosing the site of the case studies since this study aims to assist architects in designing sustainable buildings based on lessons from nature.

As discussed, out of 17 office buildings, one building in an urban area from each size category will be selected. Where no case studies in a group appear to be urban, the second and third options would be suburban and rural sites respectively. For building height, 2-3 storey buildings will be the first option, followed by buildings with 4-9 or 1 storey.

6.9.1.1.2 Selection of climates

Cory (2016) has used Moffat (2001)'s method for New Zealand climate classification. This puts the New Zealand climate into seven groups each representing a geographical region (Auckland, Waikato/Hamilton, Napier, Manawatu, Wellington, Christchurch-Canterbury, and Dunedin). All Cory's 48 buildings are modelled in all of these climates.

In this research three New Zealand climates are selected based on population and climate type. Table 6-4 lists the largest cities in New Zealand with their populations (Butler, 2009). The climate data of the selected cities is available from NIWA (2016) and the table also compares the climate data of the selected cities. For temperature, sunshine and humidity, dark red, orange, and blue show the highest values.

Table 6-4 Climatic data of most populated cities adapted from Butler (2009); The National Institute of Water and Atmospheric Research (2016)

City	Population	Mean monthly air temperature		Mean monthly total sunshine		Mean relative humidity	
		JUL	FEB	JUL	FEB	JUL	FEB
Auckland	417,910	10.9	19.7	138.6	194.9	88.9	79.8
Wellington	381,900	8.9	17.2	118.9	210.9	86.3	83.3
Christchurch	363,926	6.6	17.2	127.1	195	92	86.2
Hamilton	152,641	8.9	18.8	126.4	192.9	90.8	84.3
Dunedin	114,347	6.6	15	110.6	158	80.2	77.6
Palmerston North	75,996	8.6	18.3	103.8	191	86.8	77.7
Nelson	59,200	7.2	17.9	159	231.4	90	78.5
Napier	56,787	9.4	19.4	134.7	202.6	79.6	73.9
New Plymouth	49,168	9.5	18	138	225	88.9	83.5
Invercargill	47,287	5.3	13.9	97.9	167.2	88.1	83.3
Gisborne	34,274	9.7	19.1	124.1	200.7	82.9	77.6
Timaru	28,007	5	15.5	131	170.2	85.4	83.5
Taupo	22,469	6.5	17.1	116.5	202.6	87.6	79.2

Auckland is the first chosen climate and Dunedin the second as it is the coolest climate in New Zealand.

New Zealand is divided into three climatic zones (Figure 6-8), based on average temperature, for the NZ Building Code compliance document H1/AS1 Energy efficiency. Minimum R-values are determined for buildings in these zones (Standards New Zealand, 2007).

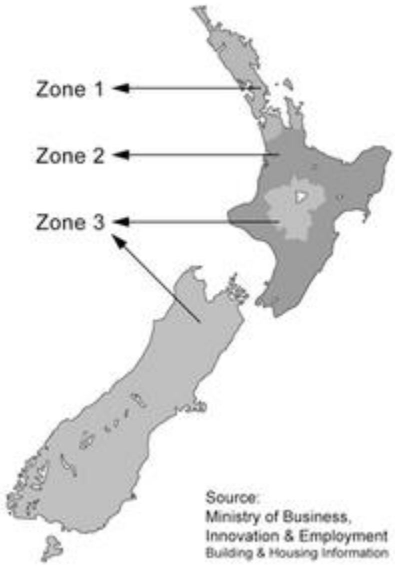


Figure 6-8 New Zealand climate zones (Standards New Zealand, 2007)

At a global scale, the latitude difference between Dunedin and Auckland is almost equal to that between Los Angeles and Seattle in USA, Tunis in North Africa, and Zurich in Europe. While the latter vary from hot to cold, in New Zealand the climate changes from warmish to coldish as the two extremes of a mild climate.

6.9.1.2 Selection of energy simulation program

For evaluating building energy use the geometric shape of the building, its geographical location, physical characteristics, equipment and operating schedules, and HVAC system need to be defined. This research will use *EnergyPlus* as trusted thermal simulation software (Crawley et al., 2001; Maile et al., 2012). For the second round of energy simulation in this research, translated biological principles as architectural parameters will affect and add to the input data.

A comprehensive comparative survey of twenty major building energy simulation programs showed EnergyPlus is the only software with the most features available and in common use compared to other rigorously validated software such as Ecotect, TRNSYS, and IES (Crawley et al., 2008). The fact the original energy models of the case studies used in this research were originally modelled in EnergyPlus version 7.2, made it reasonable to use the same software so as to limit the chances of losing data related to thermal characteristics of models. Other software cannot be trusted to import all the contents an EnergyPlus file holds as it is possible for some settings not to be transferred from one building performance simulation tool into another (Imani et al., 2019).

6.9.1.2.1 *EnergyPlus* for energy simulation of commercial buildings

Looking at the proposed steps of this study, there are two different stages of energy simulation. Energy simulation of the case studies in the first round (see 6.9.1) is aimed at discovering their thermal issues. The design parameters at this level are not required to be changed repeatedly in a parametric manner.

In contrast to the first round of energy simulation, data collection in the second round needs to be carried out for several times as there are expected to be alternative design options at this stage that need to be tested and analysed at the same time.

For the simulations, models from the BEES study (Saville-Smith et al., 2009) that have been calibrated by Cory and validated against BEES measured data will be used. Because EnergyPlus had been updated since Cory produced his calibrated energy models, before running the energy simulation for the first time to find the thermal challenges, it was necessary to run new simulations and compare these with the calibrated energy models of Cory (2016) (section 7.2.2).

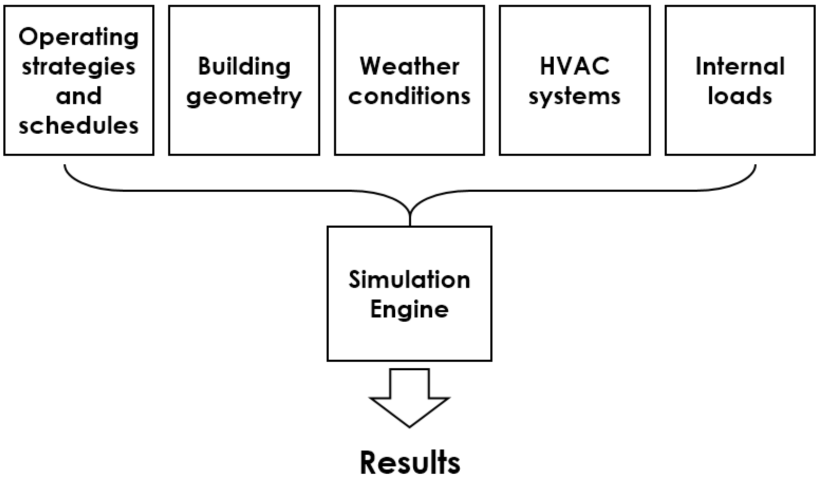


Figure 6-9 General input data for *EnergyPlus*

Whole building energy simulation accounts for one of the most important types of energy simulation analysis for commercial buildings (Oh & Haberl, 2016). Different parameters are used as inputs, such as weather data, internal loads, and patterns of occupant energy consumption. These are the requirements for assessing HVAC systems and analysing imposed cooling and heating loads.

The most accurate method of energy simulation analysis is the heat balance method (HBM), since it calculates heat gains and cooling loads simultaneously (Oh & Haberl, 2016). The HBM is an analysis method used for calculating dynamic cooling loads in *EnergyPlus* (Crawley et al., 2001). In the redesign stage of this research, certain characteristics of the case studies are expected to be modelled to reflect the design inspirations provided by the ThBA. *EnergyPlus* is selected as a suitable energy simulation software as it calculates the three main factors in the heat balance method of the outside surface, inside surface, and inside air heat balances (Strand & Pedersen, 2002).

6.9.1.2.2 Rhinoceros/Grasshopper

Designing high performance buildings is of high importance in the field of architecture. Having a good understanding of the environmental conditions of the building site enables designers to evaluate and consequently address thermal issues more effectively (Roudsari et al., 2013). This can be done even before finalising the formal configuration of the building. *Grasshopper* provides a scripting language for a 3D modelling environment in which the *Ladybug* (LB) and *Honeybee* (HB) are written. LB/HB provide a graphic interface to environmental simulation packages such as *EnergyPlus* enabling their user to analyse multiple building design options.

This powerful platform improves a user's understanding of the environmental analysis during the design process through 2D and 3D graphical visualisations. This research uses *grasshopper* interface to visualise the energy results.

6.9.1.2.2.1 Ladybug and Honeybee

There are other plugins developed for performing energy analysis such as *Heliotrope*, *Geco*, *Gerilla*, and *Diva-for-Rhino*. These can be downloaded from food4rhino.com (McNeel Europe, 2019). However, as noted by Roudsari et al. (2013) almost none support weather data analysis.

Ladybug (LB) in this sense makes a better contribution to the environmental design decision-making process, as it not only supports climate analysis, study of massing/orientation, daylight analysis, and energy modelling, but also enables users to produce multiple design options instantaneously.

Honeybee is another plugin developed for *Grasshopper*. *Honeybee* (HB) as a *Python* library is capable of creating, running, and visualising the building performance data generated by validated energy simulation software and daylight engines such as *Radiance*, *OpenStudio* and *EnergyPlus* (Roudsari et al., 2013).

It was necessary for this research to visualise the simulation results of the new *EnergyPlus* models in the first and second rounds of energy simulation. While HB and LB support the building performance simulation along with visualisations of the energy results, reading the new energy models of the selected case studies into the *Grasshopper* and then to HB, did not guarantee importing all the settings determined during the modelling process.

Given this, a new component was developed to solve the visualisation problem. Visualisation of the energy results was important as the main purpose behind running the energy simulation of the case studies was to identify the thermal challenges if any existed. Likewise, visualisation of the effect of a series of energy efficient design strategies that the ThBA was expected to suggest seemed to be important, so as to allow comparison between the thermal performance of the original and redesigned office buildings. However, LB and HB were used only once in this research and for the solar radiation analysis of only one case study (R0831 in Table 7-5).

6.9.1.3 Data mining biological databases

The planned outcome of the second step of the data collection (Step 2 in Figure 6-4) will be a draft ThBA. The ThBA will be developed to test the hypothesis that a systematic search process can be constructed. The ThBA is expected to be a roadmap that will bridge the two scientific domains of biology and architecture. As a road map it will collect the scattered thermal adaptation principles and the corresponding examples of animals and plants in one place and organise them in such a way that it will be possible to find appropriate biological solutions to thermal challenges in buildings.

What this step will attempt to achieve is a process that employs biological terminologies but that links these to architectural principles (Chapter 8, Figure 8-6, Figure 8-7, and Figure 8-10). This is what has not been considered by previous, similar frameworks. The consequent road map will be a chain of nodes that systematically narrows down the research to the specific key-concepts and principles.

The overarching aim of this research is to seek if it is possible to develop a roadmap (framework or systematic process) through which architects can independently find their way through the vast expanse of biological science with the aim of identifying relevant organisms. The first draft developed in this step is expected to be changed during the process of data analysis, so as to connect effectively the thermal issues of a building to the most relevant organisms, through the configuration of its categories and sub categories.

6.9.1.4 Consulting biologists

When the first draft of the ThBA has been developed, it will require a critique by experts in biology. There is thus the need to examine the advantages and disadvantages of the most relevant data collection techniques to choose the most appropriate research method for collecting their opinions of the biology side of the ThBA. In the third step of the data collection (Step 3 of Stage 3 in Figure 6-4), the first draft of the ThBA will be evaluated by biologists. A group of experts with diverse areas of expertise will be consulted to confirm, modify, or reject the ThBA. This will also be used as an appropriate research method for collecting qualitative data from experts to be used as input to this research (see 6.10.1). If the ThBA is rejected for not being promising in terms of exploring the relevant biological thermal principles, an attempt will be made to modify it. This will be done with the assistance of experts, as analysis of the data collected in reviewing the first ThBA should suggest appropriate pathways for amendments.

Nielsen (1994, p. 209) suggested interviews and questionnaires as useful techniques where a system needs to be critiqued by several respondents. He also identified that critiquing such a system requires only 5-7 experts to produce a comprehensive list of the issues.

Even though the most appropriate research method for enabling researchers to achieve group consensus is the *Delphi* method (Okoli & Pawlowski, 2004; Landeta, 2006; Hsu & Sandford, 2007), a survey seems to be unnecessary for this research as consensus can be achieved to some extent by a focus group (Morgan, 1996, p. 47) but in this case consensus emerges from a collective procedure rather than from individual opinions (Smithson, 2000).

Envisaging the ThBA framework as a tool to be used by architects, it is important to evaluate its usability when it comes to identifying and solving the probable issues it might have when it comes to the human-system interaction (Nielsen, 1994, Preface). Besides, for the ThBA, the collection of independent views and slow development of a consensus does not seem necessary, as the aim is to collect as complete list as possible of its faults and omissions rather than ranking or evaluating the order of its hierarchical categorisations. Allowing experts time to consider other possible classification scheme options would be assisted by the *Delphi* process, but here the main concern is to obtain a level of assurance about whether the ThBA is comprehensive and whether the thermal adaptation strategies are correctly generalised and systematically branched into sub-categories leading to examples of organisms.

In order for the appropriate method to be determined for this study, it is useful to compare the advantages and disadvantages of focus groups and the *Delphi* method. Thus, this research went through an extensive appraisal of the two approaches (see Appendix C). A summary of the results of this appraisal is given below.

6.9.1.4.1 Focus group: significance and relevance

Reviewing the advantages and disadvantages of the *Delphi* method and focus groups, it seemed the latter was more appropriate for this research.

The term "focus group" has been associated with market research and it has also been referred to as "group discussion" by social researchers who work with academic and applied research studies (Ritchie et al., 2013, p. 212).

Compared to a *Delphi* survey, a focus group is more about prioritisation and facilitates decision making while the latter is usually used to achieve consensus (Barbour & Kitzinger, 1998, p. 4). Another reason behind selecting a focus group was to enable participants to explore the developed framework as group discussions are known to generate more critical comments (Watts & Ebbutt, 1987), to yield insights, and to enable the creation of ideas (Bowling, 2014, p. 394). Due to the interdisciplinary characteristics of this research, there was a need to get the input of biological knowledge from professionals, and this would not have been obtained effectively without a series of open-ended questions. Individual interviews and responding to direct questions does not necessarily provide access to people's knowledge (Kitzinger, 1995). Instead, framing questions in a clear way eases group discussion (Freeman, 2006), and the focus group is also a suitable technique for brainstorming (Carnaghi, 1992), which might help the further development of the ThBA.

The ThBA evaluation not only requires a general and shared knowledge of biology but also needs to explore the different branches of biological science in more depth. Bringing together biologists from various fields in a group provides the chance to examine ideas and exchange knowledge. Given the ThBA will be a design tool, group discussions seems to be a good fit as focus groups are extensively used in situations where design has been recognised as the central issue (Ritchie et al., 2013, p. 212).

Focus groups enable the amalgamation of multiple viewpoints as a number of participants engage in a conversation around a topic at the same time. Focus group discussion provides the researcher with the opportunity to hear divergent opinions (Roller & Lavrakas, 2015, p. 104). Also, as stated by Carson et al. (2001, p. 116), the spontaneity of the opinions can lead to unexpected results and participants can contribute more actively in the topic analysis and reasoning (Kitzinger, 1995).

The rationale underlying the focus group technique is that complex settings and the reasoning behind them can be described by the group members who are guided by the focus group leader or moderator (Carey & Smith, 1994). The questions around the ThBA could possibly create complexity for the participants due to the large amount of embedded information within its structure, especially for participants coming from non-architecture backgrounds. This meant the probable ambiguity of the ThBA structure and its application in building design needs to be explained carefully so as to increase the interaction of group members and to guarantee that the opinions of participants would emerge from a thorough understanding of the framework and more specifically the parts rooted in biology. To this end, a focus group discussion is identified as more useful for data collection.

By its nature a focus group includes positive and negative aspects. While the interaction of participants leverages the quality of gathered data, the major pitfall of the focus group method has been recognised as censoring or conforming. This means some members may suppress their opinions if they are not in line with the collective view of the discussion panel (Asch & Guetzkow, 1951). Morgan and Krueger (1993) do not support having heterogeneity regarding the status of participants. However some researchers believe that even in the absence of a heterogeneous sample population, participants will ultimately express their opinions meaning that homogeneity does not negatively affect the discussion (Freeman, 2006). From another perspective, a focus group can also encourage participation of the relatively inactive members with little knowledge (Kitzinger, 1994).

To reduce the chance of losing some valuable opinions, participants will be also asked to write down their opinions. This will be done to manage any possible power dynamic within the focus group.

6.10 Data analysis

6.10.1 Qualitative (focus group)

This research uses *NVivo 12 plus* (Edhlund & McDougall, 2019, p. 11) for focus group data analysis. *NVivo* is a qualitative data analysis software that has been recognised as being effective in managing data and ideas, together with data querying, visualisation, and analysis (Bazeley & Jackson, 2013, p. 3). While the basic versions of *CAQDAS* were merely helpful in coding the data, the recent versions (*NVivo 12 Plus*) have been developed to facilitate data management and exploration, specifically where the research is using multiple datasets from several surveys and multimedia sources. Although this research will use only one dataset, this being the transcript from the focus group, *NVivo* will be employed to accelerate the coding process. It may also be used to count the number of times participants each contributed to a theme-related discussion. These will provide a reliable and general picture of the data (Morison & Moir, 1998).

The quick and accurate search of the transcript enabled by *NVivo* will add rigor to the analysis process. The plan is to code the entire text of the session first, and then to group similar codes in a series of nodes. Sections 9.4.2 and 9.4.2.1 detail the process of focus group data analysis introducing the data type used for the analysis, the coding process and development of the themes and sub-themes. However, the main themes were partly predetermined as they were expected to be linked to the pre-prepared list of focus group questions.

6.10.2 Quantitative (simulation)

Dynamic thermal simulation programs such as *EnergyPlus* are used by building researchers to assist them in achieving goals such as reducing environmental impact, improving internal thermal comfort, or enhancing the energy performance of a building (Garber, 2009). This study only focuses on the second and the third purposes. However, this research will use energy simulation to test the use of the ThBA through a series of case studies. Figure 6-10 shows where the energy simulation fits into the research.

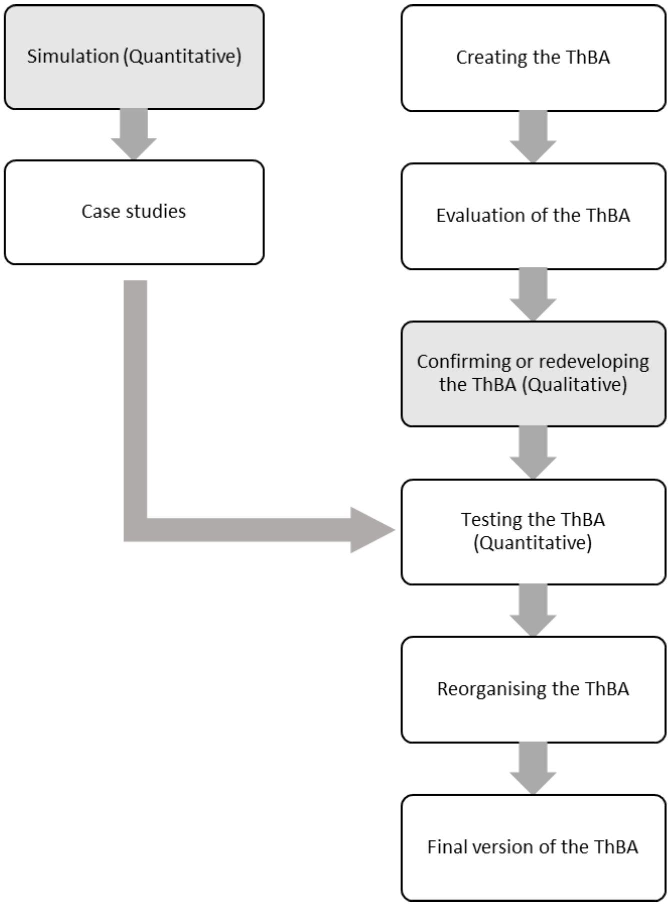


Figure 6-10 The role of energy simulation in this research

6.11 Chapter summary

This chapter presents the research aims, objectives, and scope in detail. The methodological approach taken in this study is a mixed methods approach as the data will be collected and analysed through qualitative and quantitative methods. This research uses a case study approach for the research design. The two quantitative and qualitative data collection and analysis methods are conducted in parallel and separately, however, their results will be merged when answering the research question (Stage 4 in Figure 6-4). In each approach, the same method of data collection will be used for data analysis, meaning that quantitative and qualitative data analysis will be related to the collection of quantitative and qualitative data respectively.

The case study approach will allow identification of thermal challenges in selected New Zealand office buildings. The quantitative data collection and analysis is based on a number of energy simulations to collect and analyse the energy consumption data of five case studies. Two different qualitative data collection techniques are explained and by comparing these and reviewing the advantages and disadvantages of each, the focus group technique is selected for validating the ThBA framework, and qualitative data analysis software will be used for analysing the focus group results.

The next two chapters present the parallel qualitative and quantitative methods, with Chapter 7 discussing the selection of case studies and the energy data collection and analysis.

7 Investigating the Thermal Challenges of the case study Office Buildings

7.1 Introduction

This chapter introduces the thermal challenges identified for two case study buildings in Auckland and Dunedin (Figure 7-1). As discussed in section 6.10.2, running energy simulations for the chosen case studies is a means of testing the thermo-bio-architectural framework (ThBA). Since the intention was the ThBA would be a roadmap to connect thermal challenges in a building to relevant biological thermoregulatory solutions in a systematic way, it was first important to investigate a process through which the thermal behaviour of a building could be understood. In this context a thermal challenge is defined as a high energy use, which might be the need for considerable heating energy or cooling energy. The process required several runs of the energy simulations in order to reveal the appropriate approach to narrowing down the results so as to identify the main thermal issues or challenges in a building.

Figure 7-1 explains the process of the first round of energy simulation through which the main thermal issues are explored. In order to identify two challenging buildings, the energy simulation is run for all case studies in Auckland (the dashed lines in Figure 7-1). Analysing the thermal performance of the office buildings revealed two challenging buildings for which another iteration of energy simulation and analysis was carried out for both Auckland and Dunedin to identify the thermal challenges at the zone scale.

At the end of the chapter, the thermal issues for each case study and their heat balance characteristics were determined. The intention is then to feed these into Chapter 10 where the ThBA framework will be used for connecting thermal challenges to biological solutions.

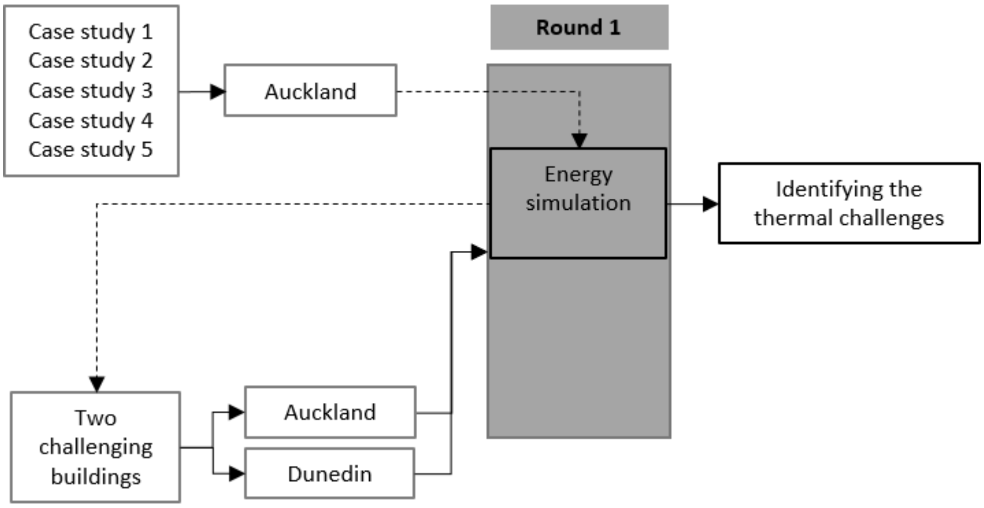


Figure 7-1 Methodology snapshot: energy simulation round 1, identifying thermal challenges

In this chapter, heating energy and cooling energy are defined as:

Heating/cooling energy "*…represents the sensible heating/cooling energy in kWh that is actually supplied by the system to that zone*" (US Department of Energy, 2015). It is the amount of energy that needs to be delivered to the zones by the HVAC systems in the building to maintain the indoor temperature at the set comfort level.

At the thermal zone scale (for example Figure 7-7), the violet range represents the energy used with light violet showing the lowest and dark violet the highest energy consumption. This means, for both cooling and heating energy, the darker violet represents higher energy use, while white represents the lowest value which is not necessarily zero energy use. Cooling and heating energy are shown in blue and red respectively.

This research uses the British style for naming building floors. The floor of a building which sits on the ground is called ground floor. The floor on top of this is the first floor, and the floor above that is the second floor. The same style is used for naming the remaining floors, except for the floor under the roof, which here is called the top floor (Figure 7-37 and Figure 7-48).

7.2 Modelling and simulation approach

As discussed in section 6.9.1.1, a series of criteria were used for selecting the case studies. For each case study, an energy simulation was run once in the first round of energy simulations and is planned to be run multiple times for the second round of these. For the first round, energy simulation was done only once as the output results revealed the thermal issues while for the second round in which the energy consumption of the redesigned case studies needs to be evaluated, there will be multiple simulation runs. These simulations are expected to be run with different input data based on the selected parameters for the redesign (see 10.4.2.1, 10.5, and 10.6). The purpose of energy simulations for the second round is to identify the most effective redesign parameter(s) in improving the energy performance of the selected case study office buildings.

Before running the energy simulation in the first round, it was necessary to resimulate the models to ensure they matched with Cory's calibrated energy models (see 7.2.2). Subsequently, as explained earlier in this chapter, energy simulations in the first and the second rounds were run to identify the thermal issues so as to use the ThBA for suggesting innovative energy efficient solutions.

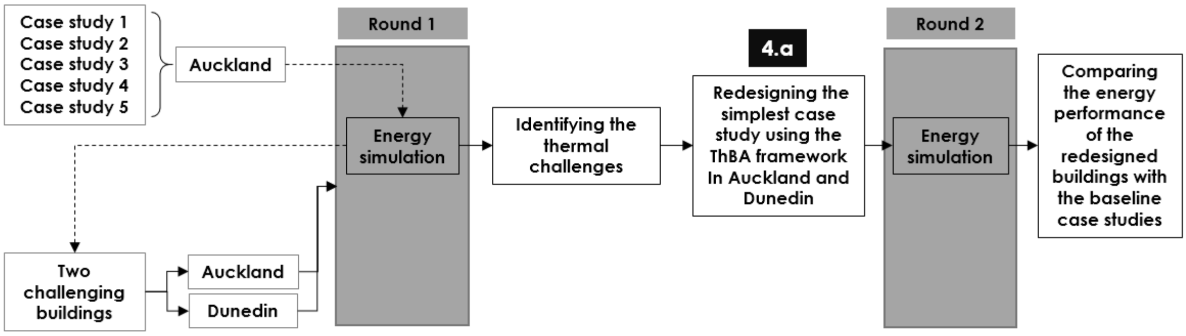


Figure 7-2 Diagram of the iterative process of energy simulation (identical to Figure 6-6)

7.2.1 Selected models

The energy models used for this thesis came from the standardised calibration process undertaken by Cory (2016). By manipulating the input features based on as-built information, Cory's calibrated models (see 6.9.1.1.1) were made to match the thermal performance of the real buildings. Table 7-3 shows the comparison between real building Energy Use Intensity (EUI) (kWh/m^2) with that of the final calibrated model created by Cory (2016). Other attributes such as total building floor area, total building height, number of the storeys, and building age are also reported in this table. Out of Cory's categorisation of commercial buildings (office, retail, and mixed) only office buildings were used in this research. All office buildings are labelled with a number and can be found in the Building ID column (Table 7-2). The next column shows the difference between the calibrated result and that of the real building. The main criterion for selecting office buildings for this thesis was to pick one building from each strata related to the size of the building (1-5) (Table 7-1) based on the closest match in Cory's calibration results.

Looking at Strata 1 in Table 7-2, the closest match is R0031, but it was not chosen as it was a rare office building without windows. Instead R0017 was selected. Strata 2 offers almost similar results for all three cases with smaller differences with the real data for R0087 and R0831.

Table 7-1 Size of buildings by sample strata (Saville-Smith & Fraser, 2012). (The strata represent the floor area quintiles, with approximately the same floor area in each)

Building Size (m^2)	Sample Strata				
	Strata 1	Strata 2	Strata 3	Strata 4	Strata 5
1-649	**53**	5	2	1	0
650-1499	6	**56**	11	2	0
1500-3499	0	8	**88**	13	0
3500-8999	1	2	16	**144**	25
9000 or more	0	0	1	17	**204**
Not estimated	6	15	23	50	42

In Table 7-1 (Saville-Smith & Fraser, 2012), there are few cases, including R0087, with a floor area less than 649m^2 in strata 2. The majority of office buildings are 650-1,499m^2 in floor area. Therefore R0831 was chosen from all three valid cases in strata 2 (Table 7-2). The selection criterion for choosing R0738 over R0173 in strata 4 was the level of accuracy in the annual energy use report, as a -1 % difference in Cory's calibration for R0713 is achieved when January and March information data are ignored. Even though this case seems to show the closest match it may not be reliable due to the lack of precision in the 12 monthly report. For that reason, R0738 was preferred as the best representative of office buildings in this category.

Table 7-2 Building selection from Cory's existing cases in each size category

ID	Difference between calibrated result and actual	Strata	Year of construction	Number of storeys	Total building floor area (m^2)	Building height (m)
R0017	15%	1	1962	1	599	4.75
R0031	11%	1	1945	1	188	3.125
R0037	31%	1	1940	1	209	3.79
R0020	-3%	2	1977	2	1356	9
R0087	-2%	2	1965	1	638	8.5
R0831	2%	2	1999	2	742.49	6.5
R0056	-4%	3	1990	4	3555	10
R0471	24%	3	1960	4	1311	25
R0813	0%	3	2006	2	2674.5	11.5
R0054	-3%	4	1980	10	5861	25
R0811	-3%	4	1990	8	5840	29
R0173	-1%	4	2000	8	6018.45	22
R0738	2%	4	1989	9	9439	22
R0198	39%	5	1960	20	33628	62.1
R1017	342%	5	1984	18	19843.2	48
R1586	4%	5	2000	4	6029.30	15.5
R1663	-17%	5	1981	10	12891	35

7.2.2 Resimulation: examining the reliability of the case studies

Cory (2016) produced a calibrated set of *EnergyPlus* models. By definition *"Calibrated simulation is the process of using a building simulation program for an existing building and tuning or calibrating the various inputs to the program so that predictions match closely with observed energy use"* (Reddy et al., 2007).

Research shows that building modellers who run the energy simulations have a great influence on the energy results (Van Dronkelaar et al., 2016; Imam et al., 2017). The Cory's calibrated models were generated using *EnergyPlus* Version 7.2 and so it was important to ensure they could be trusted in a new version. This necessitated the inclusion of a stage for validating his calibrated models of the five office buildings, which would hopefully ensure that the generated energy use results were close to reality. Deviation between energy performance results and building energy use is related to four components: accuracy of the model, accuracy of the inputs, weather data, and building operation (L. P. Wang et al., 2012). The process of using Cory's calibrated energy models and the new simulation in this thesis is shown in Figure 7-3.

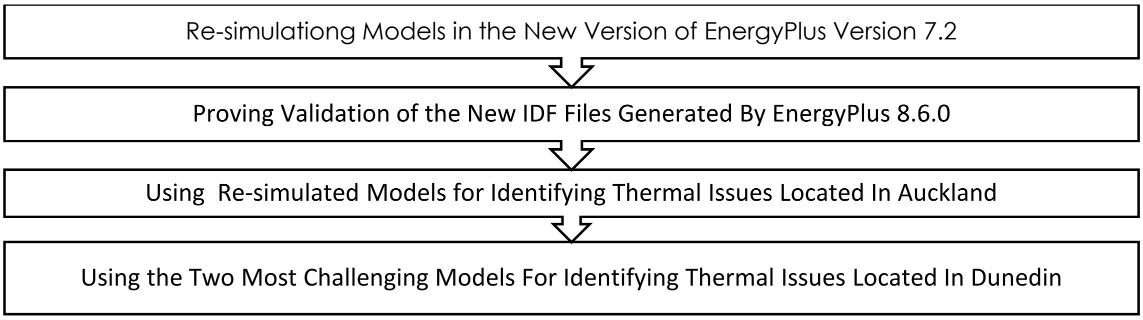


Figure 7-3 Process of validating the models and identifying thermal issues

To confirm the validity of the energy models created between 2012 and 2016, energy simulations were run for the chosen case studies and the monthly EUI calculated for comparison with the real data. Table 7-3 illustrates the EUI result reported for R0017 and is presented as a sample to demonstrate the validation process used for each office building. The monthly EUI column is divided into three sub-sections showing results for the real building, Cory's calibrated energy model (2016), and simulated models in this thesis, in that order. The left-hand column shows the difference as a percentage.

Table 7-3 R0017, monthly EUI report

Month	Monthly EUI (kWh/m2)				Dissimilarity	
	Real	CEM	Re-simulation		1 - CEM/Real	1 – Re-simulation/Real
JAN	1,944.00	2,175.58	2,296.69		-11.9%	-18.1%
FEB	2,194.00	2,009.10	2,211.20		8.4%	-0.8%
MAR	1,896.00	2,064.43	2,117.31		-8.9%	-11.7%
APR	3,152.00	2,906.17	2,409.33		7.8%	23.6%
MAY	3,454.00	3,540.90	3,076.02		-2.5%	10.9%
JUN	3,643.00	3,660.70	2,984.72		-0.5%	18.1%
JUL	3,169.00	3,292.97	2,983.95		-3.9%	5.8%
AUG	2,474.00	2,509.69	2,894.03		-1.4%	-17.0%
SEP	2,359.00	2,477.48	2,331.72		-5.0%	1.2%
OCT	1,970.00	1,977.43	2,079.18		-0.4%	-5.5%
NOV	2,076.00	2,095.75	2,391.34		-1.0%	-15.2%
DEC	2,244.00	2,122.22	1,980.44		5.4%	11.7%
Total EUI	**30,575.00**	**30,832.42**	**29,755.93**	**Total Difference to Real**	**-0.8%**	**2.7%**

Two calibration methods can be used to determine whether the simulated performance data are matched to the monitored data of a building (ASHRAE, 2002). These are (MBE) and CV(RMSE) standing for *Mean Bias Error* and *Coefficient of Variation of the Root Mean Squared Error* respectively. CV(RMSE) indicates how accurate the simulation results are compared to the measured data with negative values representing over calculation and positive values under calculation (Schiller et al., 1996).

$$MBE = \frac{\sum^{n}(y_i - \hat{y}_i)}{(n-p) \times \bar{y}} \times 100$$

$$CVRMSE = 100 \times \left[\sum \frac{(y_i - \hat{y}_i)^2}{n-p}\right]^{1/2} / \bar{y}$$

Equation 1- Calculation of BME

Equation 2- Calculation of CV(RMSE)

These two methods (Equation 1 and Equation 2) were used here to investigate if a simulation match of ±5% using the MBE formula and ±15% using the CV(RMSE) equation could be attained. In the CV(RMSE) and MBE equations, n indicates the number of data points or periods in the baseline period (number of samples); i stands for the number of data points starting from 1 and ending with n; and p stands for the number of parameters in the baseline model developed by a mathematical analysis of the baseline model and mostly used in cases where a large number of data points exist. This parameter is considered 0 in this equation due to having only 12 data points (12 months). $\bar{y}$ is the mean of the sample of n observations and in this context is the mean value of the actual energy use. y_i represents the actual energy use value while $\hat{y}_i$ stands for the simulated energy use value.

The other four chosen case studies (R0813, R0831, R1586, and R0738) underwent the same calculation process as R0017. Table 7-4 shows the MBE and CV(RMSE) report for the five office buildings.

Table 7-4 BME and CV(RMSE) report of all case studies

	BME	CV(RMSE)	Difference: 1 - Simulation/Calibration
ASHRAE	±5%	15%	
R1586	0.96%	3.33%	2.7%
R0017	-2.68%	14.74%	3.5%
R0738	2.71%	7.38%	-0.7%
R0813	-2.25%	8.28%	2.0%
R0831	1.11%	6.87%	1.0%

As suggested in ASHRAE Guideline 14-2002 (2002) any standard deviation of ±5% for MBE and ±15% for CV(RMSE) recognises the case study as valid . Here, all energy models were acceptable and this led to the first step in the energy simulation analysis.

7.3 Analysing data: first round of energy simulation

Looking at the literature, the following data have been used to report and facilitate the comparison of energy analysis results:

1) Planimetric (showing the horizontal position of features) representation of the building (Balocco & Colaianni, 2018)
2) physical characteristics of the buildings such as total floor area, number of storeys, location, and internal loads (Pollock et al., 2009)
3) description of the base cases and also modified energy models by providing details on
a) energy submetering of major end uses such as: cooling and heating loads, lighting, and electric equipment (K. Zhang & Zhu, 2013; Jung et al., 2018)
b) detailed HVAC system operating conditions if it comes to HVAC analysis, such as: chiller power consumption, chilled water flow rate, inlet and outlet water temperature, air handling unit (AHU) supply airflow rate, fan power, and supply air temperature (Pan et al., 2011; Xia et al., 2014)
4) indoor and outdoor conditions such as space air temperature and humidity, outdoor conditions including outdoor air temperature and humidity, wind speed and direction and solar radiation (Xia et al., 2014)

5) characteristics of the building envelope including: thermal conductivity (W/mK), specific heat capacity (kJ/kgK), mass density (kg/m^3), U-values of exterior walls and solar transmission (Jung et al., 2018)
6) ventilation air flow rates and efficiency of heat recovery for individual zones (Kalema et al., 2008)

From these data set for the first round of energy simulation, number 1 was picked to represent the case studies, numbers 2 and 3a to facilitate comparison. The rest of data (3b, 4, 5, and 6) are expected to be used for the second round of energy simulations where the original and redesigned models need to be compared for their energy efficiency. Visual thumbnails were provided so the differences in output data can be easily understood (Kalema et al., 2008).

Generally, the simulation outputs selected for this round included: 1) annual and/or monthly building energy consumption (EC), whole building EC broken down into the heating, cooling, lighting, and electrical demands of either each storey or each zone as appropriate, and 3) either monthly or hourly load profiles for each individual input parameter. However not all of these three outputs have been provided for each case study.

7.3.1 Case studies: energy analysis

All case studies were simulated in the Auckland climate. The algorithms used for outside surface heat transfer convection is "*DOE-2*", for the heat balance is "Conduction Transfer", and for the outside surface heat transfer convection is *TARP*.

7.3.2 Pilot energy analysis report for R0813

The first energy simulation was run for R0813 located in Auckland. R0813 is a two storey office building with a floor area of 2674.4 m^2. The pie chart shows the breakdown of components in the whole building end use energy consumption (Figure 7-4). For R0813, because the water heating system uses gas this energy use falls in the "fans and other" section in Figure 7-4.

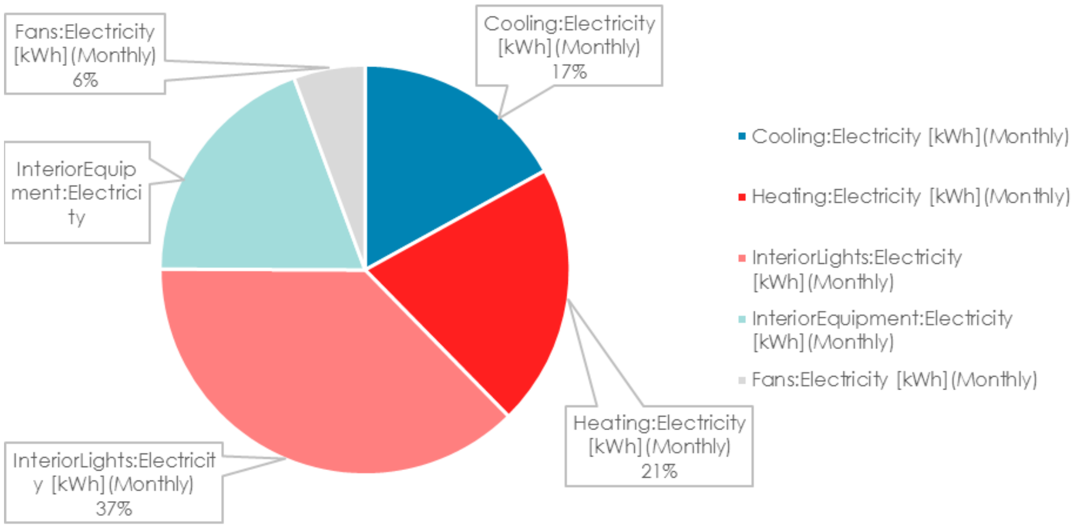


Figure 7-4 End-use energy consumption: electricity and gas (R0813)

Based on the results, the electricity percentages required for running HVAC systems (cooling, heating) was approximately the same at 17% and 21% respectively. Lighting exceeded both at approximately 37% of total energy consumption. Although providing more natural light should decrease the lighting share this might affect indoor temperature. This is because with bigger openings, interior temperatures could decrease in cold months or increase in hot months, and in turn cooling and heating demands would rise. Since cooling and heating percentages were almost equal, optimising either could diminish the total energy use, providing optimising one did not significantly affect the other detrimentally.

The following sections introduce the heating and cooling energy analysis of the whole building and each floor of R0813. The same detailed energy consumption analysis was performed for all case studies but is only presented in detail for the first case study (R0813) to avoid repetition.

These detailed levels of energy analysis at the thermal zone scale have been carried out to investigate any major thermal challenges in thermal zones as well as to facilitate comparison of heating and cooling trends related to annual weather averages at the case study locations.

7.3.3 Heating energy analysis

7.3.3.1 Whole building

For both storeys (ground and top floor), August, July, June, May and September showed considerably higher energy usages, with August having the highest (Figure 7-5) and July close behind. Values gradually rose from May to August but dropped steadily by almost 40% each month moving from August to November. Overall, a significantly larger amount of heating energy was consumed in August, June, and July. The lowest heating energy use was reported for February, this being nearly the same as heating energy use in December and January.

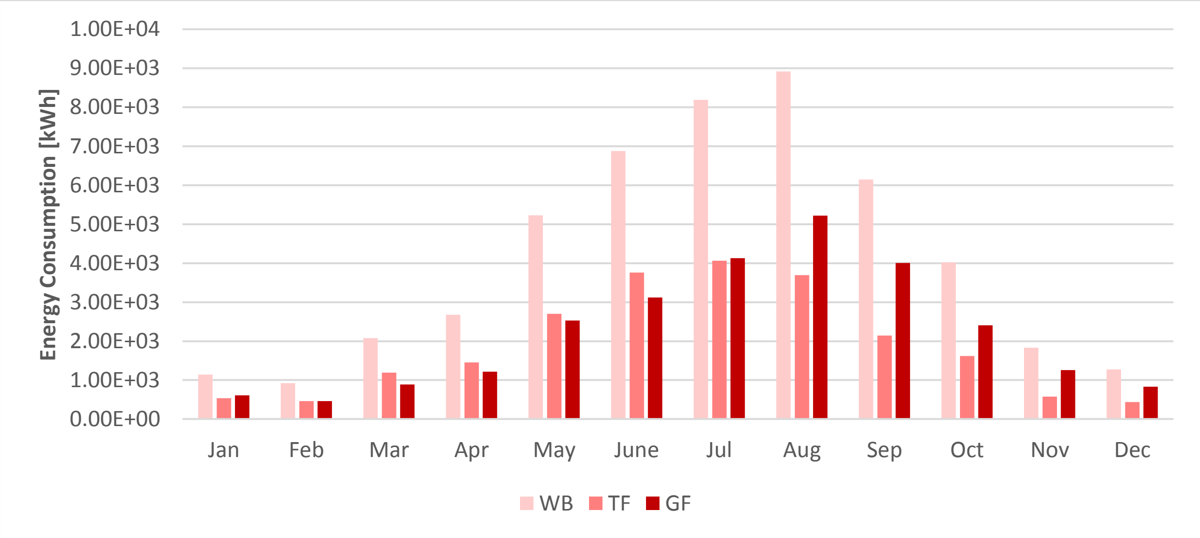


Figure 7-5 Whole Building (WB), Ground Floor (GF), and Top Floor (TF) heating energy consumption (R0813)

Observing annual temperature averages recorded for Auckland (Figure 7-6), July is the coldest month whereas December, January and February have the most daily sunshine hours with the average temperature around 20 °C. When annual temperature averages were compared to heating energy use, the reason for the sharp decrease in heating energy consumption from August to April was understood as this drop was more gradual moving from August to December. These gradual and sharp drops in heating energy use fully correspond to the average temperatures if August is not taken into account.

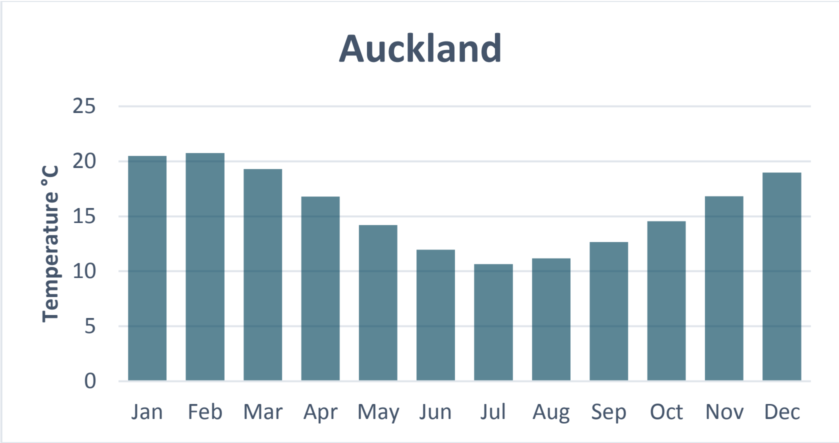


Figure 7-6 Auckland annual mean temperature based on data adapted from Chappell (2013)

7.3.3.2 Ground Floor

Heating energy use for the ground floor and top floor were almost the same (Figure 7-5) dropping by approximately 20% each month moving from August to May and falling by 40% from August to November. Among all zones on the ground floor, those labelled South West and North West consumed the same amount of cooling energy, and this was considerably more than for the other zones (Figure 7-7).

The violet colour coding shows the heating and cooling energy use with the highest value shown in dark violet and the lowest in white. The reports for heating and cooling energy use at the thermal zone scale are comprised of two parts both representing the same energy results but in two different ways:

1) A scattered plot on top; and
2) A table with individual cells showing the planimetric representation of the case study in different months.

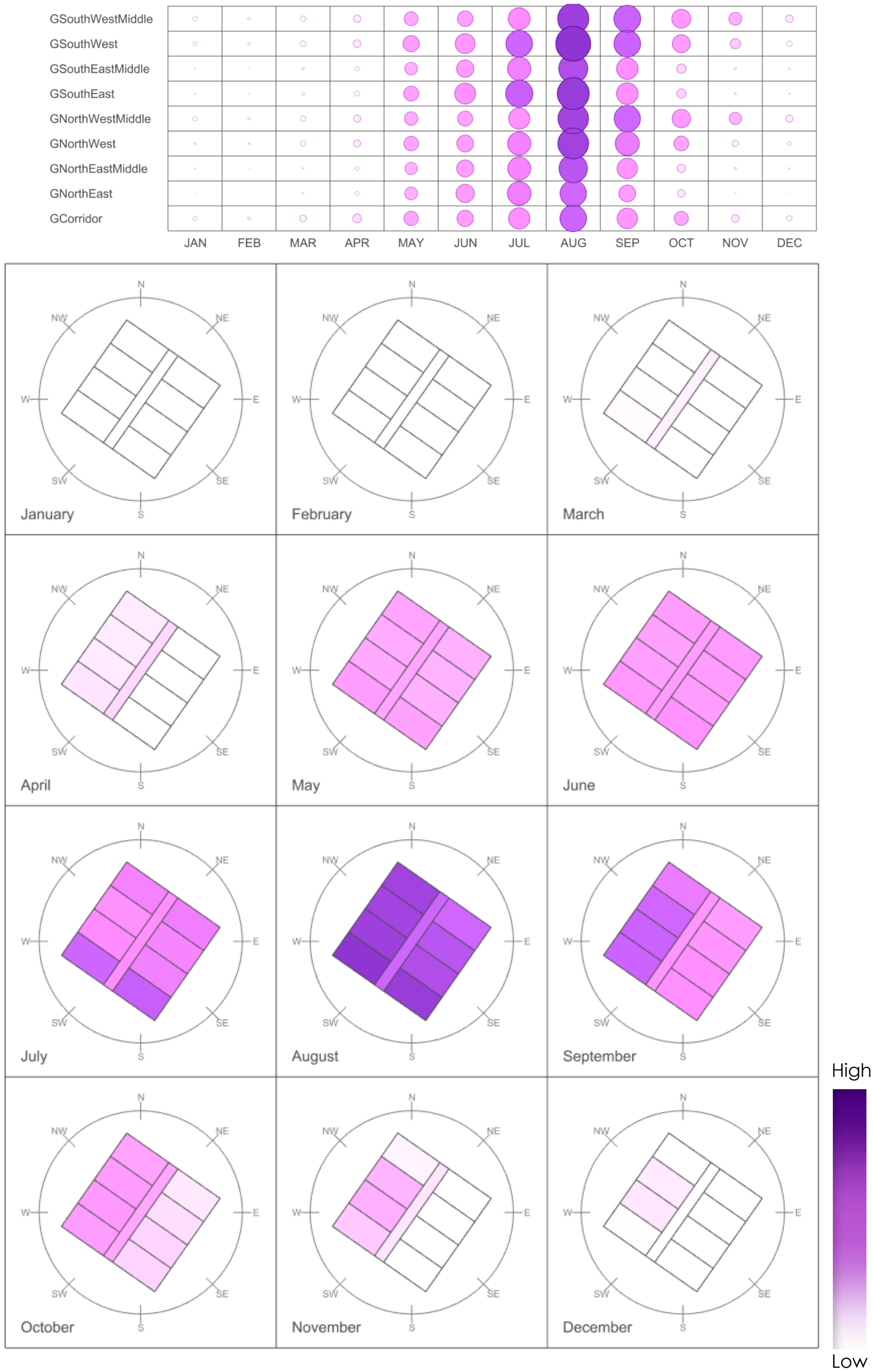


Figure 7-7 Zone air system sensible heating energy (kWh) Monthly Ground floor

For each case study at the thermal zone scale, the maximum and minimum cooling and heating energies are different for the individual floors. This means the colour codes only allow for comparison of the energy consumption of thermal zones in individual floors and not between them. In other words, zones with the same colour in different floors do not have necessarily a similar heating/cooling energy use. The graphs and bar charts, however, enable comparison of the energy results between floors.

For example, Figure 7-12 shows that the difference between cooling energy use of the zones on the top floor is small for October to April, but quite large for the zones on the ground floor (Figure 7-13). However, the cooling energy use for the ground floor is considerably higher than that of the top floor. For the former, the higher energy use is indicated by larger and darker circles. A similar colour code also applies to the latter.

Zones facing South West required more energy to reach comfort level than those facing North West. One probable reason might be the passage of the sun across the site. As shown by the sun path diagrams for Auckland (Figure 7-8), the sun position throughout the year (rising in the east, moving through north and setting in the west) affects the temperature of zones facing those directions.

This content is unavailable. Please consult the print version for access.

Figure 7-8 Left) Auckland sun path diagrams(Tukiainen, 2019); Right) Representative sun path diagram for a building in New Zealand (Propertytoolbox 2015)

South West zones receive little sunshine during the day which is why they consume more heating energy in winter to reach the comfort point (Figure 7-9). The difference between heating demand in the East and West zones points to the unequal solar gain morning and evening (Figure 7-9).

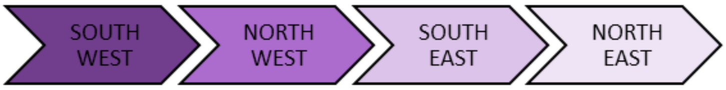


Figure 7-9 Zone heating demands (R0813)

Overall, the maximum heating demand occurred in the South West and North West zones in August. There was a slight growth in energy consumption in all zones moving from May to August followed by a downward heating energy trend in September and October.

7.3.3.3 Top floor

For the top floor, the greatest heating energy use occurred in July with 4.06E+03 (kWh), slightly decreasing to 3.73E+03 (kWh) in August and June. Heating energy consumption in July, August, and June was close to double that of September and May and over ten times more than January, February, November, and December.

South East and South West zones consumed more energy than the others. According to Figure 7-10, energy use for the corridor is only slightly less than that of the South East and South West zones. There was a sharp decrease in heating energy use from June to May and August to September. January, February, March, April, November, and December were months with a very small share in the total heating energy consumption.

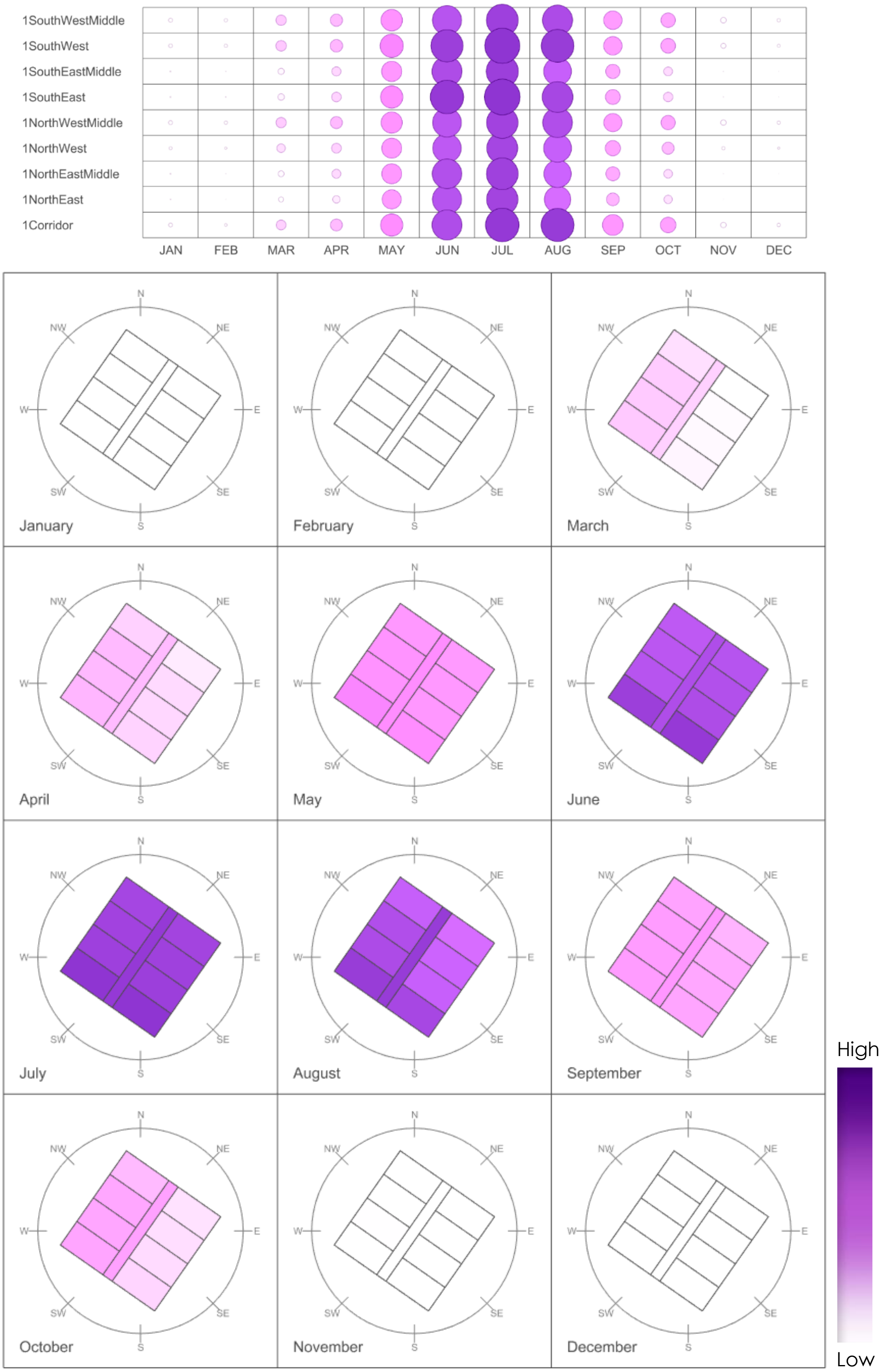


Figure 7-10 Zone air system sensible heating energy (kWh) Monthly Top floor

7.3.4 Cooling energy analysis

7.3.4.1 Whole building

Taking into the account all zones in all months, the cooling energy consumption reached the highest level in March (Figure 7-11). The months most similar to March in terms of energy use were February, January, November, and December. Cooling energy for all others was very small, with lowest values for June and July. There was big difference between the ground and top floor, with the latter using substantially more energy.

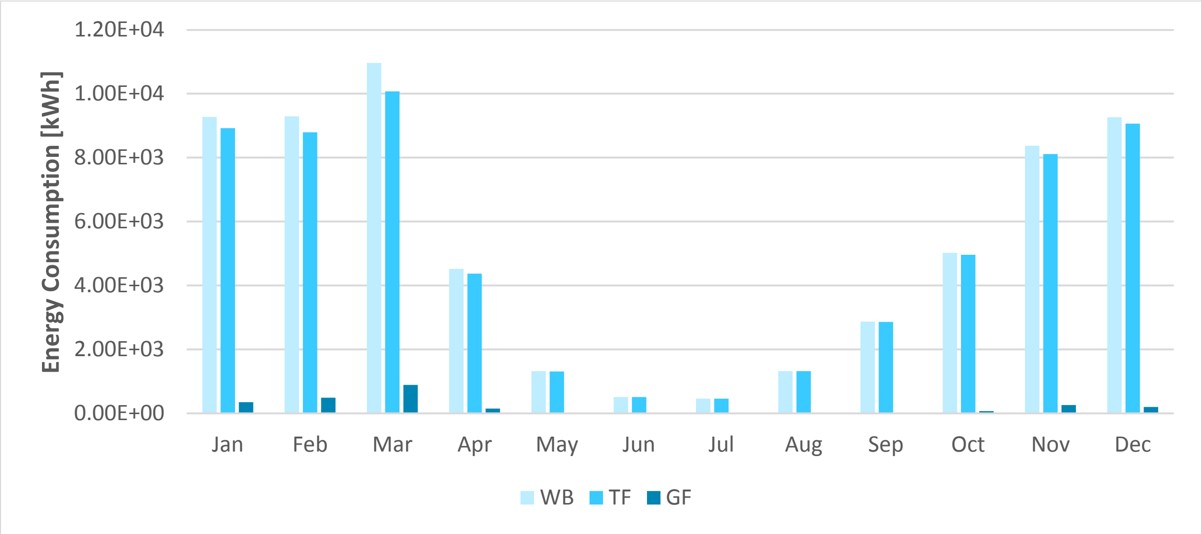


Figure 7-11 Whole Building (WB), Ground Floor (GF), and Top Floor (TF) Cooling Energy Consumption (R0813)

7.3.4.2 Ground floor

Cooling energy for the ground floor followed almost the same pattern as for the whole building. In the whole building there was a small decline in March compared to February, January, November and December, while for the ground floor values dropped suddenly from 1.10E+04 to around 9.29E+03 in February, January, November and December.

Among all ground floor zones the North East consumed more cooling energy in March, February, January, and November (Figure 7-12). Figures for other zones were considerably lower than those of the North East. Figure 7-13 shows the cooling energy use for the top floor.

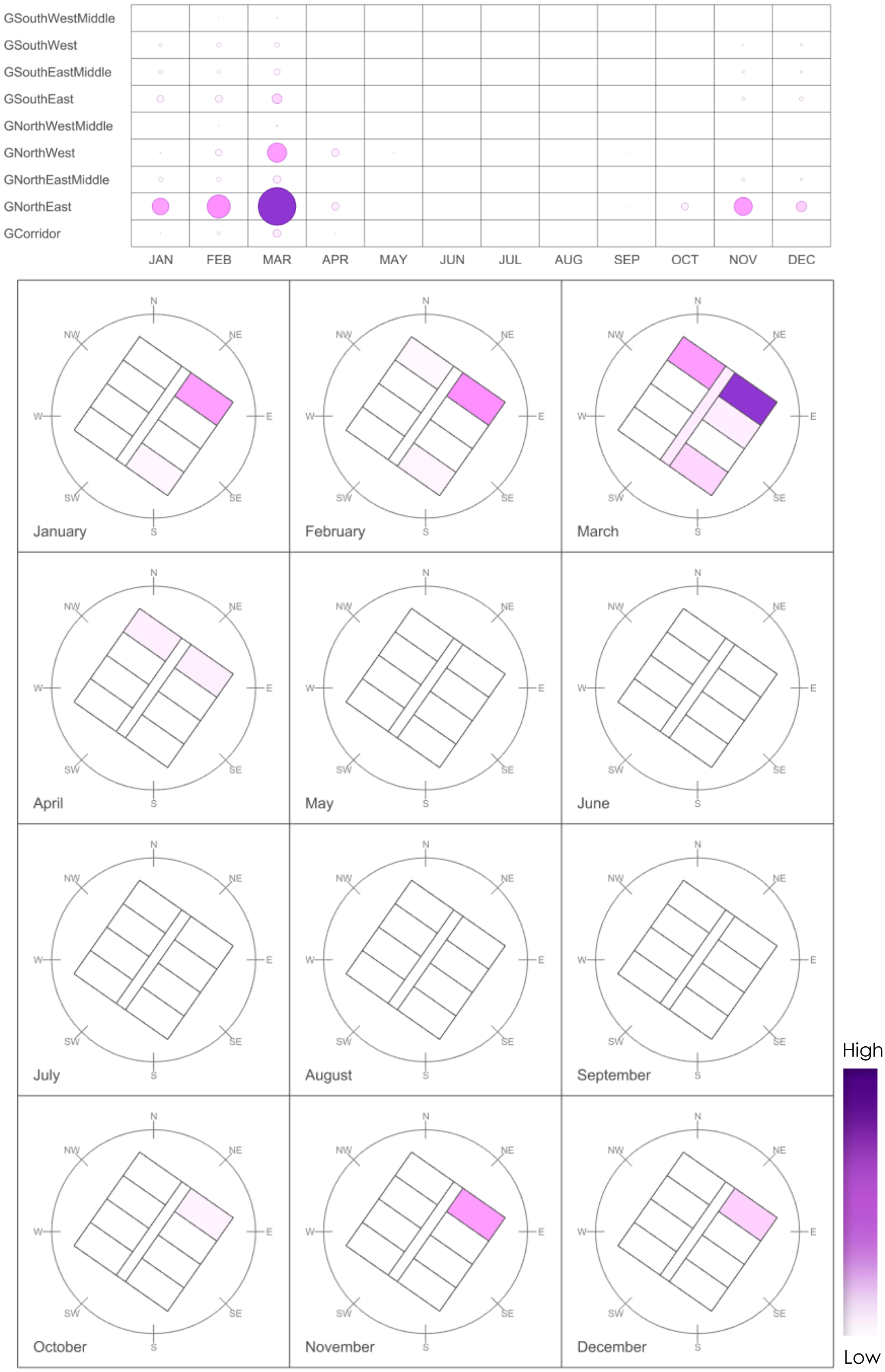


Figure 7-12 Zone air system sensible cooling energy (kWh) Monthly Ground floor

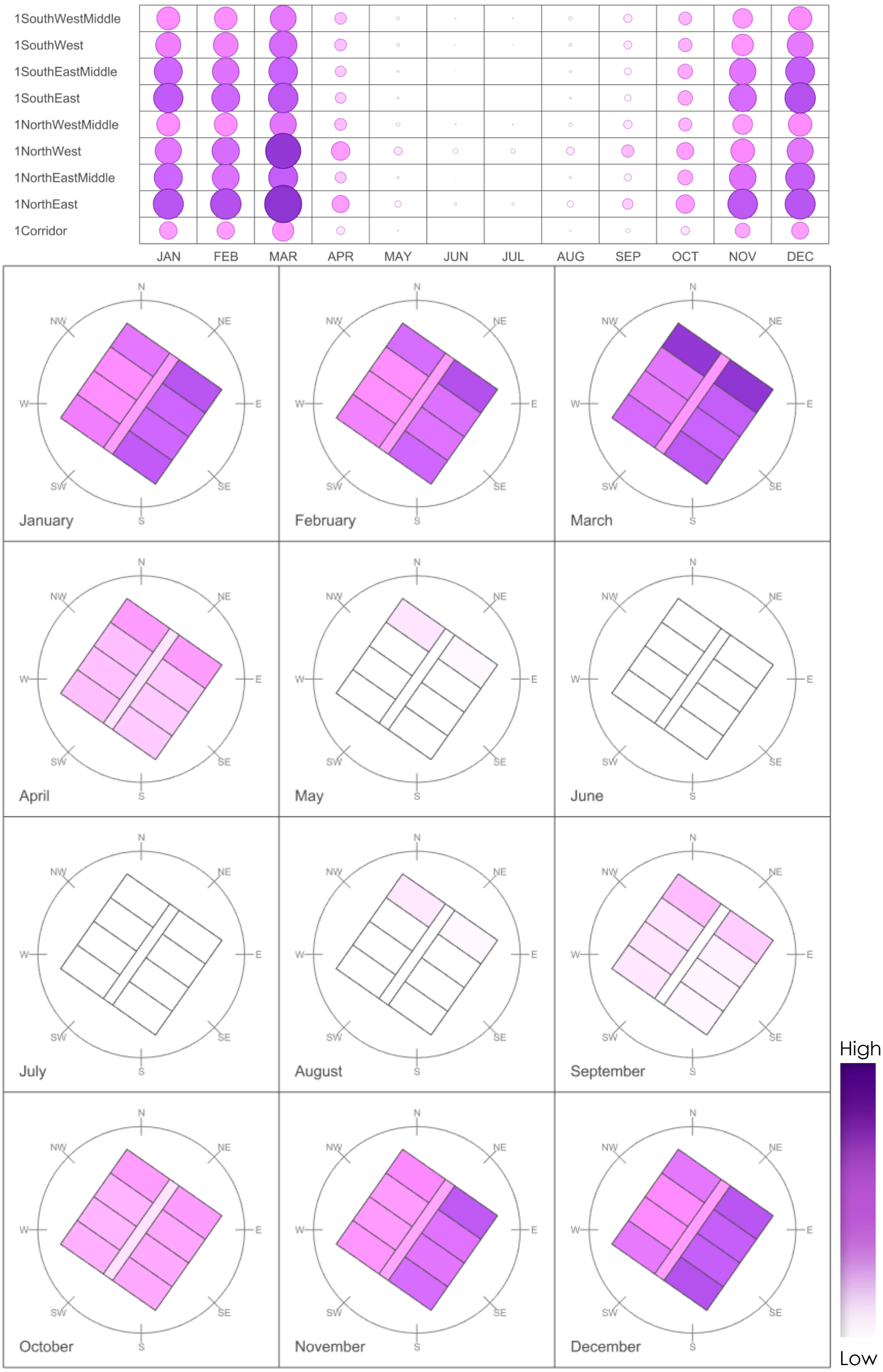


Figure 7-13 Zone air system sensible cooling energy (kWh) Monthly Top floor

Moving from April to October there was little difference in cooling energy usage for all zones. Figure 7-12 shows that the major difference between cooling energy use for thermal zones on the ground floor is found in the North East zone but only for four months of the year.

The heating and cooling energy graphs (Figure 7-14) were created to show the patterns of energy use in order to discover high and low points. For example, Figure 7-14 shows that all zones located on the ground floor have the same cooling/heating trend. A similar cooling/heating trend was also observed for all top floor zones, but there is an obvious difference the cooling energy for the first and ground floors. The next step was to try to understand what was causing these differences (Figure 7-15).

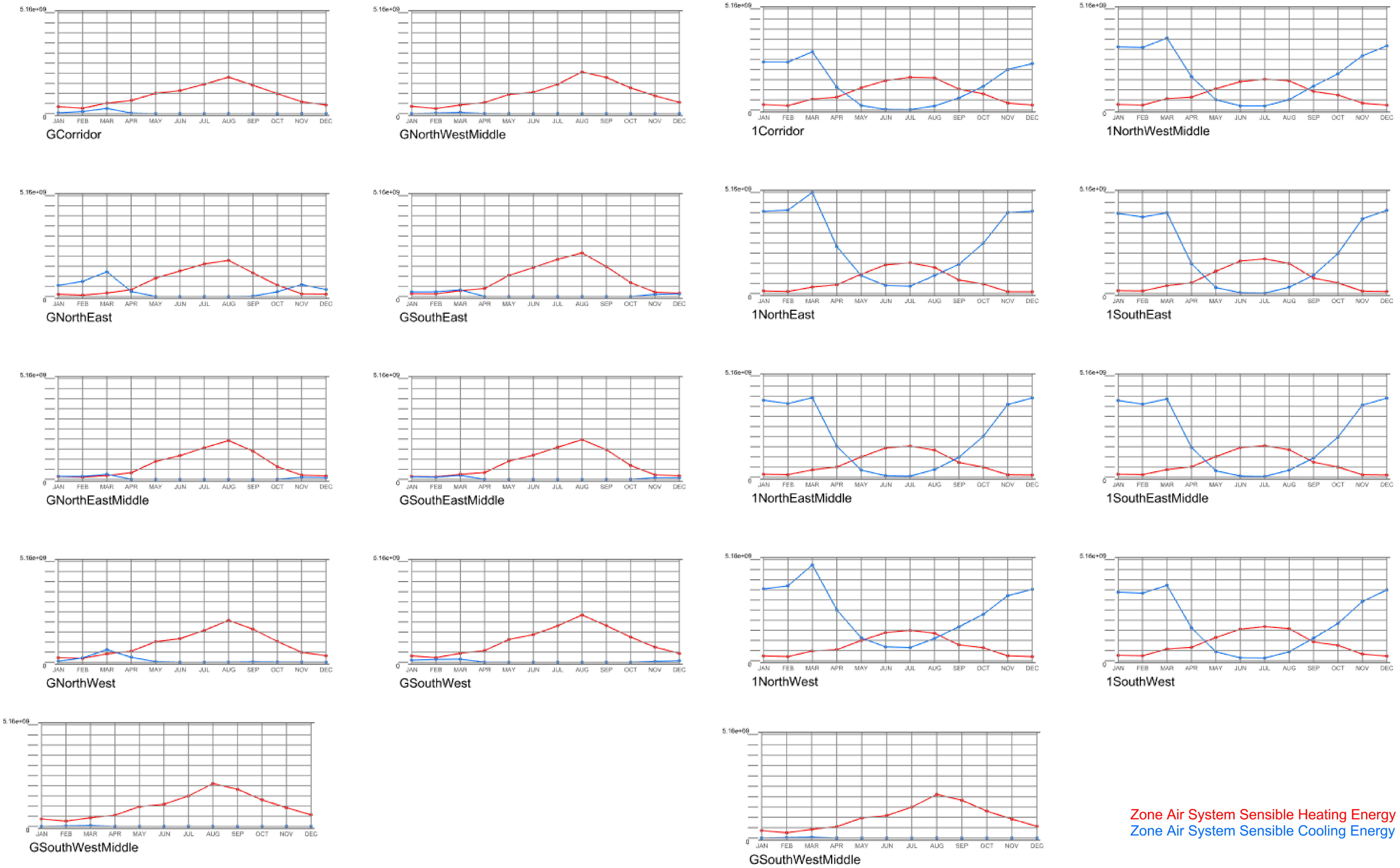


Figure 7-14 Heating and cooling energy use of all zones, (kWh) Monthly

To check whether the ground (soil) temperature affected the lower cooling energy use in the ground floor, the energy simulation was run again with the ground boundary conditions replaced with those of the outdoors. However, the results (Figure 7-15) show that nothing changed significantly except for a small increase in the ground floor cooling energy seen in the right and left hand sides of the graph. There was still a big difference between ground and top floor cooling energy.

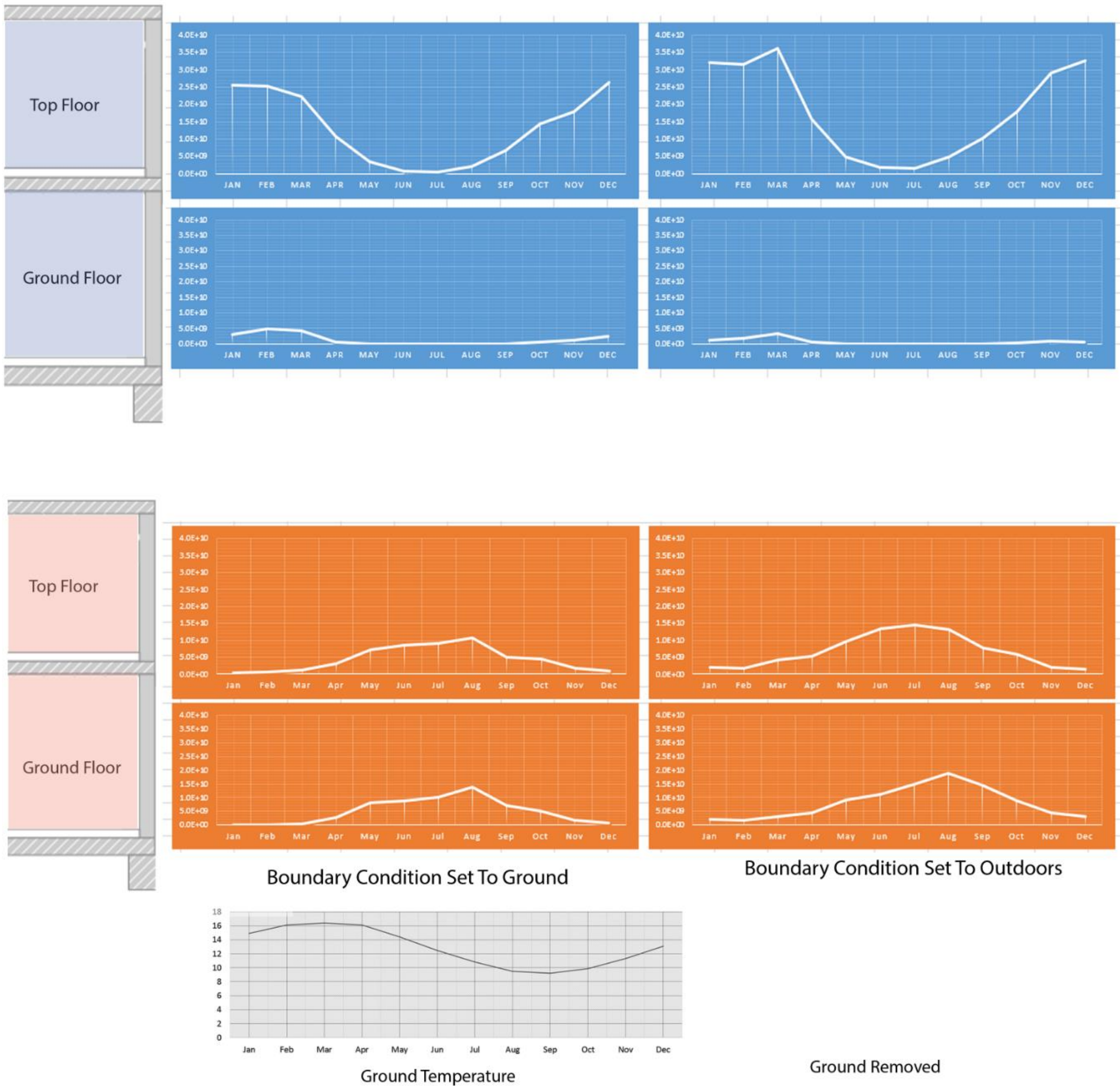


Figure 7-15 Heating and cooling energy use [kW] for investigating the reason for the high top floor cooling energy use

To investigate to what extent solar radiation might contribute to the cooling energy differences, a solar radiation analysis was done in two steps: first for the building in normal conditions (original case) and second for the building with additional roof shading (modified cases). The chart (Figure 7-16) can be interpreted as showing the solar energy absorbed by the roof is large enough to cause the massive difference in the cooling energy consumption of the ground and top floors. Given the effect of the roof solar gain on the total cooling energy depending on the season, the reason for the dissimilarity in energy use can be understood. This was supported by the result from a third energy simulation run. As can be seen in Figure 7-17, by shading the roof, cooling energy decreased to almost the same level as for the ground floor.

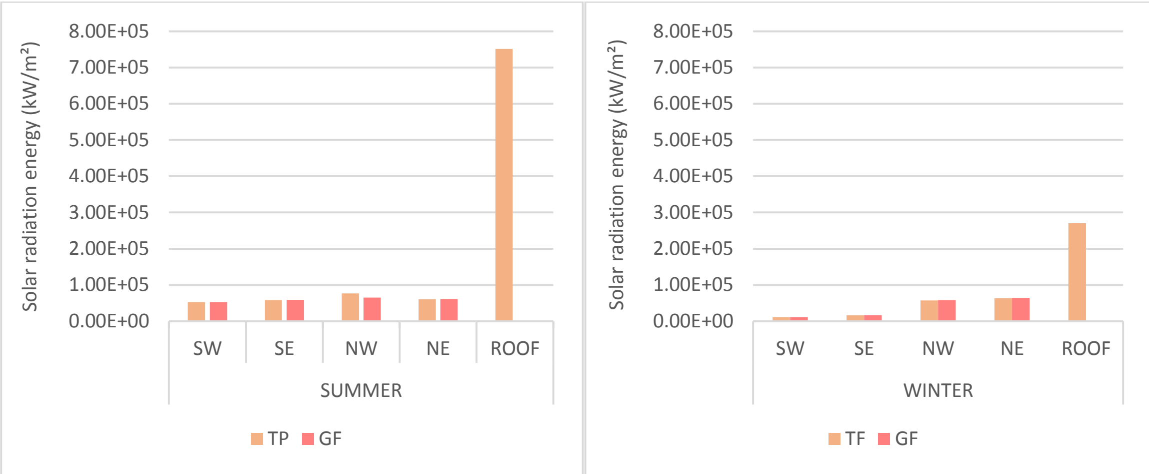
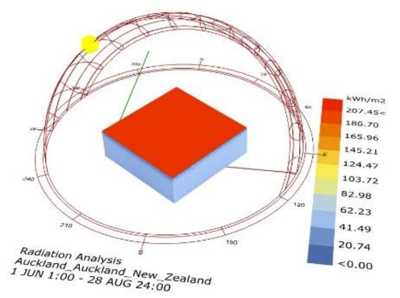
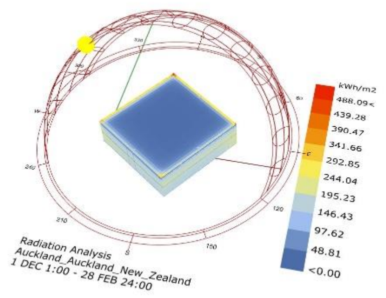
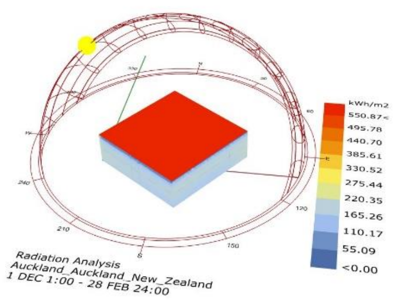
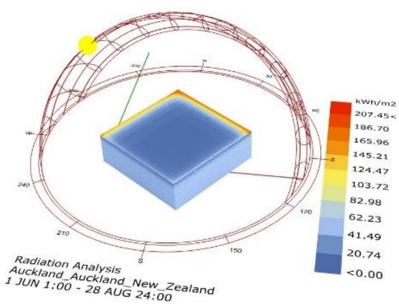


Figure 7-16 Solar radiation energy (kW/m²) absorbed by the building facades facing South East, South West, North East, and North West in ground floor and top floors of R0813 in summer and winter

Table 7-5 shows the thumbnails for solar radiation analysis calculated for summer and winter. The left-hand side of the table shows the solar radiation analysis run for the original model of R0813 whereas the right-hand side shows the results for a modified version of this building with a shaded roof.

Table 7-5 Comparing shaded and non-shaded roof radiation analysis for R0813 for summer and winter

	Roof without shade	shaded roof
Winter		
Summer		

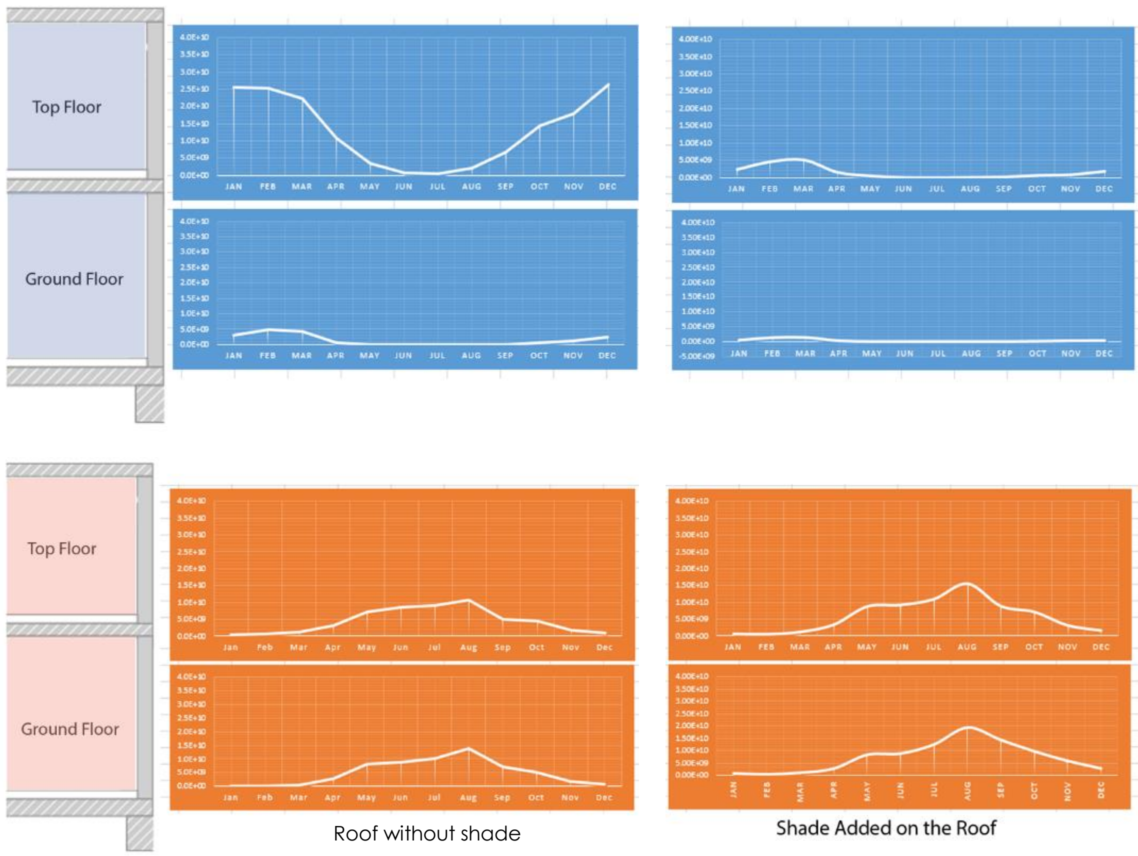
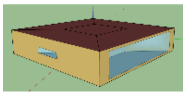
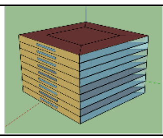
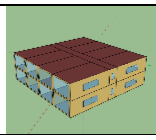
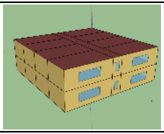
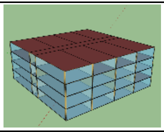


Figure 7-17 Heating and cooling energy use [J] calculated for investigating the high top floor cooling energy use

7.3.5 Comparative energy analysis of R0017, R0738, R0831, and R1586

This section presents the energy analysis of all five case studies including the pilot energy simulation run for R0813.

The reason for adding the energy report of R0813 was to facilitate a quick interpretation of the energy reports related to the rest of the case studies.

Site	Auckland New Zealand	Auckland New Zealand	Auckland New Zealand	Auckland New Zealand	Auckland New Zealand
Visual thumbnail					

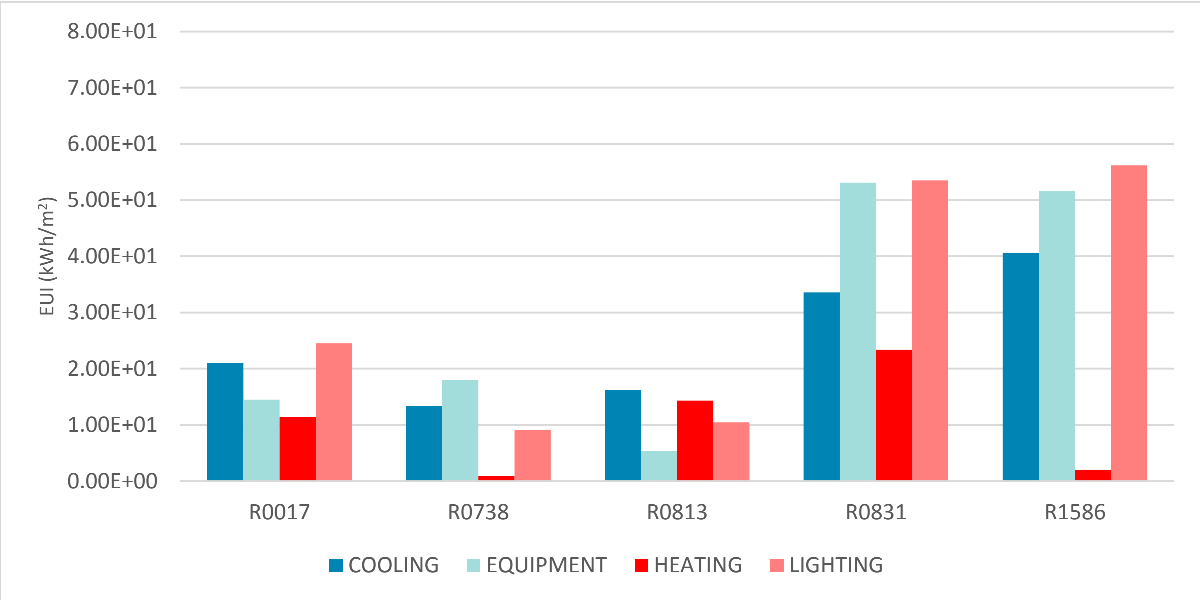


Figure 7-18 Major end use energy consumption for all case studies (Auckland)

Because the main focus of this research was the improvement of the energy performance of office buildings for all the components of end use energy consumption, the heating and cooling energy provided by either electricity or gas was analysed for the other four case studies. The lighting and equipment electrical energy is also reported here to show the relative contribution of cooling and heating energy to the total building energy consumption.

Figure 7-19 displays the cooling and heating energy in kWh/m² for the individual floors of all case studies. While heating energy for R0017, R0831 and R0813 was quite similar, there was a considerable difference for R0738 and R1586.

In *EnergyPlus* simulation M stands for all floors between the ground floor and top floors. The simulation gives the total energy for M. In order to have an idea of the energy use for one mid-floor, M is divided by the number of such floors to give an approximate value for the energy consumed per mid floor.

For a single storey building such as R0017, the cooling energy was greater than the heating energy, and the other case studies also used more cooling than heating energy. However, for R0017 the heating energy during autumn and winter was almost twice the cooling energy consumed by the building during spring and summer (Figure 7-20).

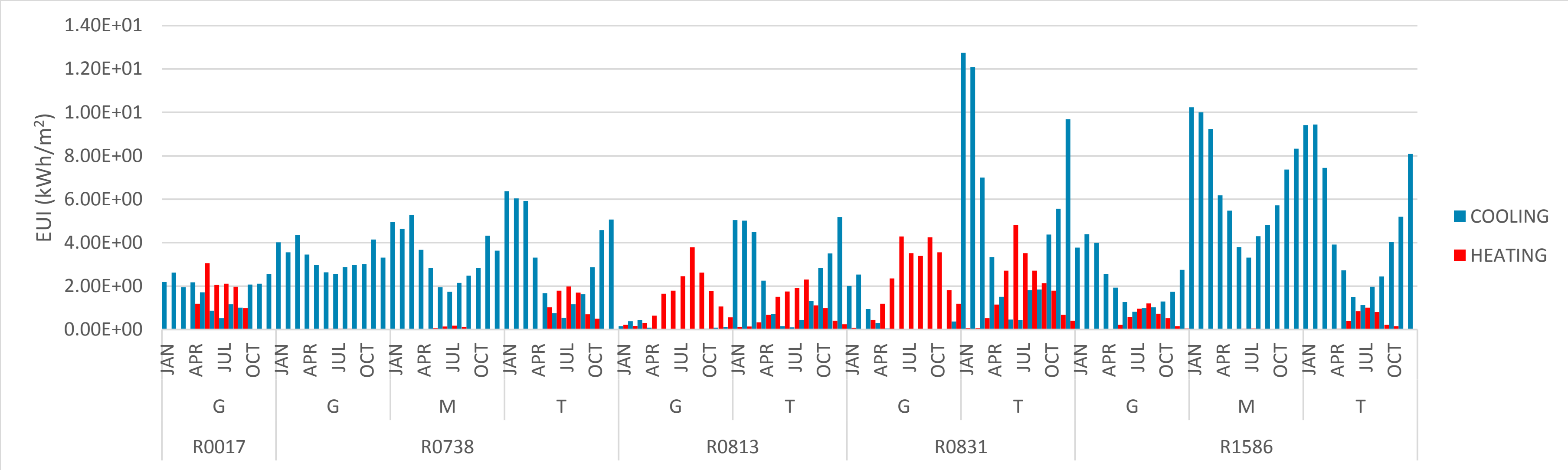


Figure 7-19 Cooling and heating energy for the individual floors of all case studies

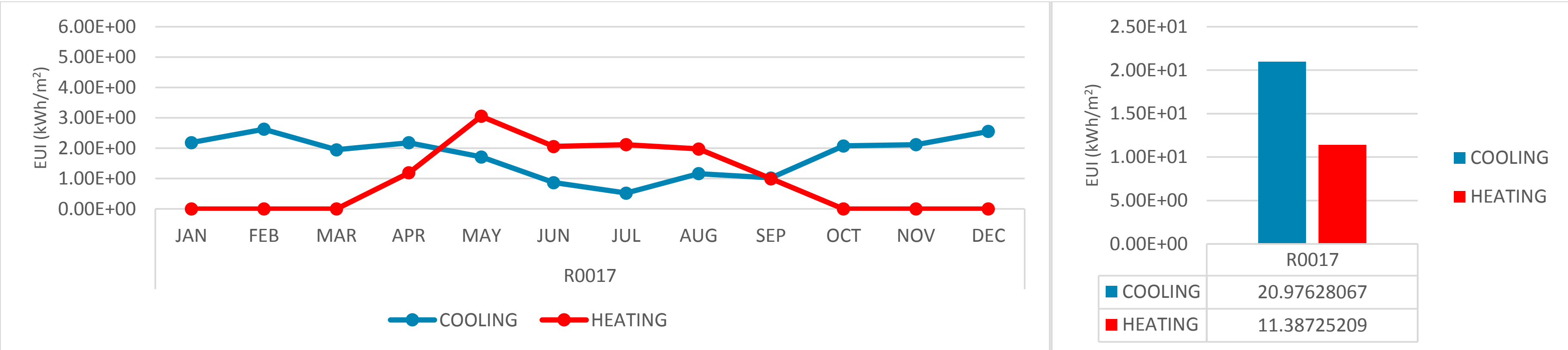


Figure 7-20 R0017 monthly energy use

R0813 and R0831 produced very similar patterns (Figure 7-21 and Figure 7-22) for energy use indicating the top floor consumes more energy for cooling while the heating energy is similar for both floors. However, cooling energy was greater in R0831 with cooling almost twice that of R0813 for the top floor (Figure 7-23 and Figure 7-24).

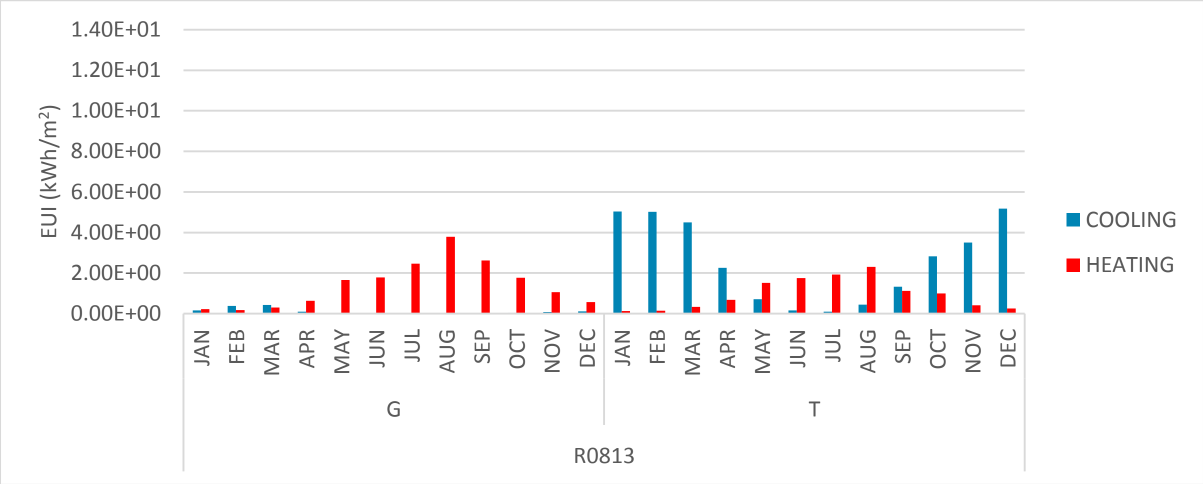


Figure 7-21 R0813 monthly energy use

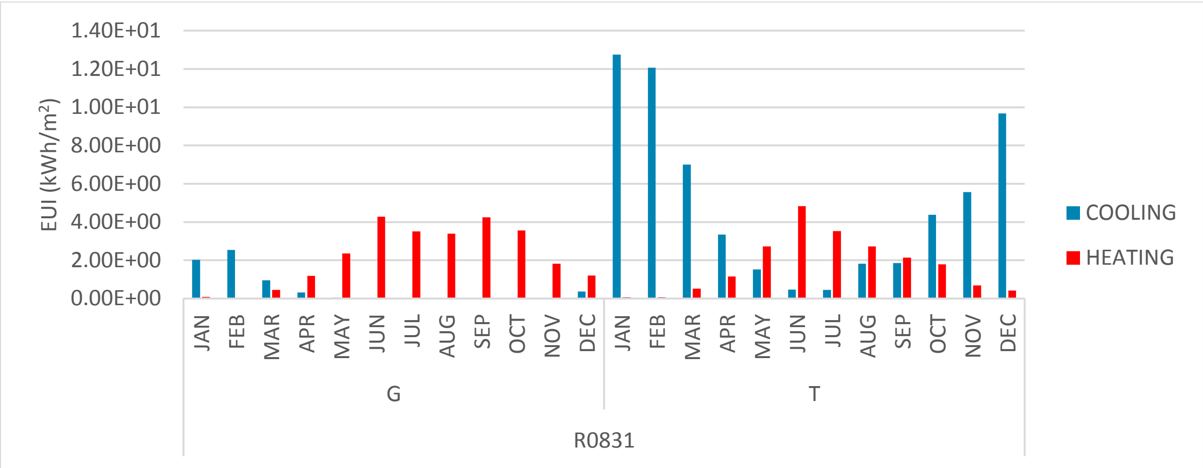


Figure 7-22 R0813 monthly energy use

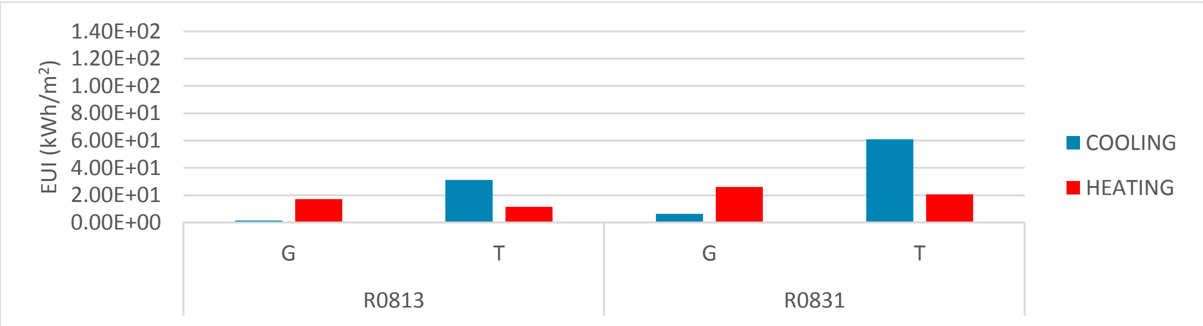


Figure 7-23 R0813 and R0831 annual energy use

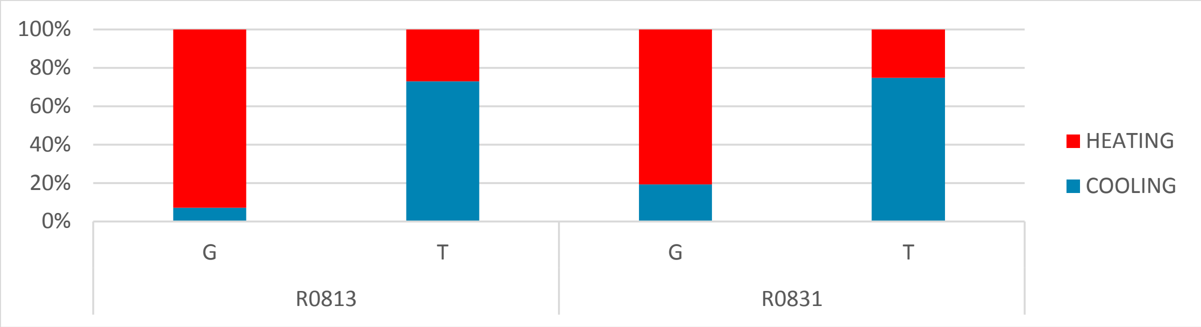


Figure 7-24 R0813 and R0831 annual energy use

For both R0738 and R1586 (Figure 7-25 and Figure 7-26) cooling energy was substantially greater than heating energy for all floors. However, R1586 showed a gradual increase in cooling energy with the lowest for the ground floor and the highest for the top floor while for R0738, the monthly cooling energy uses of the top and ground floors were approximately the same. Given that heating and cooling energy uses reported as M were the sum of energy uses for all floors between the ground and top floor, the mid-floors showed a very low level of energy use for R0738.

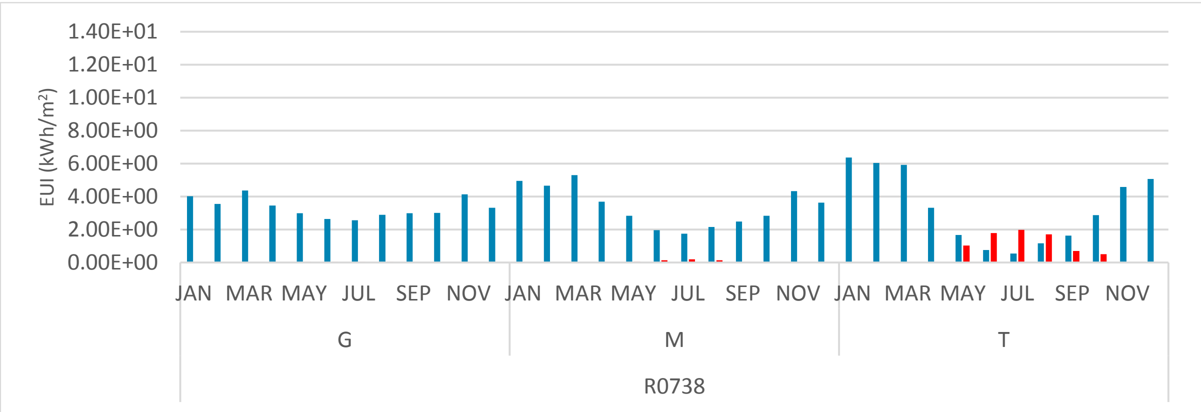


Figure 7-25 R0738 monthly energy use

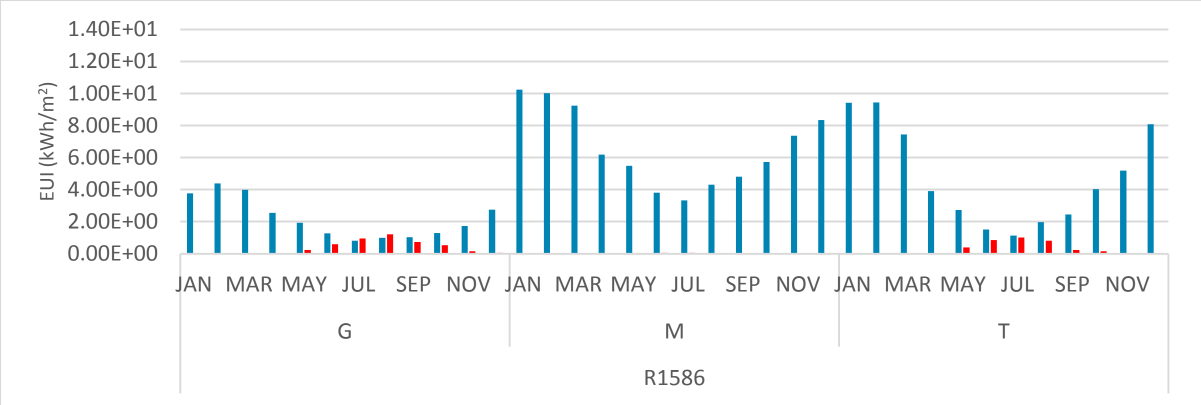


Figure 7-26 R1586 monthly energy use

According to Figure 7-27, the other difference between R0738 and R1586 was in the cooling energy use reported for the mid-floors with this being nearly seven times greater in R1586 as M was the sum of the energy uses for all floors between the top and the ground floor.

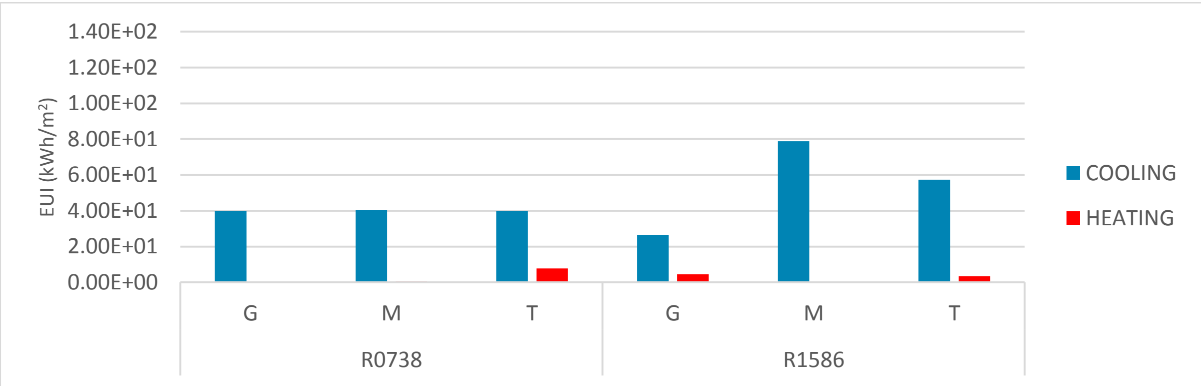


Figure 7-27 R0738 and R1586 annual energy use

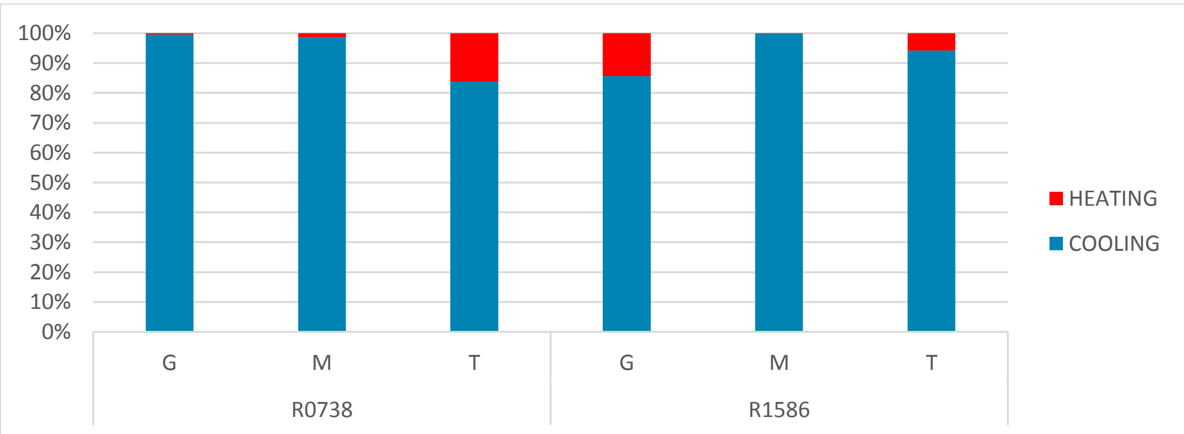


Figure 7-28 R0738 and R1586 annual energy use

Recognising a series of similarities in the patterns of energy consumption, a different bar chart was generated to group the case studies with the most similarity. The two new categories were composed of 1) R0813, R0831, and R0017, and 2) R0738 and R1586 (Figure 7-29). The rationale behind this categorization was the cooling and heating energy use with the latter being almost negligible for R1586 and R0738. On the contrary, for R0017, R0813 and R0831, a considerable amount of energy was used for heating and thus, reducing either cooling or heating energy could contribute to improving the whole building energy consumption.

The grouping was performed to facilitate the energy analysis comparison. According to section 7.3, a series of the input data needed to be presented to allow critical comparison of the energy consumption. Figure 7-30 presents visual thumbnails, physical characteristics, occupant behaviour, and internal loads for all case studies.

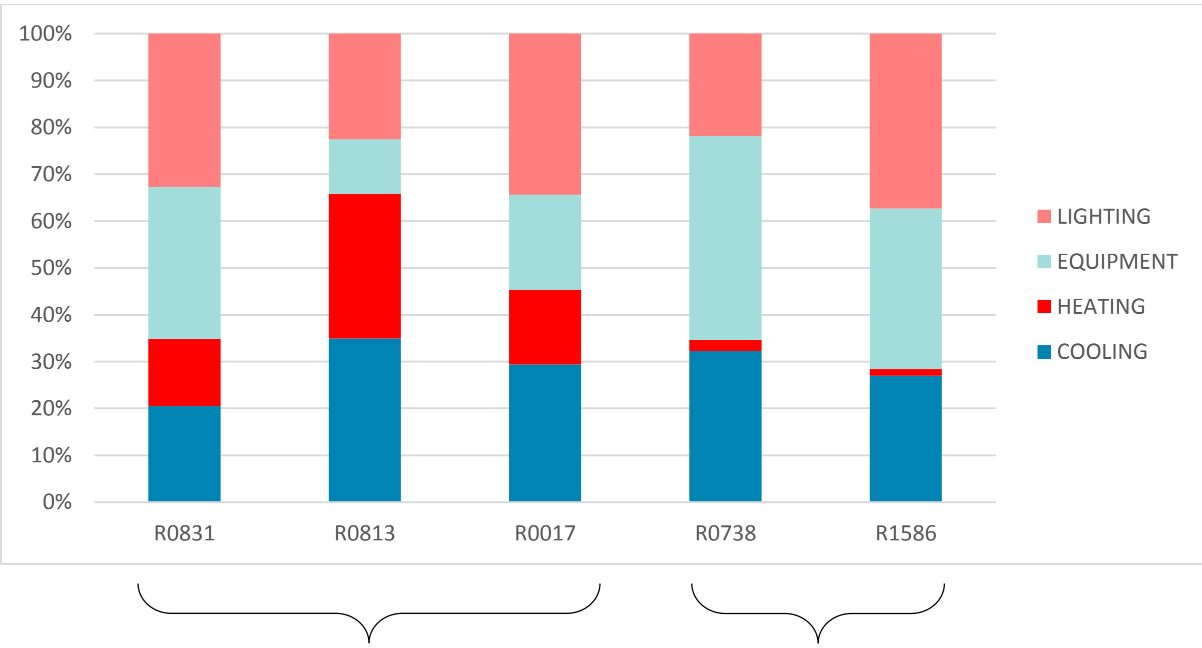


Figure 7-29 Breakdown of energy end use for the five buildings

Figure 7-29 shows the cooling energy was greater than the heating energy in all case studies and for some there was a substantial difference between the two. That said, the next step was to identify whether the high cooling energy use was caused by the internal loads or the heat flow through the building envelope.

7.3.5.1 Heat balance calculations: two most challenging case studies

As affirmed by *EnergyPlus*, space heat gain energy and heat transfer energy through windows and opaque surfaces can be calculated using the following variables in order to find the building heat balance. In *EnergyPlus*, the energy reports for opaque surfaces are labelled as surface outputs which differ from the total building surface energy flow, as the term surface as used in the latter refers to both windows and opaque surfaces of the building. The following sections summarises the outputs used to calculate the heat balances for all case studies. Studying the heat transfer parameters of the office buildings allowed for identification of case studies with similar thermal behaviours. This led to recognition of those with a thermal challenge.

Space Gains Monthly (US Department of Energy, 2015, p. 2716)

- Zone people total heating energy (sum or average): People heating energy is calculated based on the activity schedule and the number of occupants in each thermal zone.
- Zone lights total heating energy (sum or average) = zone lights electric energy
- Zone electric equipment total heating energy (sum or average) = zone electric equipment electric energy
- Zone gas equipment total heating energy (sum or average)
- Zone hot water equipment total heating energy (sum or average)
- Zone steam equipment total heating energy (sum or average)
- Zone other equipment total heating energy (sum or average)
- Zone infiltration sensible heat gain energy (sum or average)
- Zone infiltration sensible heat loss energy (sum or average)

Opaque Surface Output Variables

- Surface Average Face Conduction Heat Transfer Energy [J]: This output variable is a combination of conduction report values calculated for inside and outside faces of the building opaque surfaces. The positive values identify the heating energy flow coming from outside through the thermal zones while the negative ones show the heat flow in the opposite direction (US Department of Energy, 2015, p. 190).

Window Output Variables

- Zone Windows Total Transmitted Solar Radiation Energy [J]: shows the total solar energy transmission through all exterior windows in a zone
- Zone Windows Total Heat Gain Energy [J]: is the sum of the heat flow from all of the exterior windows in a zone when that sum is positive.

- Zone Windows Total Heat Loss Energy [J]: is the sum of the heat flow from all of the exterior windows in a zone when that sum is negative (US Department of Energy, 2015, p. 191)

The "Surface Average" represents the total heat transfer energy through opaque surfaces. For window heat gain energy it was necessary to calculate the heat gain from both the solar energy transmitted through windows (not absorbed by the glass) and the conductive heat gain through windows (absorbed by the glass and transferred through conduction).

While window conductive heat gains and heat losses, and radiant heat gains were reported separately, the sum of these values together with the "Surface Average" indicated the total surface (Opaque surfaces and windows) energy flow for each case study. In each diagram these measures not only accentuated whether glazing or opaque surfaces formed the bigger contributor to the heat flow through the envelope but also facilitated comparison of internal and external heat gain for each case study. The total heat transfer through the building envelope (opaque surfaces and windows) could be either positive or negative, and here the positive numbers indicated heat flow towards the thermal zones.

Energy simulation was run for all case studies to calculate the energy balance parameters (Figure 7-30). These parameters for the whole building are set out below:

- People: people total heating energy
- Lights: lights total heating energy
- Electric equipment: electric equipment total heating energy
- Solar: solar heat gain energy transmitted through all windows (not absorbed by the glass)
- Win H Gain: conductive heat gain energy through all windows (absorbed by the glass)
- Win H loss: conductive heat loss energy through all windows
- Infil H Gain: infiltration sensible heat gain energy from all windows
- Infil H Loss: infiltration sensible heat loss energy from all windows
- Surface Average: the total heat transfer through opaque surfaces
- Surface Heat Storage: this variable is the difference between the conductive heat transfer and loss with positive values indicating heat is being added to the core of the surface material.

The heat balance of each case study included all energy flows through the building envelope as well as from all the heat sources inside the building. Heating loads and cooling loads were not reported. This is the reason for the inequality between heat gain energy and heat loss energy in the heat balance diagrams. The heat balance diagrams were constructed in order to find the major contributors to internal heat gains and heat losses (Table 7-6).

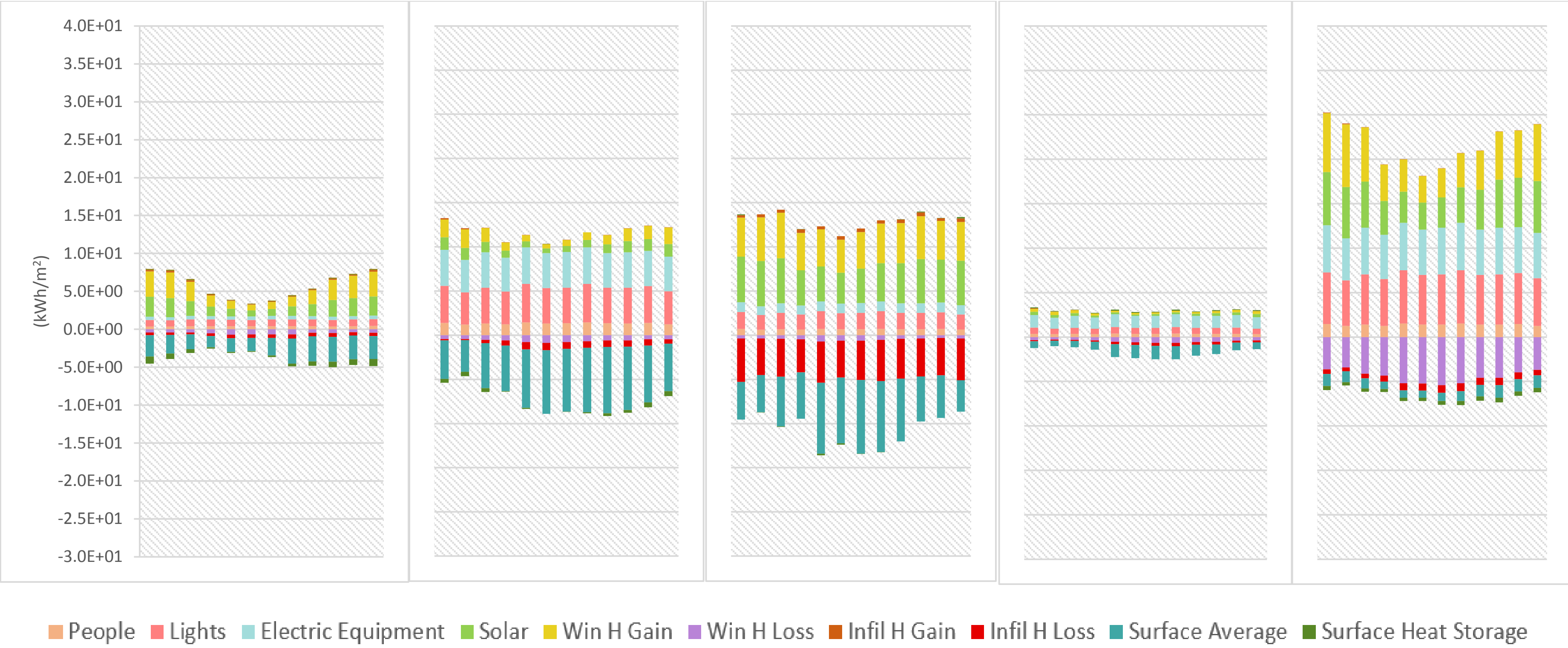
Figure 7-30 shows the heat balance parameters for each case study. Three visual thumbnails are also provided to give the physical characteristics of each office building. The two at the top show the south and north elevations whereas the one on the bottom illustrates the shading made either by neighbouring buildings or from shading installed on the facades.

Looking at Table 7-6, the heat balance results reported for R0738 and R0831 indicated that the major proportion of the heat gain was from lighting, equipment, and occupants. By contrast, for R0813 and R0017 the main drivers of heat gain were conductive heat gain through opaque surfaces and conductive and radiant heat gain through windows. There was also considerable infiltration heat loss from windows.

Heat balance results for R1586 suggested the neutrality of the windows as the absolute value of heat loss through them was very close to that of the internal heat gain.

As shown by the circle charts in Table 7-6, the high cooling energy consumption of R1586 was due to both the internal loads and the probable poor characteristics of the windows. Accordingly, reducing the interior electrical energy consumption would contribute to a lower cooling energy. One possible approach could be replacing current lighting devices and electrical appliances with energy efficient luminaires and equipment. The cooling energy consumption could also be reduced by improving the thermal performance of the building envelope through changing the windows, as the heat loss through the opaque surface of this building was small (Figure 7-30). Both heat gain and heat losses through the windows were substantial and could be caused by either a low U-value or a big window to wall ratio. As shown in the thumbnail, the high cooling energy seems to be caused by the glass curtain wall. Overall, internal heat gain was greater than heat gain through the windows.

As illustrated by Table 7-6, the main drivers of cooling energy use in R0738 were the internal loads with the largest contribution related to electrical devices. Solar radiation transmitted to the zones through the windows was small compared to the internal loads. Conductive heat gain through the window surfaces was also minor. Altogether, the building envelope of R0738 made a lesser contribution to heat gain and subsequently cooling energy use. This underlined the significance of cutting down on the internal energy use for reducing the whole building energy consumption. The results also indicated a significant heat loss through the opaque surfaces despite this being less than the internal gains.



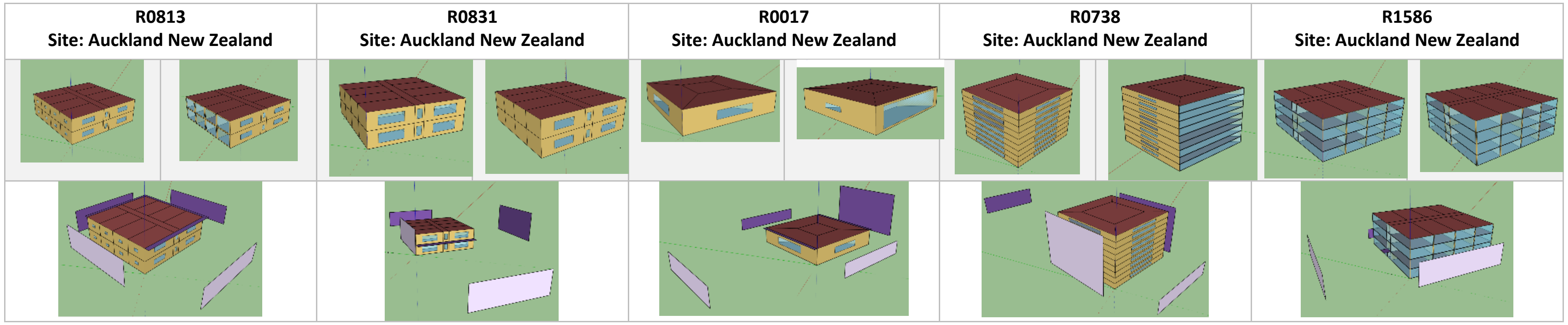
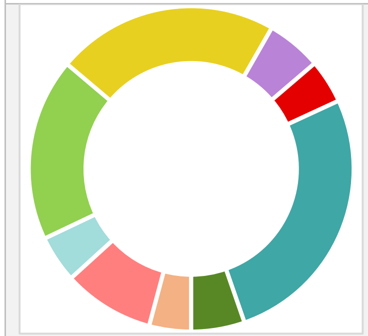
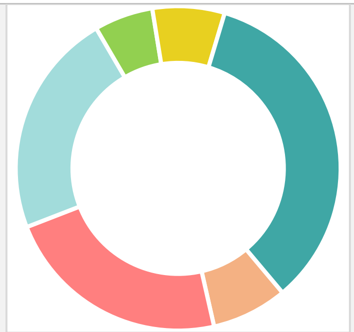
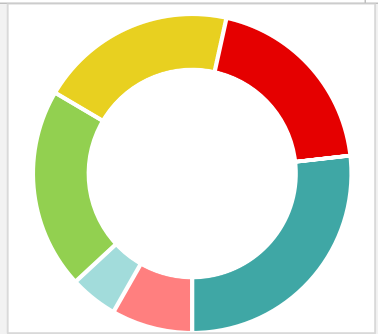
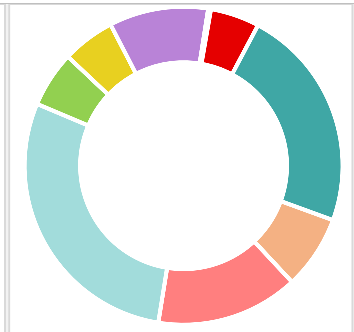
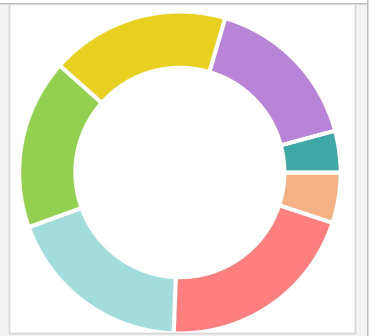


Figure 7-30 Top) Breakdown of normalized space heating gains and losses ; Bottom) visual thumbnails of case studies

Table 7-6 Top) Breakdown of the major space heat gains and heat losses; Bottom) internal loads and physical characteristics of case studies. Grey scale represents the higher (darker) and lower (lighter) values reported for each cell. Where the numerical difference was small, the same colour was used.

R0813 Site: Auckland New Zealand	R0831 Site: Auckland New Zealand	R0017 Site: Auckland New Zealand	R0738 Site: Auckland New Zealand	R1586 Site: Auckland New Zealand
				
Total floor area 2674.73 m²	Total floor area 742.67 m²	Total floor area 523.95 m²	Total floor area 3145.41 m²	Total floor area 4520.97 m²
Windows Window opening area [m²] 455.99	Windows Window opening area [m²] 62.87	Windows Window opening area [m²] 119.52	Windows Window opening area [m²] 1076.17	Windows Window opening area [m²] 2180.01
Glass u-value [W/m²K] 5.471	Glass u-value [W/m²K] 5.471	Glass u-value [W/m²K] 5.117	Glass u-value [W/m²K] 5.470	Glass u-value [W/m²K] 5.471
Lighting Lighting power density [w/m²] 3.17	Lighting Lighting power density [w/m²] 18.34	Lighting Lighting power density [w/m²] 9.37	Lighting Lighting power density [w/m²] 8.5	Lighting Lighting power density [w/m²] 18.45
Lighting Scheduled hours/week [hr] 63.94	Lighting Scheduled hours/week [hr] 57.41	Lighting Scheduled hours/week [hr] 51.39	Lighting Scheduled hours/week [hr] 51.39	Lighting Scheduled hours/week [hr] 79.34
Occupancy People per zone floor area 0.0142	Occupancy People per zone floor area 0.0545	Occupancy People per zone floor area 0.0278	Occupancy People per zone floor area 0.0466	Occupancy People per zone floor area 0.0556
Equipment Equipment power density/ watts per zone floor are [w/m²] 1.46	Equipment Equipment power density/ watts per zone floor area [w/m²] 8.13	Equipment Equipment power density/ watts per zone floor area [w/m²] 4.07	Equipment Equipment power density/ watts per zone floor area [w/m²] 7.42	Equipment Equipment power density/ watts per zone floor area [w/m²] 12.91
Air change per hour 0.1	Air change per hour 0.1	Air change per hour 0.5	Air change per hour 0.1	Air change per hour 0.1

While Figure 7-30 shows all the heat flow parameters (except heating and cooling loads) that contribute to heat gain and heat loss in each case study, the top part of Table 7-6 presents a separate breakdown of the major space heat gains and losses as the purpose is to find the main thermal challenges for each building. This means in the pie charts the parameters related to small heat gains and losses were not included.

Having R1586 and R0738 in one category as shown in Figure 7-29, meant there was a need to scale up the R0738 heat balance reports by a factor of 10 (Figure 7-31 and Figure 7-32) to facilitate analysis of the heat balance patterns.

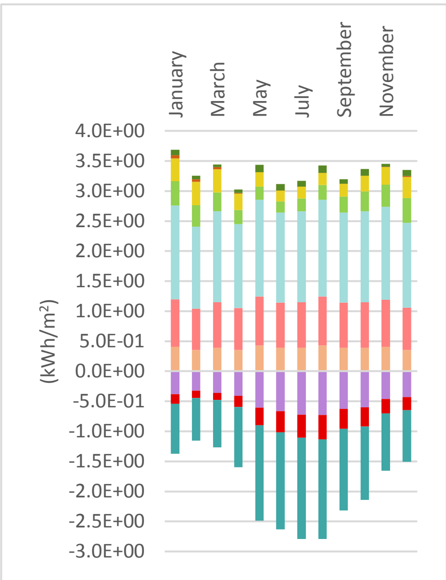


Figure 7-31 Heat balance (space heat gain and heat loss) for R0738

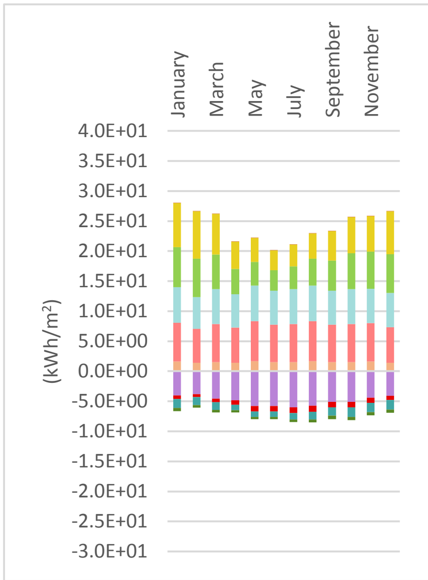


Figure 7-32 Heat balance (space heat gain and heat loss) for R1586

Looking at the pie charts in Table 7-6, the results showed that:

- For R0831 and R0738, internal heat gain was more than external heat gain.
  a) For R0831, a great deal of heat was lost through the opaque surfaces.
  b) For R0738, there were heat losses through both windows and the opaque surfaces, although the surface average heat loss though the opaque surfaces was almost twice that of heat lost through the windows.
- For R1586 internal heat gain was almost the same as external heat gain. A significant amount of heat was lost through the windows.
- For R0813 and R0017 internal heat gains were less than external heat gains.

a) For R0813, there was a considerable heat loss through the opaque surfaces. While windows also contributed to heat loss, their contribution was much less than that of the opaque surfaces.
b) For R0017, the conductive heat loss was only through the opaque surfaces however, the infiltration heat loss through the windows was high.

The values presented in Table 7-6 and Figure 7-30 were normalised by dividing the heat gain and heat loss energy by the total building floor area. Using these normalised values, Figure 7-33 shows R0813 and R0738 seem to consume a reasonable level of energy compared to R0831, R0017, and R1586.

As highlighted in the literature, a variety of factors affects the thermal performance of a building among which heat gain from electrical equipment, lighting, occupancy level, and building envelop have emerged as most important for energy consumption. As shown in Table 7-6, all these parameters were calculated for each case study. Generally, buildings can be determined as skin-load dominated or internally-load dominated (Kwok & Grondzik, 2018, p. 203) with the former referring to buildings with high internal heat gain. Where the internal heat gain is small, the building skin plays the most important role in energy behaviour. Where the building enclosure determines the heating and cooling energy use, there is a need to design a high-performance building envelope to optimise total energy consumption. In this case, shape, orientation, and the material properties of the building skin need to respond efficiently to the thermal loads imposed by the exterior climatic conditions (Keeler & Vaidya, 2016).

The two buildings with the most challenging thermal issues emerged as R0017 and R1586 and these were selected for a zonal energy report. The division of the case studies into two different groups (Figure 7-29) was done in order to select one building from each category. R1586 was the most challenging from the first group, and in the second even though R0831 had higher cooling and heating energy use compared to R0017, it was not selected for further analysis. The main reason for determining R0017 to be the more challenging building came from comparing the heat balance diagrams and base case descriptions of these two buildings as presented in Table 7-6.

Looking at Table 7-7, R0831 and R0017 had almost similar characteristics in their heat loss from the opaque surfaces but R0017 had higher heat gain as well as high infiltration heat loss from the windows.

Table 7-7 Characteristics of heat loss and heat gain parameters for R0017, R0831 from the first category, and R1586 from the second category

R0017	R0831	R01586
External heat gain	Internal heat gain	Internal heat gain+ external heat gain
Conductive heat loss through opaque surfaces	Conductive heat loss through opaque surfaces	Conductive heat loss through windows
Infiltration heat loss through windows	-	-
Conductive and radiative heat gain from windows	Low conductive and radiative heat gain from windows	High conductive and radiative heat gain from windows
*		*

R1586 showed higher values in almost every greyscale sub-category, except for the air change level that was five times less than that of R0017. Looking at Figure 7-33, the sum of cooling and heating use for R0831 was approximately double that of R0017, however, the difference between the energy consumption of these two case studies was due to the difference in their heat gain patterns (Table 7-6). Accordingly, when it came to comparing their energy consumption by looking at just their cooling and heating demands, the energy use difference diminished while R0017 had a higher conductive and radiative heat gain through the windows as explained by Table 7-7.

R1586 was selected as a representative case study for an almost equal skin and internal load building based on the heat balance parameters (Table 7-6) and R0017 for externally load-dominated buildings in New Zealand (Table 7-6). Choosing R0017 over R0831 also enabled investigation of the energy behaviour of a building that showed almost equal energy use for heating and cooling, and lighting and equipment.

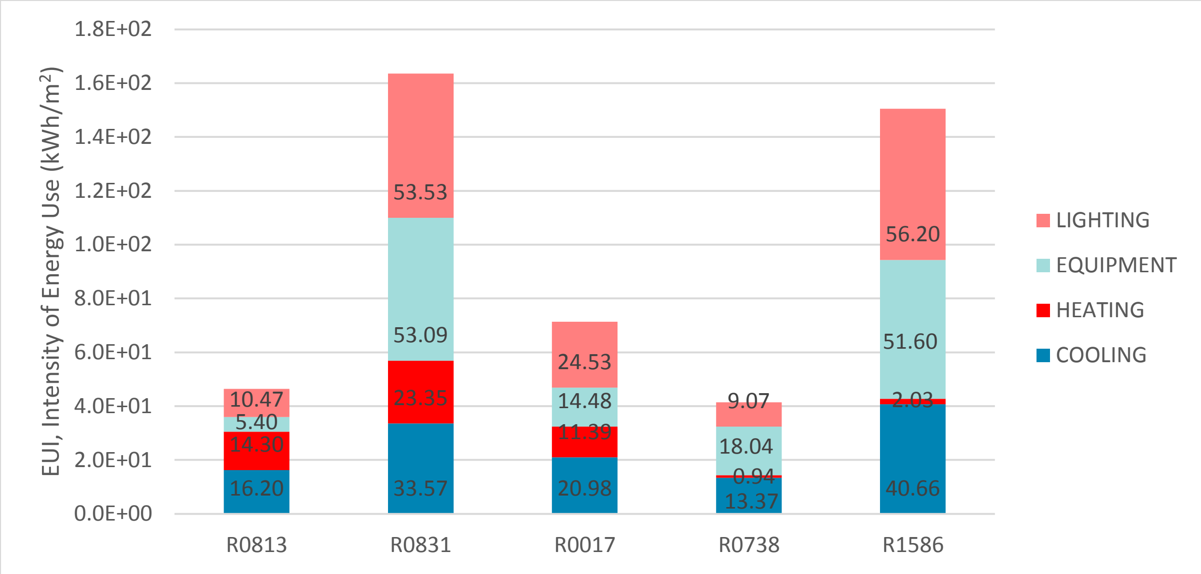


Figure 7-33 Contribution of the major end use energies to the whole building energy consumption

To this end, R0017 and R1586 were selected for analysis in more detail. The thermal zone energy analyses performed for these two case studies were identical to the pilot energy analysis carried out for R0813.

7.3.6 Comparative energy analysis of thermal zones: R0017 and R1586 in Auckland

As explained in the previous section, R0017 and R1568 were identified as the most challenging case studies representing 1) an external load dominated and 2) a more balanced internal and external load office building respectively.

The right-hand side of Figure 7-34 to Figure 7-37 show the cooling energy use of each thermal zone in the individual floors for R0017 and R1586. On the left-hand side the graphs report both heating and cooling monthly energy use. While the blue and red colours on the left side show cooling and heating energy use respectively, the violet to white gradient on the right-hand side of the figures only shows the level of energy use. The maximum energy uses are different for the two case studies of R0017 and R1586 in Auckland.

For R1586, the heating energy use of the thermal zones was not reported visually as the cooling energy was the main thermal challenge, being approximately 20 times bigger than the heating energy. For this reason, only the cooling energy consumption of this building was plotted in Figure 7-35, Figure 7-36, and Figure 7-37. However, for R0017, both cooling and heating energy were visualised since both seemed to play important roles in the whole building energy consumption.

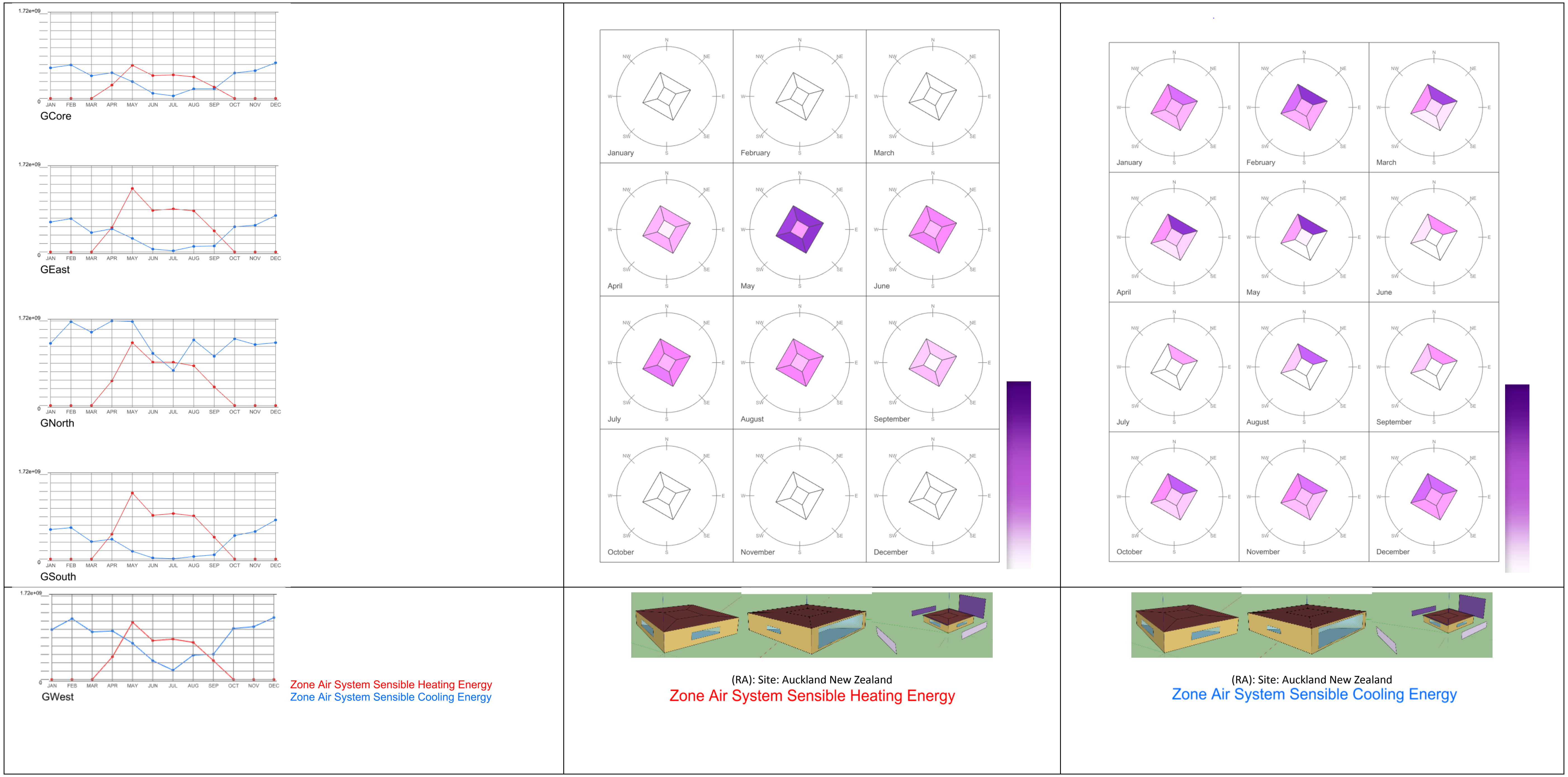


Figure 7-34 Cooling and heating energy use of each thermal zone on the ground floor for R0017- (kWh) Monthly

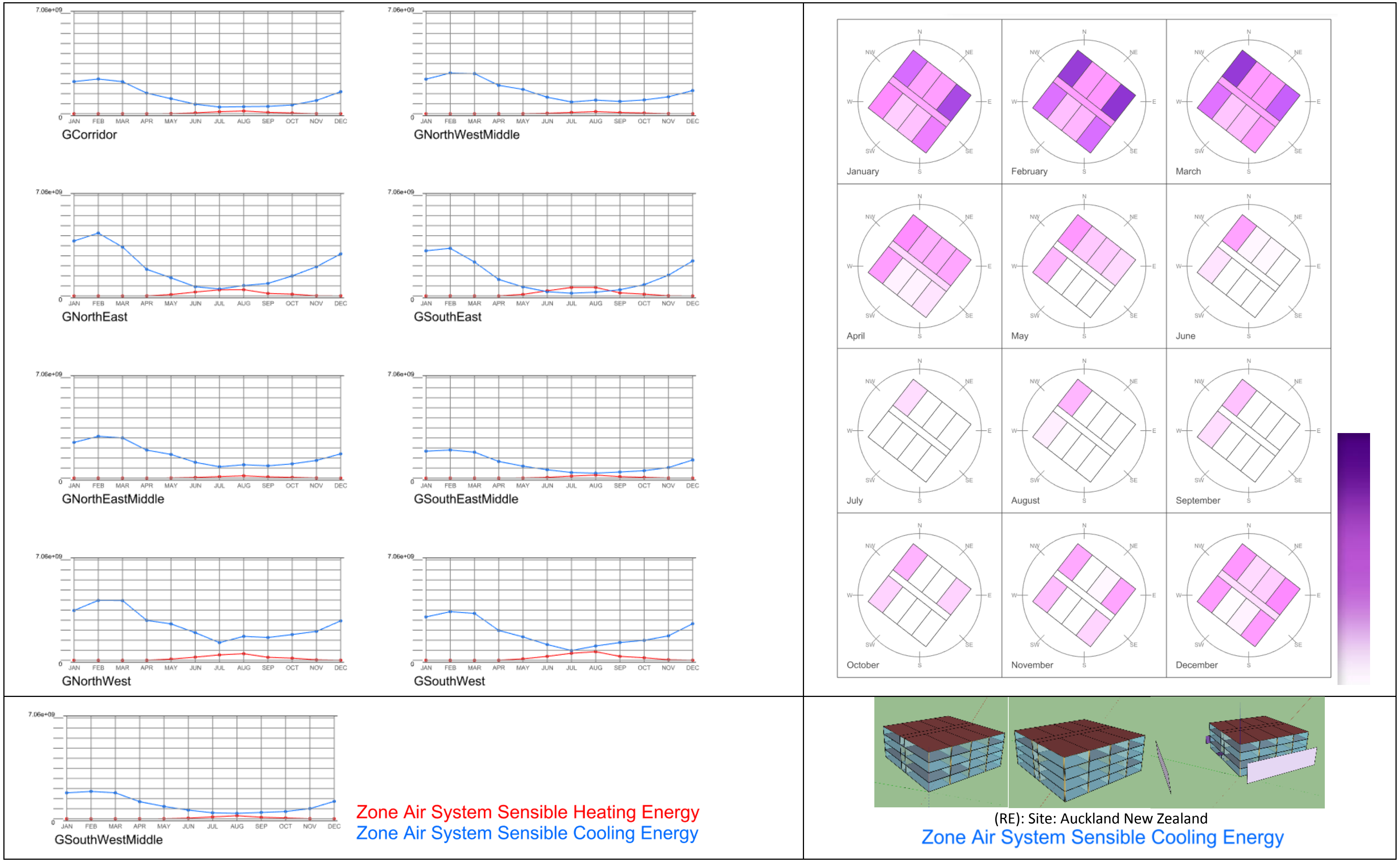


Figure 7-35 Cooling energy use of each thermal zone on the ground floor for R1586 - (kWh) Monthly

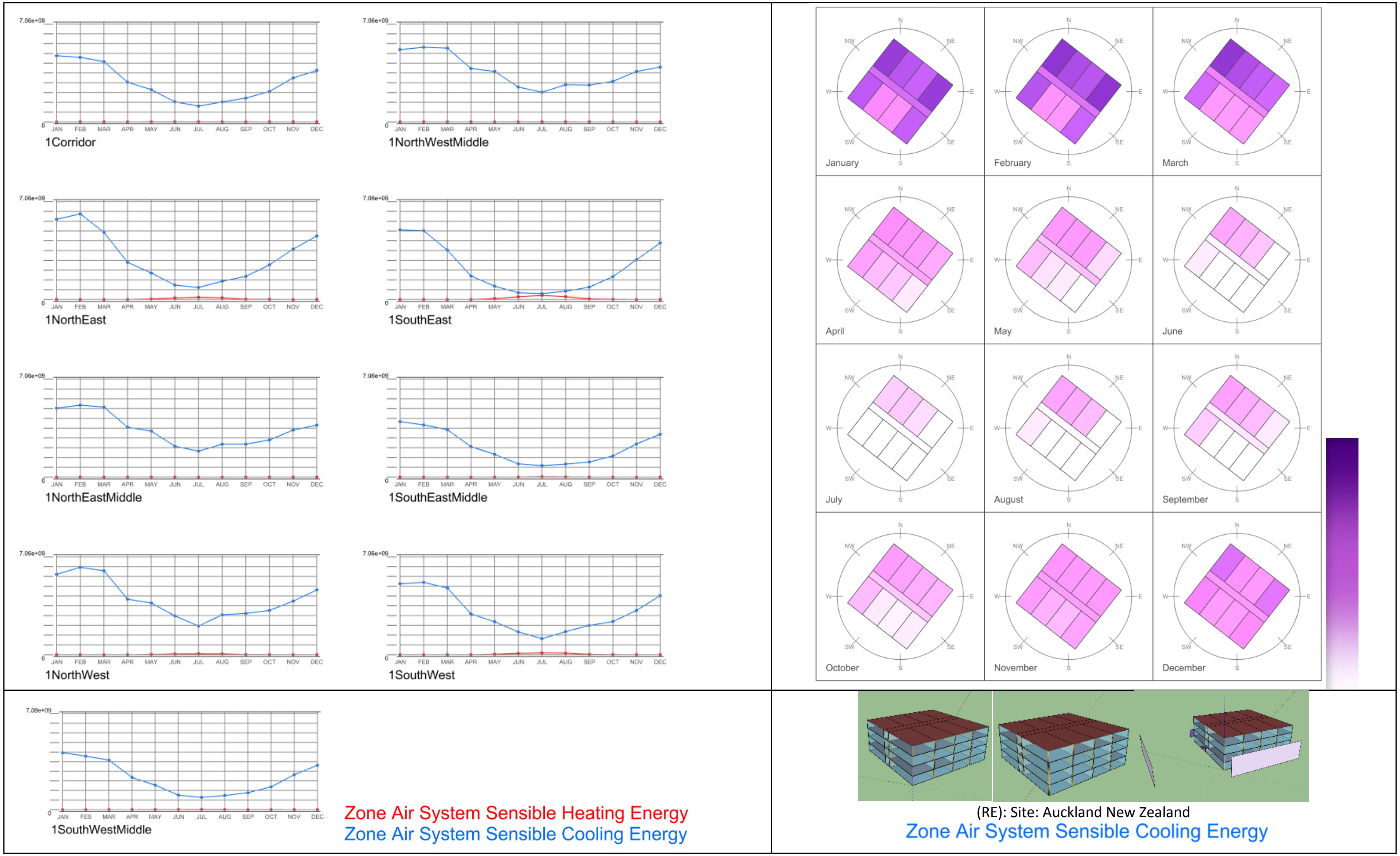


Figure 7-36 Cooling energy use of each thermal zone on the average mid-floor for R1586 - (kWh) Monthly

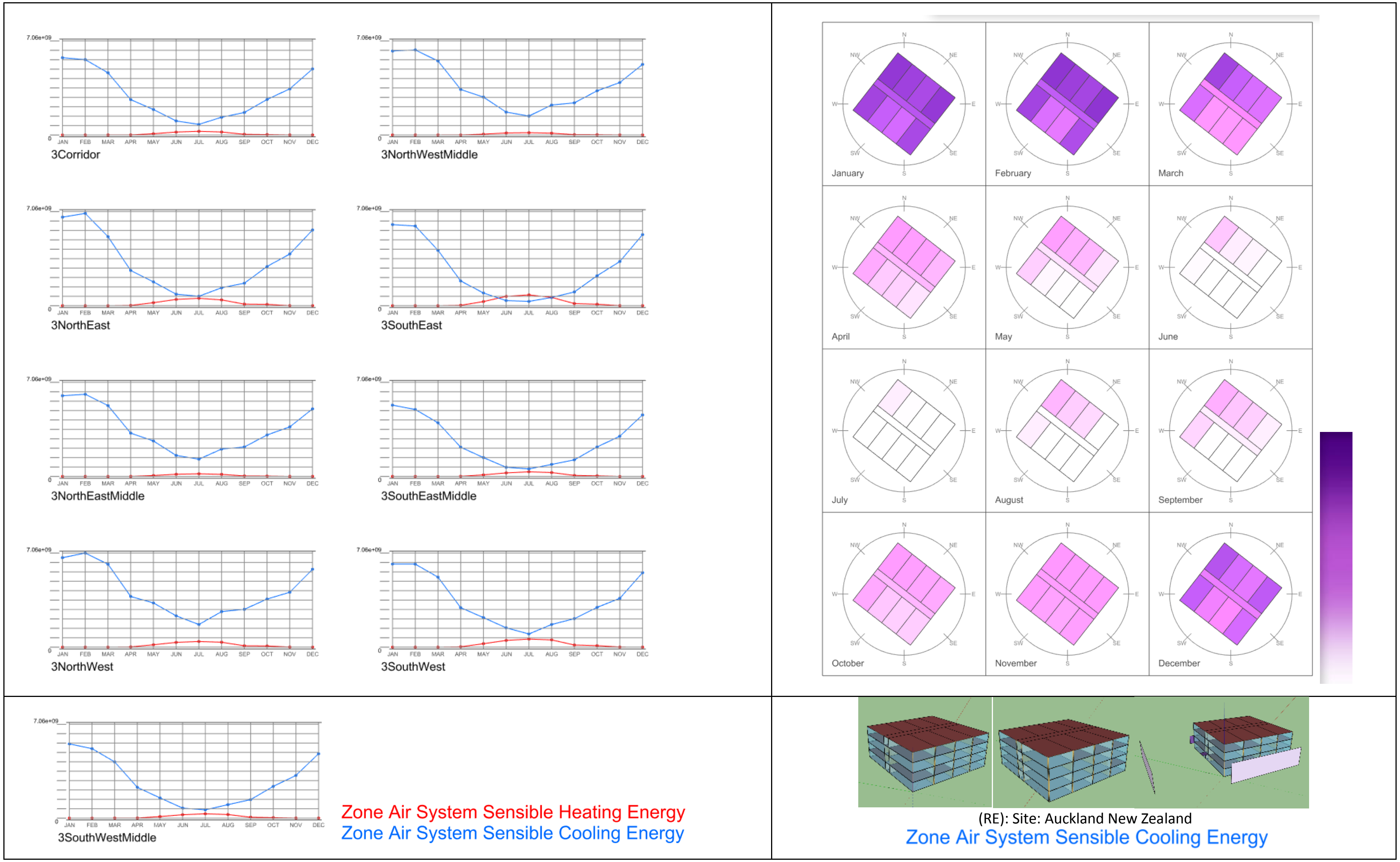


Figure 7-37 Cooling energy use of each thermal zone on the top floor for R1586 - (kWh) Monthly

Figure 7-35, Figure 7-36, and Figure 7-37 were produced to reveal the thermal challenges of R1586 at a more detailed level, and as figure 7-33 shows cooling energy was the most dominant thermal load in this building. Comparing different floors, in summer the cooling energy increased gradually from the ground floor to the top floor. This seems to be caused by the heat absorbed by the roof of the building. As the thermal influence of the roof solar gain reduced from the top floor to the ground floor, the cooling energy in winter and summer could be expected to be higher for the top floor but as shown in Figure 7-36, the average mid floor needed more cooling energy in winter.

In winter, solar radiation energy and subsequently conductive heat transfer from the window surface towards the thermal zones decreased. This happened where the sum of the heat flow was negative during winter, which meant the building was losing more heat from the windows. The increase in the heat loss through windows related to the higher inside temperature. Assuming this, on the top floor, more heat could be lost through the building surfaces in winter as the roof of this floor was in contact with the outside temperature. This was identified as the reason behind the higher cooling energy use in the average mid floor.

The thermal issues of the case studies in Auckland were identified as set out below:

- **R0017**: Both cooling and heating energy
- **R0738**: Cooling energy
- **R0813**: Both cooling and heating energy
- **R0831**: Both cooling and heating energy
- **R1586**: Cooling energy

As explained earlier, R0017 and R1586 as the most challenging buildings were further investigated for acquiring detailed information about the energy use at the thermal zone scale. The results showed that:

R0017 had:

- High cooling energy use in summer with the highest value reported for the zones facing North and even more for the NE zone;
- High heating energy use in all zones with the highest value reported for all peripheral zones.

R1586 had:

- High cooling energy consumption in summer for all zones and all floors with the highest value recorded for the zones facing North East in the top-floor.

7.3.7 Comparative energy analysis and heat balance calculations: R0017 and R1586 in Dunedin

As discussed in section 6.9.1.1.2, and with the need to evaluate the energy performance of the case study buildings in the two New Zealand climates, energy simulations were run for the two challenging case studies in the much colder climate of Dunedin. The results showed that as might be expected cooling energy declined while the heating energy increased (Figure 7-38).

For R0017 and R1586 in Dunedin, similar *EnergyPlus* output variables were used to calculate the heat balance parameters. As for the heat balance calculations in Auckland, the top of Figure 7-41 presents all the heat balance parameters except heating and cooling loads. In the pie charts at the bottom, parameters making a negligible contribution to the heat balance were removed to facilitate comparison.

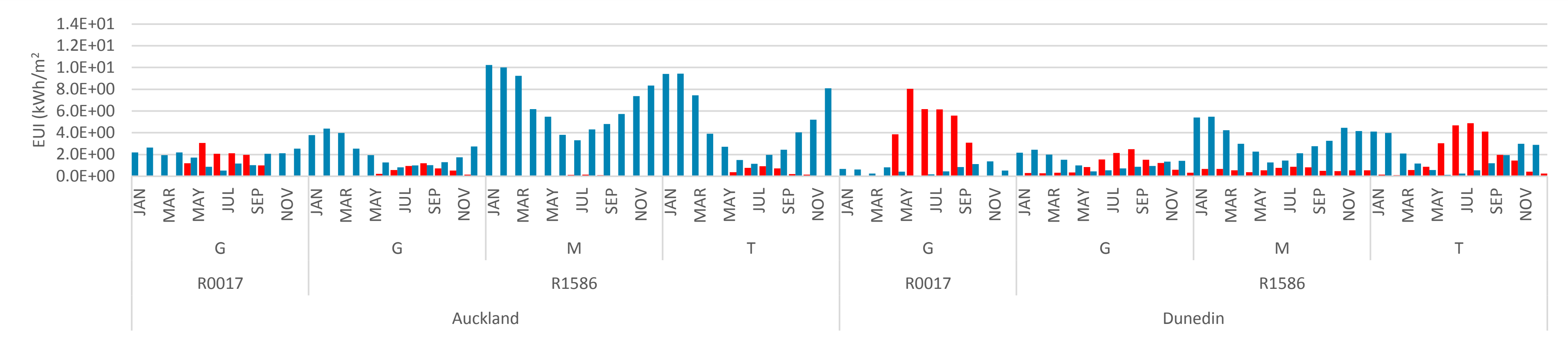


Figure 7-38 Heating and cooling energy use for individual floors, R0017, and R1586

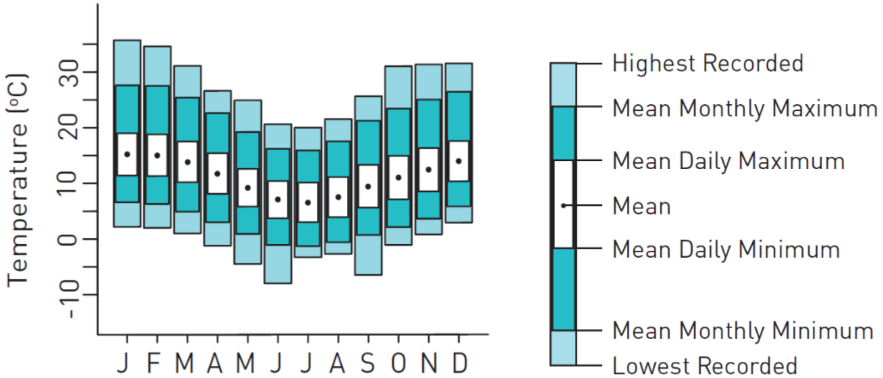


Figure 7-39 Monthly Variation in Air Temperature for Dunedin (Macara, 2015, p. 25)

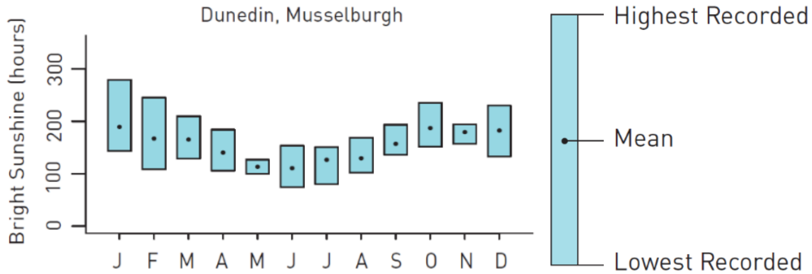


Figure 7-40 Monthly Bright Sunshine Hours for Dunedin (Macara, 2015, p. 31)

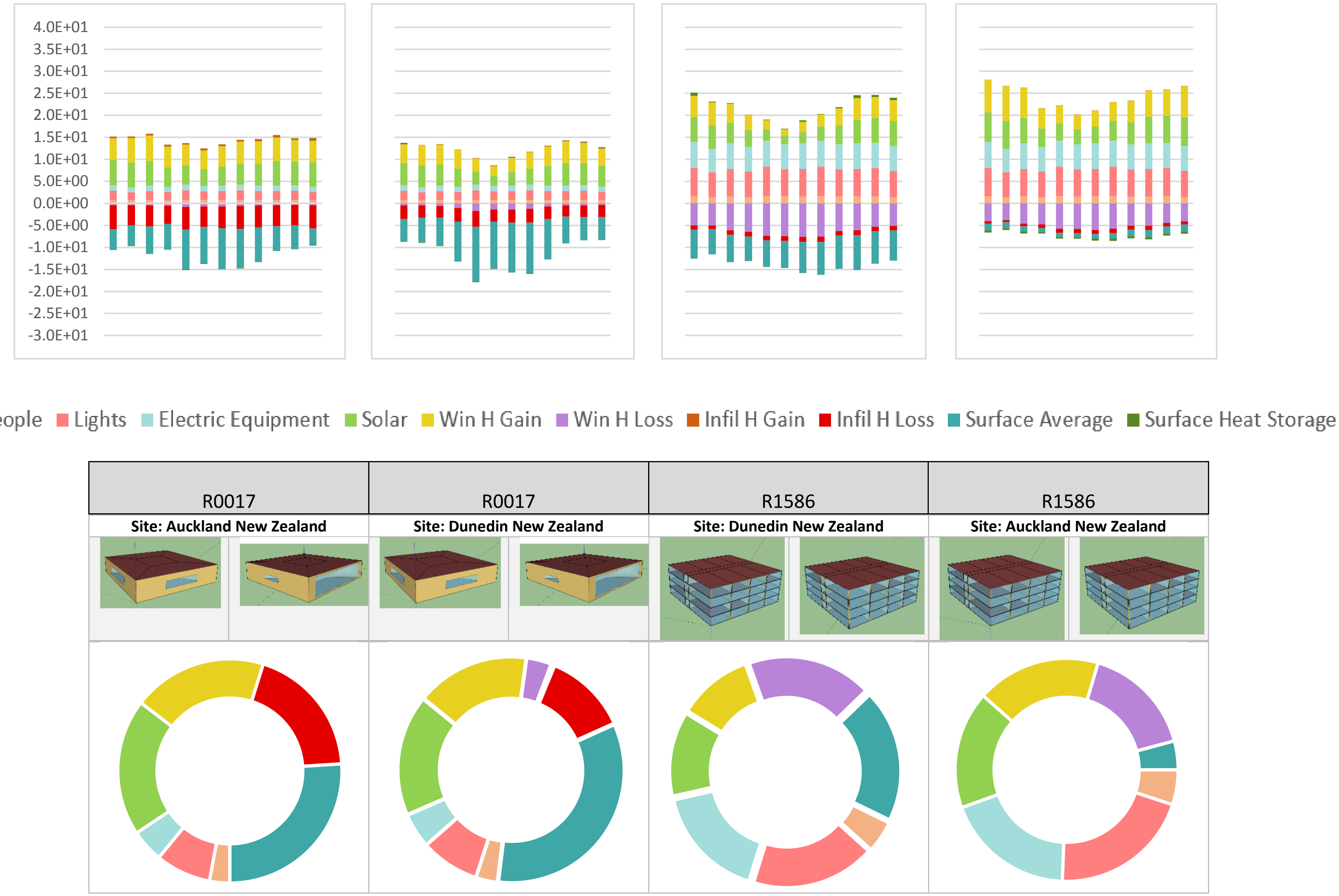


Figure 7-41 Top) Breakdown of space heat gain and heat loss, Bottom) the major space heat gains and heat losses

As can be seen in Figure 7-41, changing the site location of R1586 from Auckland to Dunedin did not influence the infiltration heat loss and heat gain significantly. In addition, the values of these two parameters were quite negligible compared to other patterns of heat flow. For example, the average heat transfer through opaque surfaces was higher in Dunedin. In both locations, the bar chart indicates the positive and negative values for window heat transfer. For Dunedin, the window heat loss was slightly more than that of Auckland, while as might be expected from the sunshine hours, window heat gains were lower than those of Auckland.

For R1586, heat loss through the building skin (windows and opaque surfaces) was greater in Dunedin than in Auckland because of the colder Dunedin climate (Figure 7-39 and Figure 7-40). As shown in Figure 7-41, in Auckland window heat gain was higher than in Dunedin. According to StatsNZ (2017), the average annual sunshine hours in Auckland are almost 24% more than those of Dunedin.

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Figure 7-42 Average annual sunshine hours Left) Auckland; Right) Dunedin

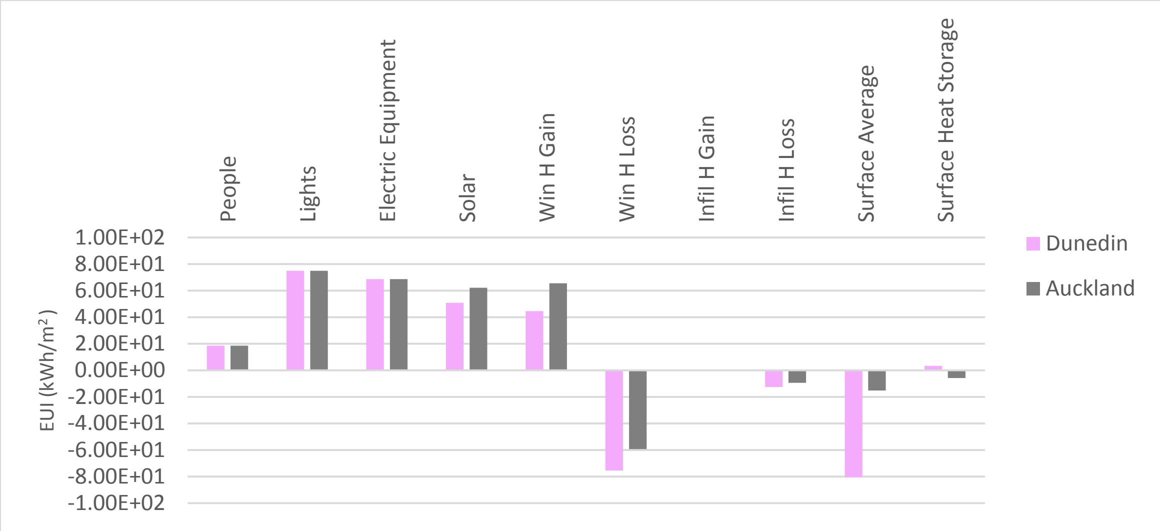


Figure 7-43 Heat balance parameters of the whole building for R1586 in Auckland and Dunedin

Figure 7-43 shows the heat balance parameters for R1586 in the two different climates. The heat flow data in Figure 7-43 are the same as those shown on the right-hand side of Figure 7-41. In Figure 7-43 the colour codes represent the climates while the heat balance parameters are shown with the same colour. This was done to facilitate comparison of the heat balance patterns of the same building in two climates.

Looking at Figure 7-43, the internal loads of R1586 in Auckland and Dunedin remained unchanged but there were changes in the cooling and heating energy patterns (Figure 7-50). This meant the thermal challenges in Dunedin were different from those in Auckland. The reason for the different thermal challenges was a subsequent change in the proportion of skin-loads (Figure 7-41).

The same analysis was carried out for R0017. As shown in the bar chart (Figure 7-50), the cooling energy was reduced and the heating energy increased. Looking at the heat balance reports, as shown in Figure 7-44, solar radiation and window conductive heat gain were both reduced in Dunedin. However, the infiltration heat loss through the windows decreased. This was in contradiction to the rest of the heat loss outputs as the opaque surfaces conductive and window heat loss both went up in the colder climate.

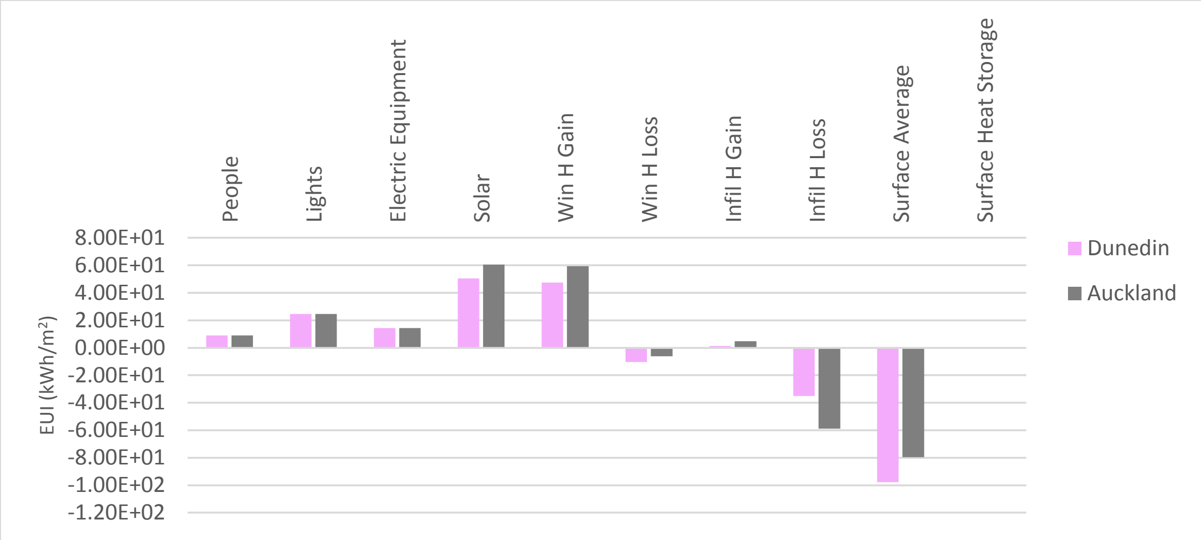
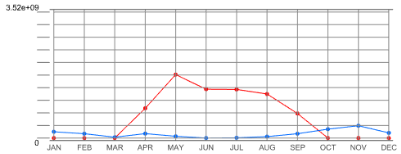
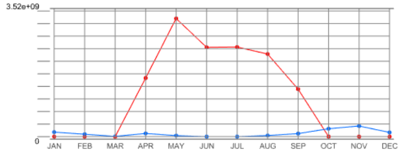


Figure 7-44 Heat balance parameters of the whole building for R0017 in Auckland and Dunedin

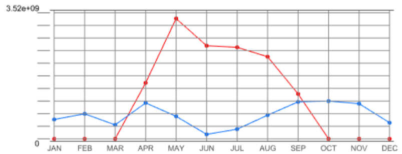
R0017 Site: Dunedin, New Zealand



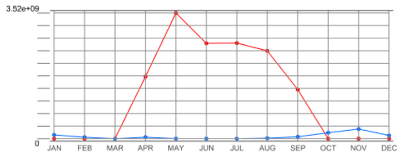
GCore



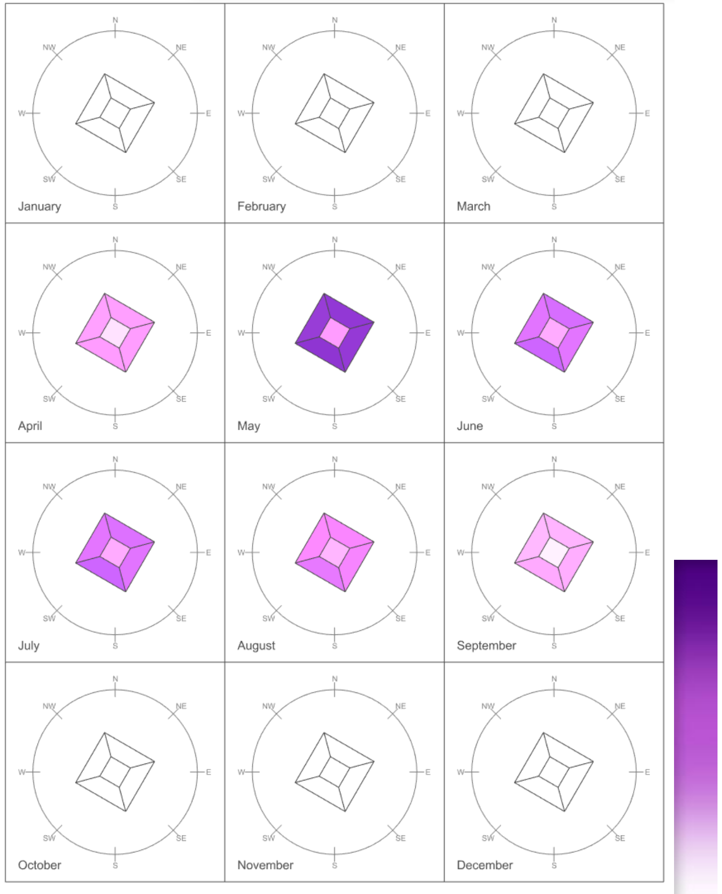
GEast

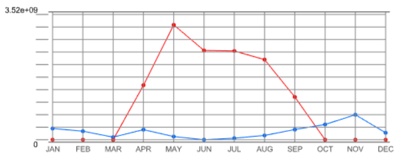


GNorth



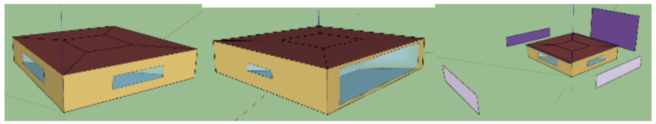
GSouth





GWest

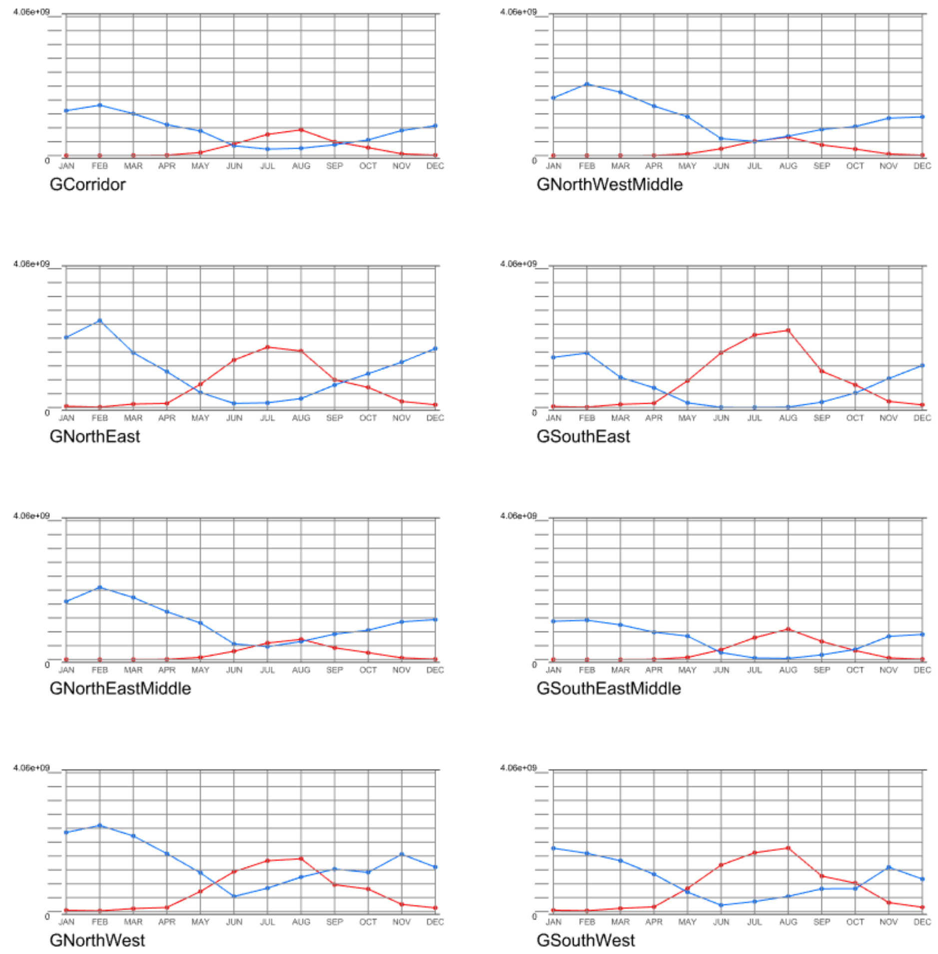
Zone Air System Sensible Heating Energy
Zone Air System Sensible Cooling Energy

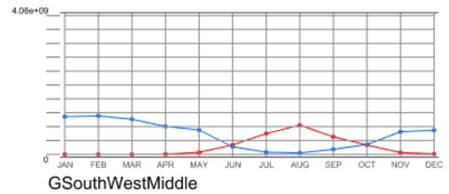


R0017- Site: Dunedin New Zealand
Zone Air System Sensible Heating Energy

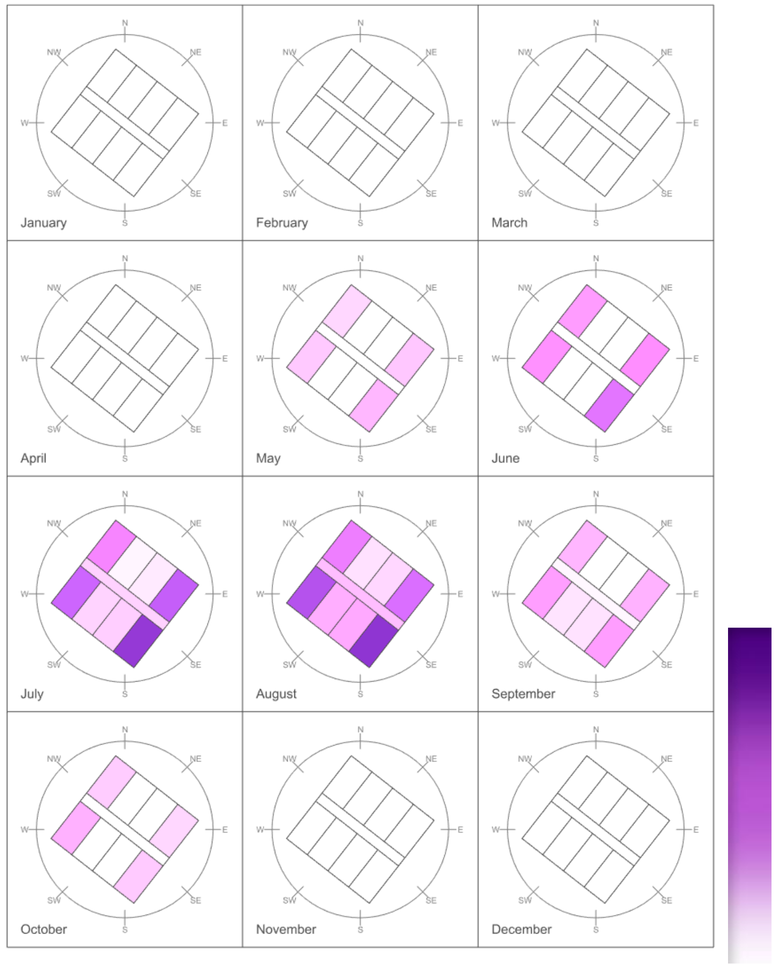
Figure 7-45 Heating energy use of each thermal zone on the ground floor for R0017- (kWh) Monthly

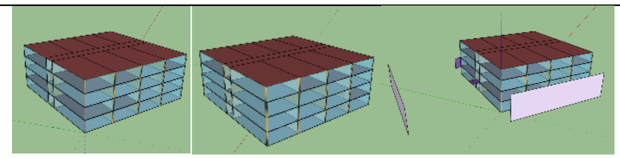
R1586 Site: Dunedin New Zealand



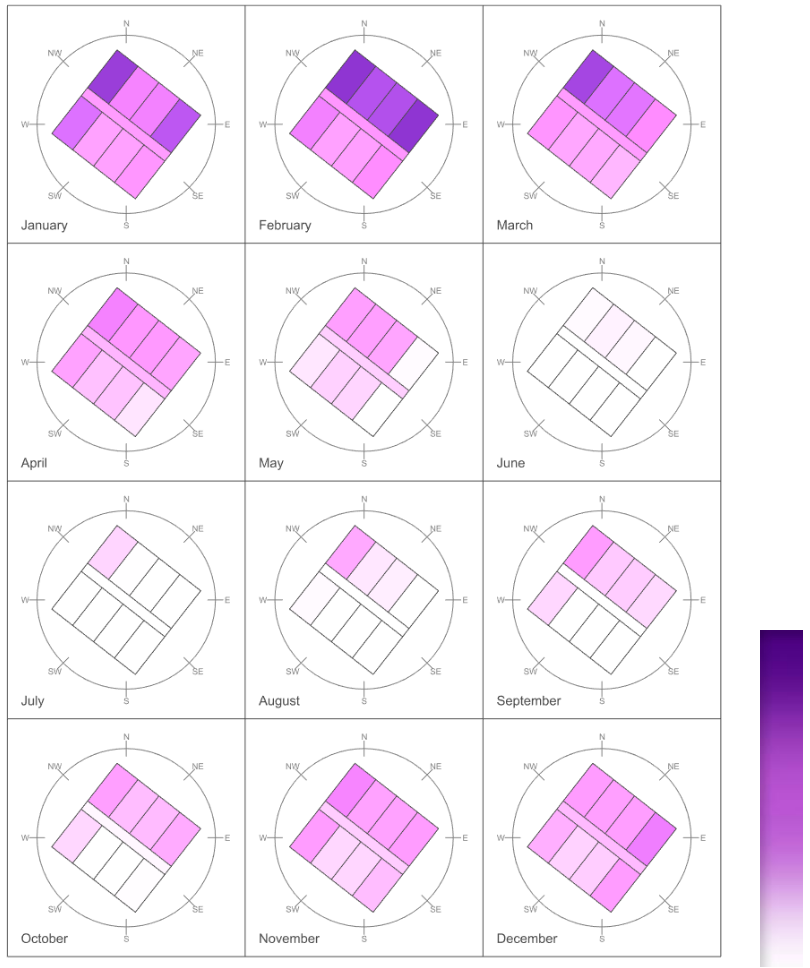


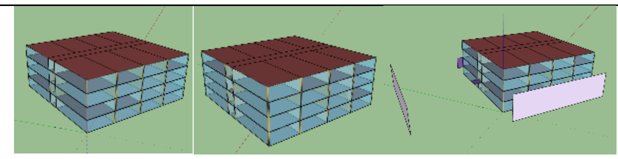
Zone Air System Sensible Heating Energy
Zone Air System Sensible Cooling Energy





R1586 - Site: Auckland New Zealand
Zone Air System Sensible Heating Energy

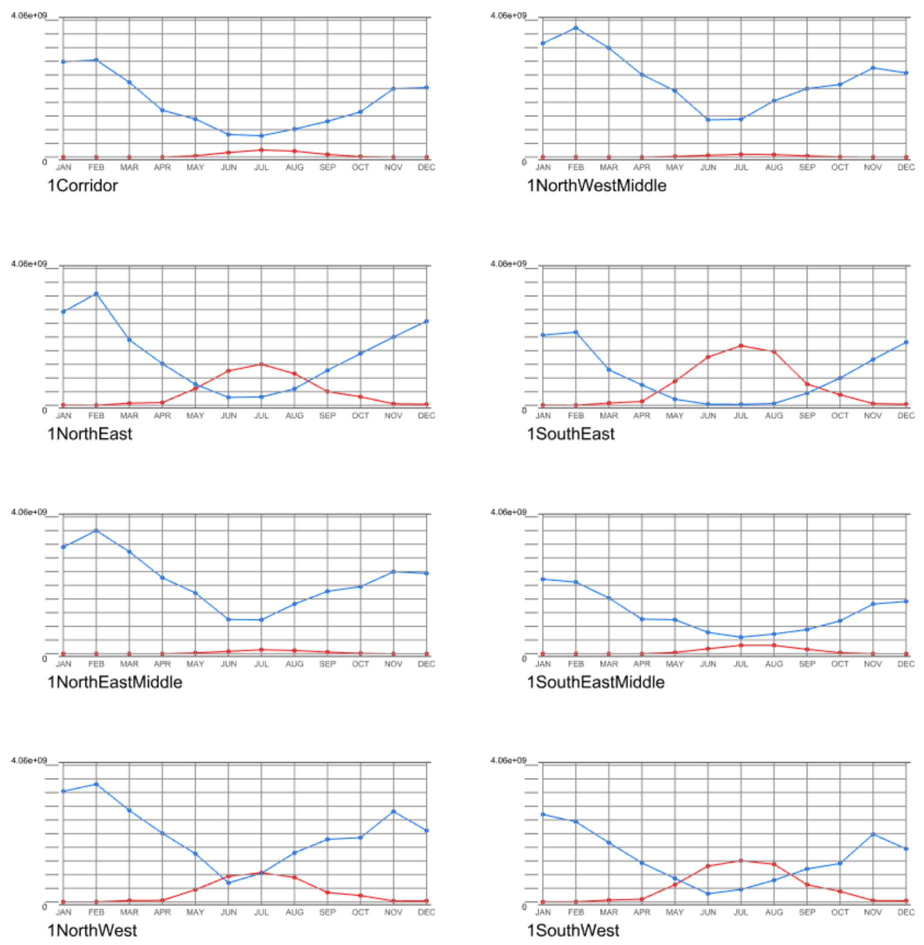


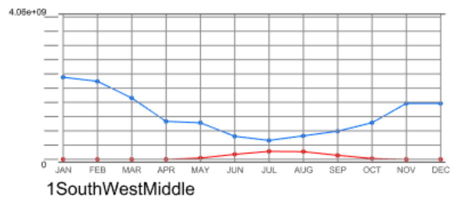


R1586 - Site: Auckland New Zealand
Zone Air System Sensible Cooling Energy

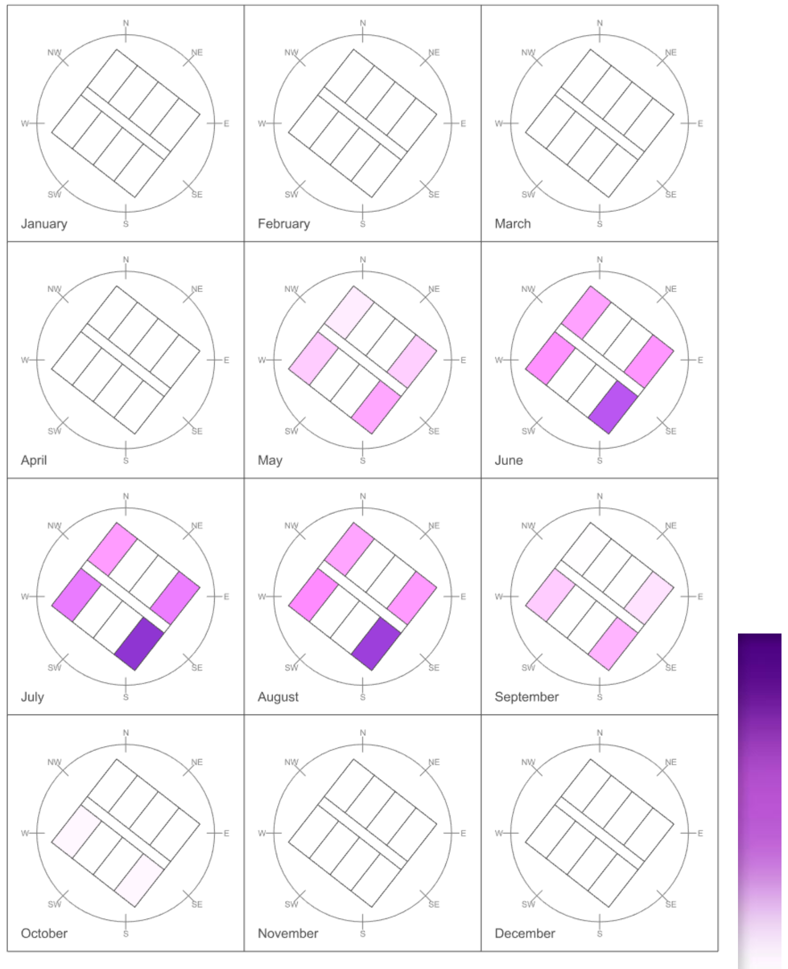
Figure 7-46 Heating and cooling energy use of each thermal zone on the ground floor for R1586 - (kWh) Monthly

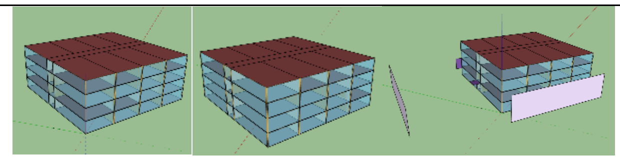
R1586 Site: Dunedin, New Zealand



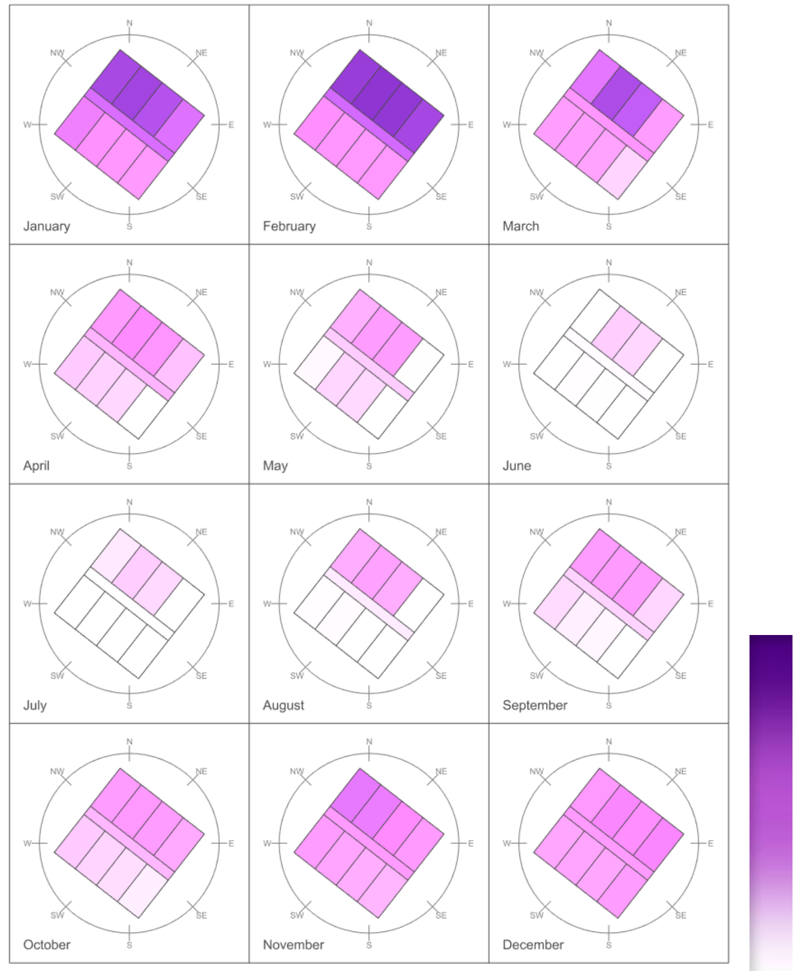


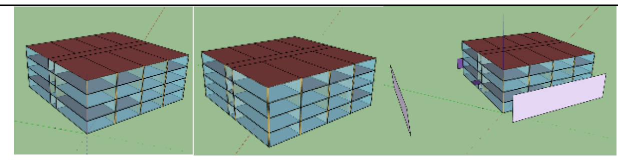
Zone Air System Sensible Heating Energy
Zone Air System Sensible Cooling Energy





R1586- Site: Auckland New Zealand
Zone Air System Sensible Heating Energy

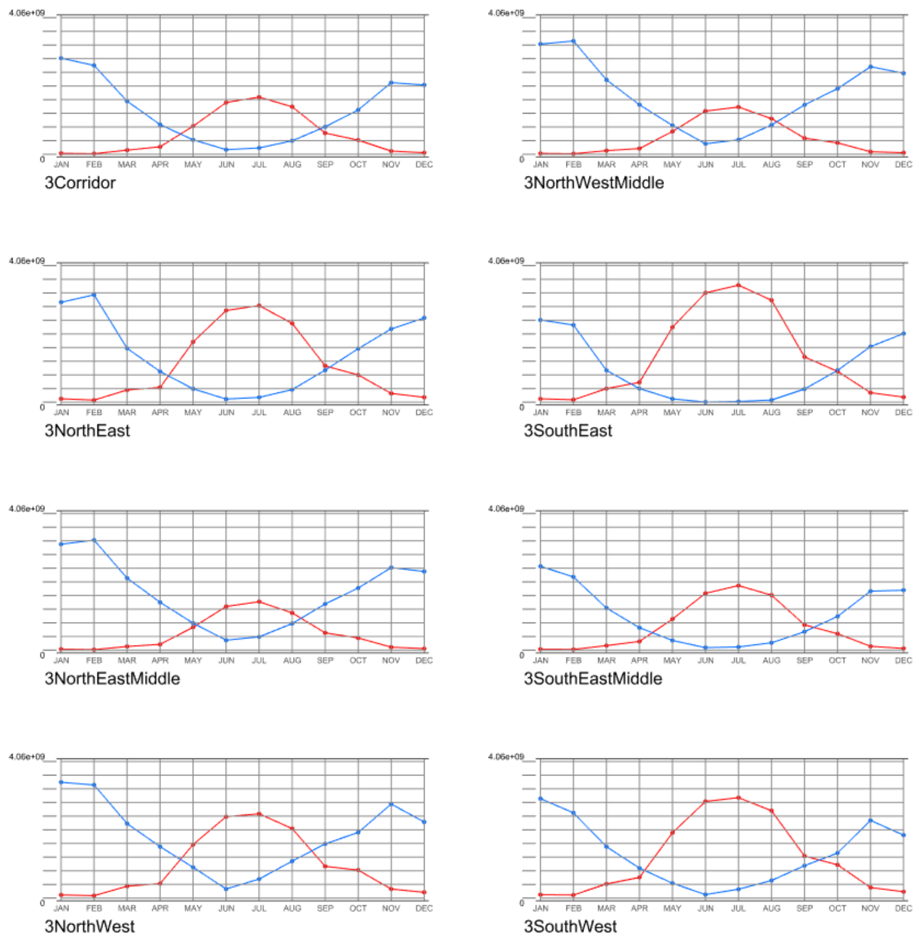


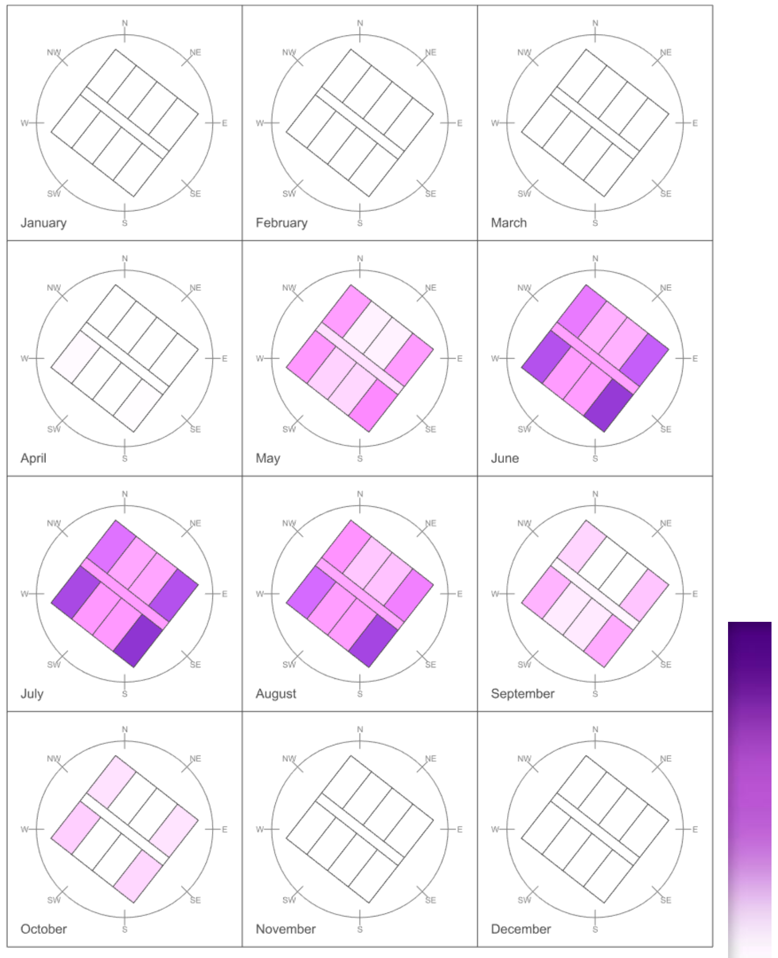


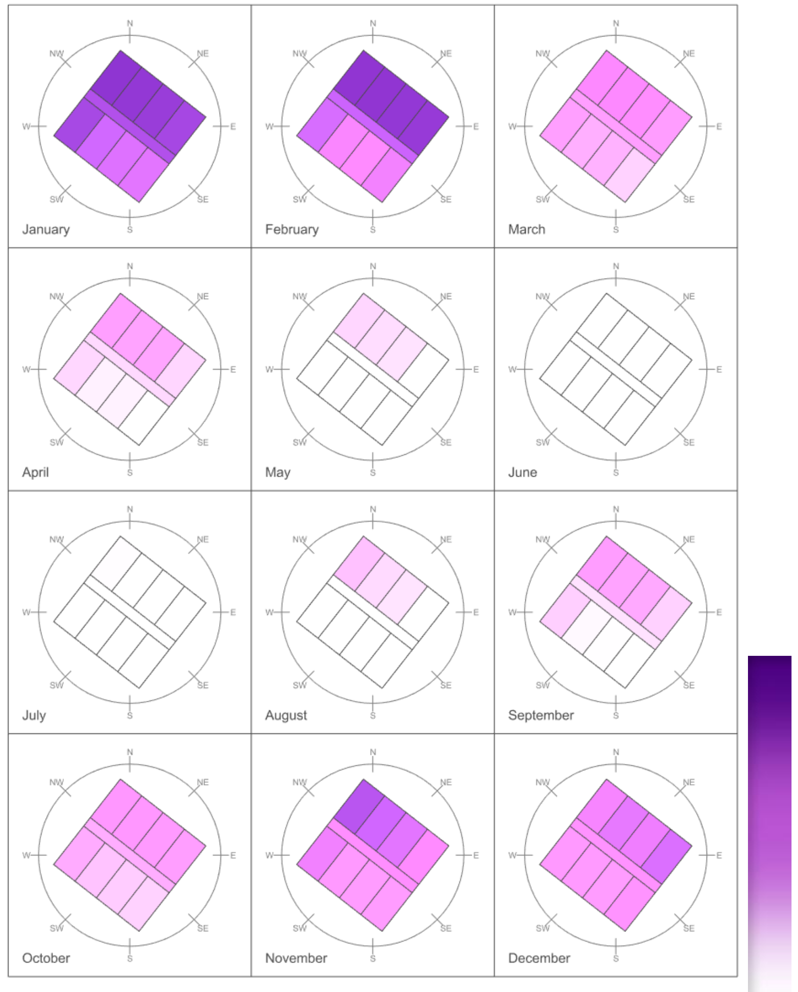
R1586- Site: Auckland New Zealand
Zone Air System Sensible Cooling Energy

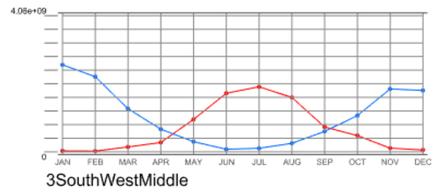
Figure 7-47 Heating and cooling energy use of each thermal zone on the mid floor for R1586 - (kWh) Monthly

R1586 Site: Dunedin, New Zealand

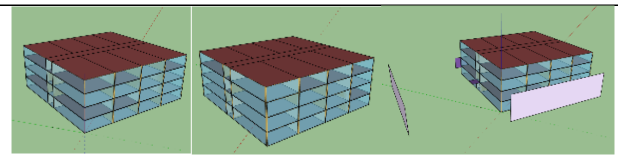




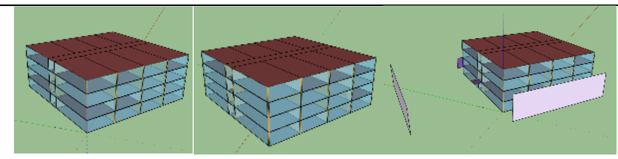




Zone Air System Sensible Heating Energy
Zone Air System Sensible Cooling Energy



R1586- Site: Auckland New Zealand
Zone Air System Sensible Heating Energy



R1586- Site: Auckland New Zealand
Zone Air System Sensible Cooling Energy

Figure 7-48 Heating and cooling energy use of each thermal zone on the top floor for R1586 - (kWh) Monthly

The energy reports generated for the thermal zones of R0017 in Dunedin indicated that the cooling energy use stayed at almost the same level in all zones except for the north zones, which showed a fluctuating upward trend (Figure 7-45). In addition, for all except the North zone, the overall cooling curve showed a relatively small energy use in winter followed by a slow rise during the summer. Similarly, the heating energy was almost constant in all zones apart from the core of the building, where there was a considerable fall in the heating energy consumption during the summer.

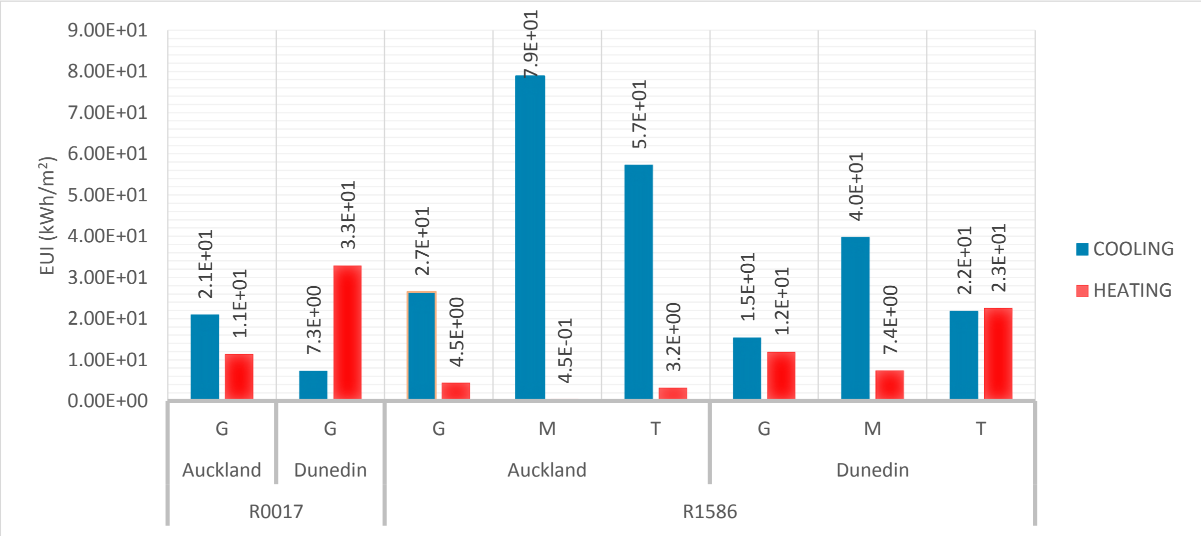


Figure 7-49 Heating and cooling energy use for individual floors in two different climates, R0017, and R1586

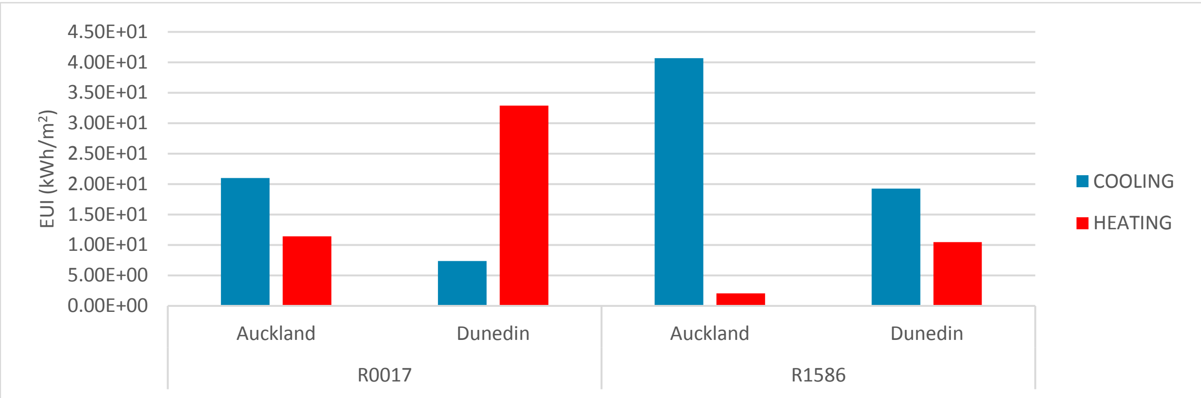


Figure 7-50 Heating and cooling energy use in two different climates, R0017, and R1586

For R1586 in Dunedin, cooling and heating curves had similar patterns for all floors with the highest values reported for the top floor (Figure 7-46, Figure 7-47 and Figure 7-48). For the heat balance parameters for R1586, more heat loss through the building skin and less heat gain from the windows appeared to influence the cooling energy use. The heating energy was also different in each floor with the lowest value for the average mid floor and the highest value for the top floor. Excluding solar heat gain, the rest of the heat flow parameters were the same for all floors as they shared the same internal loads specifications and envelope physical characteristics. The only reason for the difference in heating energy between floors was attributed to the conductive heat lost through the roof surface.

The thermal issues of the case studies in Dunedin were identified as set out below:

- **R0017**: Heating energy with the lowest value in the core zone
- **R1586**: Both cooling and heating energy

A deeper energy analysis at the thermal zone level showed that:

For R0017:

- High heating energy use in winter with the highest value reported for all peripheral zones

R1586:

- High cooling energy consumption in summer for all zones particularly those facing North East with the highest value recorded for zones on the top floor
- High heating energy consumption in winter for zones facing East and South on the ground and average mid floor and all zones on the top floor with the highest values recorded for the top floor zones facing East and West.

7.4 Discussion

From the results of the energy simulations conducted for R0017 and R1586, it seems that R0017 is a more suitable building typology for Auckland. R1586 consumes less energy in Dunedin and seems to be a better fit for this climate (**Error! Reference source not found.**).

Table 7-8 presents the thermal challenges and their location and duration for R0017 and R1586 in Auckland and Dunedin. The left-hand side of the table shows the items investigated for each case study. These were the thermal challenges in terms of cooling and/or heating, the season during which the thermal challenge(s) was identified, and the location and the name of the zones for which thermal challenge(s) were reported. The last two rows show the thermal zones and the month(s) within which cooling and heating energy use were significantly higher compared to the other challenging zones and months.

Table 7-9 shows the heat balance characteristics of each case study as derived from Figure 7-41. The characteristics of heat gains and heat losses will feed into Chapter 10 where the ThBA framework will be used for identifying relevant thermal adaptation solutions.

Table 7-8 Location and duration of thermal challenges

	R0017		R0017	R1586			R1586					
	Auckland		Dunedin	Auckland			Dunedin					
Thermal challenge	Cooling	Heating	Heating	Cooling			Cooling			Heating		
Season	Summer	Winter	Winter	Summer			Summer			Winter		
Floor	G	G	G	G	M	T	G	M	T	G	M	T
Zones	NE, NW	Peripheral Zones	Peripheral zones	All	All	All	All	All	All	SW,NW, NE,SE	SW,NW, NE,SE	All
Most challenging zones	NE					SW,NW, NE,SE	NE,SE, NEM, NWM	NE,SE, NEM, NWM	NE,SE, NEM, NWM	SE	SE	SW,NW, NE,SE
Month	Jan, Feb, Mar, Oct, Nov, Dec		Apr, May, Jun, Jul, Aug	Jan, Feb, Mar, Nov, Dec	Jan, Feb, Mar, Nov, Dec	Jan, Feb, Mar, Nov, Dec	Jan, Feb, Mar, Oct, Nov, Dec	Jan, Feb, Mar, Oct, Nov, Dec	Jan, Feb, Mar, Oct, Nov, Dec	Jun, Jul, Aug,	Jun, Jul, Aug	Jun, Jul, Aug,

Table 7-9 Heat balance characteristics

Auckland	**Dunedin**	**Auckland**	**Dunedin**
R0017	**R0017**	**R01586**	**R01586**
External heat gain	External heat gain	Internal heat gain and external heat gain	Internal heat gain and external heat gain
Conductive heat loss through opaque surfaces	Conductive heat loss through opaque surfaces	Conductive heat loss through windows	Conductive heat loss through opaque surfaces and windows
Infiltration heat loss through windows	Infiltration heat loss through windows		
Conductive and radiative heat gain from windows	Conductive and radiative heat gain from windows	Conductive and radiative heat gain from windows	Conductive and radiative heat gain from windows

7.5 Chapter summary

This chapter first explained the decision-making approach taken for selecting the case studies. As shown in Table 7-2, a series of criteria were used to determine the most appropriate building energy models. This was followed by a validation stage. A new version of *EnergyPlus* was used for energy simulation and the simulation results were compared to the real data as well as the previously generated calibrated energy models (Cory, 2016).

Different stages of energy simulation were performed to identify the thermal issues in the selected case studies. The simulations also gave the major energy end-use break down for the buildings with the results reported on a monthly and annual basis. In addition, for all case studies the values associated with the heat gain and heat loss quantities in internal spaces (heat balance diagrams) were generated. The heat balance reports revealed the two most thermally challenging case studies that were subsequently tested in the colder Dunedin climate. The 'thermal zone scale' energy analysis revealed the energy efficiency of thermal zones in terms of heating and cooling energy use. The reported simulation results were also normalised to facilitate comparison of building thermal performance despite differing geometrical features and physical properties.

This chapter has given an account of the energy simulation steps required for identifying the thermal issues of the two most challenging case studies in two different climate zones in New Zealand. The thermal issues were summarised in Table 7-8 and will be fed into Chapter 10 where these thermal challenges will be used as inputs to the ThBA framework.

8 Creating Version 01 of the ThBA

8.1 Introduction

Developing the ThBA required studying biology to find how to classify and generalise the thermal regulation strategies used by living organisms. The method of data collection used as the basis of the ThBA was to investigate the relevant literature in biology in order to extract the principles. This means there is some small repetition with chapter 4 but it seems vital to show how the data was collected in a step by step process.

In order to determine the structure of the ThBA, the first step was to study the thermal physiology of heat regulation to help create a foundation for categorising thermal adaptation strategies. At this stage it was recognised that it might be necessary to go through a number of iterations in the ThBA this chapter describes the first version (Version 01).

An important part of the data collection was to use the original glossary of thermal physiology prepared by James Mercer (IUPS Thermal Commission, 1987). The IUPS stands for the International Union of Physiological Sciences. The Original glossary was then modified following numerous comments from experts during the developmental consultation process. Currently, Version 3 which was used in this thesis contains 479 terms which are also described. To reduce misinterpretation, this research uses the many terms on which the experts have agreed. These terms and their definitions are quoted in full and are used to explain the different aspects of thermal adaptation mechanisms. To avoid unnecessary repetition a reference is given for the first quote only but applies to the following quotes without a reference.

Accepting it is possible to develop the ThBA there is the need to validate it. This will be done through a qualitative study using a focus group of expert biologists (Chapter 9). If their assessment of the ThBA is that it is useful for mining relevant biological principles of thermal adaptation, the thermal challenges of the two case study office buildings identified in section 7.4, will be used as input to the ThBA, with the aim of systematically connecting them to relevant thermal adaptation strategies and examples (Chapter 10).

8.2 Climate change and the need for adaptation

Climate change has been recognised as one of the factors that leads to extinction (Ripple et al., 2015). McCain and King (2014) state one of the reasons for the vulnerability of large mammals to extinction might be their inability to seek for and find thermal refuges. A number of studies have been conducted on the thermal effects of climate change on large mammals (Rondinini & Visconti, 2015; Brodie, 2016; Pacifici et al., 2017), including the different methods of heat exchange between mammals and their environment. This has been used for developing predictive modelling of the responses of mammals to climate change. The aim has been to see how large mammals respond to climate change by adjusting body temperature and other thermoregulatory variables (Mitchell et al., 2018).

8.2.1 Different methods of heat transfer in nature

Before coming to the development of the ThBA a general discussion of heat transfer in nature seems relevant. In general, dry heat exchange or sensible heat transfer (Bakken, 1976) is made up of three different methods of heat transfer—conductive, convective, and radiative. The overall thermal conductance of the body of an animal, the metabolic heat production, and evaporative cooling are also necessary for a full analysis of the energy budget.

The rate and direction at which heat transfers through conduction is dependent on the temperature difference between an animal's body and the surface with which it is in contact. Some species of large mammals use a specific behaviour to manipulate temperature difference to the extent that it involves conductive heat transfer. For example, *Chacma* baboons (*Papio Hamadryas Ursinus*) who live in the Namib Desert do this by sand bathing (Brain & Mitchell, 1999). This reduces their body temperature by facilitating conductive heat transfer to the cooler sand beneath the surface.

While conductive temperature is linked to the body temperature of animals, convective heat transfer is associated with the air temperature of the microclimate and thus the surrounding air where the animals live (Huey et al., 2012; Varner & Dearing, 2014; Pincebourde et al., 2016). Conductive heat exchange is 'forced' wherever the wind blows and is 'free' when there is no wind. The high-speed movement of an animal will force convective heat transfer but at the same time heat is generated by the muscular activity, so a balance needs to be achieved.

Although conductive and convective heat transfer occurs, radiant heat transfer has been recognised as the most significant method of heat exchange in large mammals (Mitchell et al., 2018). This is why, Mole et al. (2016) state large mammals seek shade, and change their posture or orientation (Maloney et al., 2005) so as to adjust the amount of heat they receive through radiation.

8.3 Approach to developing the ThBA Version 01

Given that no hierarchical classification of thermal regulatory strategies had been found in the literature review, in order to determine the hierarchical structure of the ThBA, the first step was to study the thermal physiology of heat regulation to help create a foundation for categorisation of thermal adaptation strategies. This was then reinforced by understanding the meanings of ectothermy and endothermy (see 8.4). This then informed the classification of thermal adaptation mechanisms into behavioural and autonomic mechanisms (starting from 8.4.1). The proposed structure of the ThBA is the outcome of the literature review conducted for this research.

The categorisation of biological thermal adaptation strategies was then used as a means of seeking analogies in architecture. Accordingly, for each mechanism, parallels in energy efficient building design were introduced to be used for the architectural side of the ThBA (see 8.5). Because of this flow of work the following sub-sections deal with thermal regulation strategies found in biology and only later are the architectural analogies introduced.

8.3.1 Thermal physiology

Thermal physiology concerns the laws around the regulation of heat (Blatteis, 1998, p. 3).

8.3.1.1 Adaptation

Acclimation: *"Physiological or behavioural changes occurring within an organism, which reduce the strain or enhance endurance of strain caused by experimentally induced stressful changes in particular climatic factors"* (IUPS Thermal Commission, 1987).

Acclimatisation: *"Physiological or behavioural changes occurring within the lifetime of an organism that reduce the strain caused by stressful changes in the natural climate (e.g., seasonal or geographical)."* These two adaptation processes are compared in Table 8-1.

Table 8-1 Acclimation and acclimatisation of organisms

	Type	Period	Climate scale
Acclimation	Physiological or behavioural	Within an organism (genotypic)	Particular climate factors
Acclimatisation	Physiological or behavioural	Within the lifetime of an organism (phenotypic)	Natural climate

Adaptation: *"Changes that reduce the physiological strain produced by stressful components of the total environment. This change may occur within the lifetime of an organism (phenotypic) or be the result of genetic selection in a species or subspecies (genotypic)."* (IUPS Thermal Commission, 1987)

8.3.1.2 Timeframes in adaptation

Another important aspect of adaptation is the time interval. The International Union of Physiological Sciences (IUPS) has the following terms for time frames.

> ***Crepuscular***: *"Occurring daily during the phases of twilight."*
>
> ***Nychthemeral***: *"Relating to a variation that occurs in an exact period of 24 hours."* (IUPS Thermal Commission, 1987)

8.3.1.3 Thermal regulation: adaptation to temperature

Body heat balance is a state in which total heat gain is equal to heat loss and homeostasis has been described as a "*...general term characterizing the relative constancy of physico-chemical properties of the internal environment of an organism as being maintained by regulation*" (IUPS Thermal Commission, 1987). Any deviations from heat balance need to be regulated through changes in the body of an animal.

Compared to circulation and respiration, thermoregulation is not an easily recognisable system as many systems integrate to keep the body temperature stable. In other words, thermoregulation involves multiple systems and sub-systems and as a physiological function is based on the integration of a number of processes.

There are different ways of classifying thermal regulation mechanisms. Some, as suggested by IUPS, are obsolete and have been replaced by new classification terms. The list below introduces both new and obsolete terms so as to cover every aspect from which autonomic (physiological) and behavioural thermoregulation, as the most appropriate in terms of clarity of categorisation for explaining thermal adaptation strategies, are selected for this research.

Temperature regulation, autonomic (new): *"The regulation of body temperature by autonomic (i.e., involuntary) thermoeffector responses to heat and cold which modify the rates of heat production and heat loss (i.e., by sweating, thermal tachypnea (raised breathing rate), shivering, non-shivering thermogenesis, and adjustments of circulatory convection of heat to the surfaces of the body."*

Temperature regulation, behavioural (new)**:** *"Any coordinated movement of an organism ultimately tending to establish a thermal environment that represents a preferred condition for heat exchange (heat gain, heat loss, or heat balance) of the organism with its environment."*

According to IUPS, thermotropism, where an organism like a plant bends towards a heat source, cannot be recognised as a behavioural thermoregulation as the latter is limited to specific behavioural patterns that are controlled by a nervous system. For example, the movement of some aquatic unicellular organisms towards a thermally comfortable environment has not been confirmed as a thermoregulatory behaviour or thermotropism.

Temperature regulation, chemical (obsolete): "*Body temperature regulation involving changes in heat production.*"

As suggested by IUPS, chemical thermoregulation can be achieved by four different mechanisms: 1) voluntary muscle movements; 2) involuntary muscle movements (e.g., shivering); 3) Non-shivering thermogenesis (heat production not through muscle movement); and 4) increase or decrease in basal metabolic rate.

Temperature regulation, physical (obsolete): *"Body temperature regulation involving control of the rate of heat flow into or out of an organism."*

As described by IUPS, physical thermoregulation consists of specific types of autonomic and behavioural responses by which the thermal conductance of peripheral tissues changes. Physical thermoregulation does not involve those types of behavioural responses that lead to alteration of the local environment. Examples of physical thermoregulation are:

1) Changes in peripheral vasomotor tone (affects how fast blood can be pushed through);

2) Piloerection (hairs standing on end);

3) Evaporation of water from skin by either sweating, saliva spreading, or wallowing and from respiratory tract surfaces; and

4) Changes in body conformation.

8.3.1.4 Feedback loop control

The backbone of homeostasis (the ability to maintain equilibrium) is the negative-feedback loop. This enables organisms to respond to environmental stressors in order to stabilize a changing variable. In a system, the comparator compares the received signal (variable value) with a pre-set set point and will run the process of adjustment until the received signal reaches the set point. In a homeostasis thermal balance mechanism, a sensor is responsible for monitoring variables (Waterhouse, 2013). Responses to thermal stressors can be either physiological and behavioural and have been considered as reflexes (Woods & Ramsay, 2007).

Figure 8-1 illustrates the principles of physiological feedback control in a simple and complex feedback system. Relatively the more complex system is associated with autonomic thermal regulation in which the set points detect thermal mismatches.

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Figure 8-1 Principles of feedback control in a simple and complex feedback system adapted from Willmer et al. (2009, p. 34)

8.3.1.5 Different types of thermoregulatory states in nature

The list below presents the terms verified by IUPS to explain the different levels of deep body temperature.

1) ***Normothermy*** (also known as cenothermy and euthermy) (temperature maintained within normal limits)
2) **Hyperthermia**: "The condition of a temperature regulator when core temperature is above its range specified for the normal active state of the species."
3) **Hypothermia**: "The condition of a temperature regulator when core temperature is below its range specified for the normal active state of the species."
4) **Cryothermy**: "The thermal status of a super cooled organism (i.e., with the temperature of the body mass is below the freezing point of the tissue)."

8.3.1.6 Homeothermy and poikilothermy

Considering the characteristics, limitations, and scope of responses of organisms to cold and heat stresses, IUPS has confirmed the classification of biological organisms into the following. Animals can be divided into the two categories of homeotherms—constant body temperature—and poikilotherms—variable body temperature. The two parameters that determine the body temperature are heat gain and heat loss.

> ***Homeothermy*** (Synonym: homoiothermy): *"The pattern of temperature regulation in a tachymetabolic species in which the cyclic variation in core temperature, either nychthemerally or seasonally, is maintained within arbitrarily defined limits despite much larger variations in ambient temperature, i.e., homeotherms regulate their body temperature within a narrow range."*
>
> ***Heterothermy****: "The pattern of temperature regulation in a tachymetabolic species in which the variation in core temperature, either nychthemerally or seasonally, exceeds that which defines homeothermy."*
>
> ***Heterothermy****, local: "The pattern of temperature in those parts of the body which comprise the thermal shell of homeotherms."*
>
> ***Poikilothermy****: "Large variability of body temperature as a function of ambient temperature in organisms without effective autonomic temperature regulation. As a rule, bradymetabolism implies poikilothermy with only temporary exceptions in some species (e.g., active warming-up of insects before flight)."*

8.3.1.6.1 Heat and cold tolerance

Animals can also be categorised according to the range of temperature they can tolerate. IUPS identifies the two following groups.

> ***Eurythermy***: *"The tolerance by organisms of a wide range of environmental temperatures, or the accommodation to substantial changes in the thermal environment."*
>
> ***Stenothermy***: *"Descriptive of organisms, which occur naturally in a narrow range of environmental temperatures and which, singly or collectively, are intolerant of or accommodate ineffectually to wide changes in their thermal environment."*

In another classification system, thermal adaptation mechanisms and the relative responses to thermal stresses can be approached by avoiding, conforming to, or regulating these (Figure 8-2).

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Figure 8-2 Levels at which adaptive responses can occur (Willmer et al., 2009, p. 13)

Willmer et al. (2009, p. 13) explain the three thermal adaptations in Figure 8-2 as follows.

Avoiding thermal stress: this is assigned to those mechanisms animals use to get away from the environment in which they are under thermal stress through avoiding the space (e.g. seeking microhabitats like burrows, or by migration) or avoidance by not doing normal activities (e.g. torpor, Section 8.4.1.1.3.3) (Willmer et al., 2009, p. 13).

Conforming thermal stress: the mechanisms whereby animals undergo changes in their physiological and biochemical levels. Using these mechanisms animals can function though at a very low level. In other words, conforming adaptation mechanisms do not involve huge physiological and biochemical changes but rather are used to avoid the potential damaging effects of freezing. According to IUPS, thermotolerance or heat shock response (HSR) is a short and rapid action at the molecular level for the purpose of protecting cells and enabling survival for several hours in such a way so that the animal can retain its activity.

Regulating thermal stress: comparatively, thermal regulation requires significant changes in a hierarchy and as a combination of both behaviours (e.g. basking, burrowing, huddling, erecting or concealing appendages) and substantial physiological and chemical transformations.

The regulation of thermal stresses is also described as thermal tolerance.

Cold tolerance (cold endurance): *"The ability to tolerate low ambient temperatures. This term comprises a variety of physiological properties."* According to IUPS, certain homeotherms have been identified as cold tolerant. They are capable of balancing their body temperature where the ambient temperature is low. The relevant mechanisms they use for thermal regulation are either insulation or efficient metabolic heat production. In addition to these, they are able to protect appendages from freezing. Thermal tolerance in this case, can be achieved through either vascular control of local heterothermy (protecting appendages from freezing) or general heterothermy like hibernation. Poikilotherms are also recognised as cold tolerant if they can survive low and subfreezing body temperatures (formation of ice-crystal in the state of cryothermy).

Heat tolerance (heat endurance)*:* "The ability to tolerate high ambient temperatures. This term comprises a variety of physiological characteristics." Homeotherms are often characterized as heat tolerant. They are capable of balancing heat gain and heat loss where the ambient temperature is high. Homeotherms can also be recognised as heat tolerant species if they can function normally even when their body temperature exceeds their normal range. Selective brain cooling is one of the mechanisms that makes this survival possible.

8.4 Passive and active methods of thermal adaptation

The division between ectotherms and endotherms cannot be done by merely considering variable or constant body temperatures as a number of ectotherms are capable of generating internal heat. This type of heat generation usually takes place through muscular thermogenesis (Davenport, 2012, p. 5). Another categorisation scheme divides animals based on the pattern of temperature regulation with a focus on the source of heat on which they are dependent.

The skin of ectotherms (commonly called cold-blooded animals) is usually bare hence their body temperature tends to closely follow that of their immediate environment. In contrast, the body temperature of endotherms (commonly known as warm-blooded) might not be the same as the surrounding air temperature as they maintain a near constant body temperature.

Ectotherms do not generally generate heat and accordingly, face thermal challenges as they have a very low metabolic rate and do not have physiological mechanisms to conserve heat. Endotherms use metabolic energy to keep a stable internal body temperature. Endotherms are also capable of adjusting their peripheral blood flow to conserve or dissipate body heat by reducing and increasing the blood flow respectively. Other thermoregulatory mechanisms concern water evaporation from a wet surface. The evaporation takes place if the skin of the animal gets wet either by sweating or spreading saliva (a habit of kangaroos)(Needham et al., 1974). However, this evaporative cooling cannot be used continuously by endotherms as the water from their body has to be replaced, and this is especially crtical for small emdotherms (Albright et al., 2017).

Control of heat exchange also occurs through physiological responses or physiological adaptation mechanisms. Physiological adaptation mechanisms involve strategies in which animals use either their body structures or physiological mechanisms to cope with thermal stresses. These can be classified as:

1) Circulatory mechanisms, such as altering blood flow patterns
2) Insulation, such as fur, fat, or feathers
3) Evaporative mechanisms, such as panting and sweating

Circulatory mechanisms can also be categorised into

1) Vasoconstriction and vasodilation and
2) Countercurrent heat exchange.

In both the flow of blood is a means for controlling heat gain and heat loss. The former occurs when the blood vessels near the skin surface become narrower or expand respectively. Terrestrial animals also use evaporative cooling to lose water from their mouth, skin, or nose.

In terms of behavioural adaptation mechanisms, there is a major difference between terrestrial and aquatic animals as the mediums by which they are surrounded have different heat transfer coefficients. The air surrounding land-based animals has low thermal conductivity while water permits rapid heat transfer. Relatively, terrestrial animals exploit their environment in order to adjust heat transfer as the environment suggests. Davenport (2012) states the behavioural adaptation mechanisms used by terrestrial animals to control body temperature (controlling heat gain and heat loss) can be categorised into the four groups of basking, posture, orientation, and locomotion. He states animals use specific behaviours to prevent or produce heat. These behavioural means for producing heat can be categorised as clustering and huddling. Some behaviours are used to avoid thermal stresses such as shading, migration, and burrowing. Increased heat loss is behaviourally achieved by evaporative cooling (Davenport, 2012, pp. 7-26).

Thermal adaptation strategies can be seen as active thermoregulation when they are used for generating heat by physiological changes in the body, while thermal adaptation mechanisms are referred to as passive strategies when the heat source is out of the body of an animal. This might have the potential to be developed as a parallel in buildings as a building can adapt to its environment through both passive and active design strategies.

8.4.1 Biological behavioural mechanisms for thermal adaptation

8.4.1.1 Controlling heat

This section covers how heat gains and losses are controlled in the natural world.

8.4.1.1.1 Generating heat

Huddling, clustering, and nesting or nest sharing are used to generate heat. Huddling is more widespread in endotherms (C. R. Brown & Foster, 1992; Arends et al., 1995). The geometric variations and population of clusters affect thermoregulatory heat generation. For example, in small mammals, the proportion of the exposed area to the volume of the animal impacts the efficiency of the huddle in terms of heat generation (Canals et al., 1989). Male emperor penguins join a huddle in order to generate heat and around 5,000 penguins (approximately 10 per square metre) move slowly downwind and leeward. Once they stop steam can be seen arising from the huddle (Thomas & Fogg, 2008, p. 13).

Bees also swarm into a dense cluster to maintain their body temperature within a normal range (Seeley, 2010). They change the porosity of the swarm cluster as a means of controlling the temperature of its centre. Different arrangements of bees in a cluster, as a porous mobile medium between the core and the environment, affect the thermoregulation. Ocko and Mahadevan (2014) have studied the conductivity and permeability of bee clusters by measuring the packing fraction and ambient air temperature. Bees also use clusters in the hive as a response to changing air temperatures.

Species that have not developed fur for insulation employ nest sharing as a strategy for surviving cold climates (Crawford, 2013, p. 123), and it is an important strategy for small mammals. A group of small mammals living together in a nest known as nest sharing are similar to huddling animals, where the decrease in the exposed body surface of the animals reduces heat loss (Vaughan et al., 2013, p. 441). This has been identified as an energy-saving behaviour.

8.4.1.1.2 Controlling heat gain

8.4.1.1.2.1 Stealing heat (Kelptothermy)

As stated by Brischoux et al. (2009), kleptothermy is an unusual thermoregulatory strategy used by both endotherms and ectotherms in which an animal steals heat from others to keep its body warm. For example, some species of snakes share their burrow with seabirds in order to raise their body temperature. The heat is transferred through either direct contact of their bodies or via the air as an intermediary vehicle. The latter is a convective heat transfer method in which the heat is produced by respiration and metabolism of the *donor* organism (the seabird) occupying the same space.

8.4.1.1.2.2 Increasing and decreasing heat gain

a) ***Nest building:*** In the context of some nest building such as red wood ants, the parameters affecting nest thermoregulation are population size, moisture, and the thermal conductivity of the nest materials (Kadochová & Frouz, 2014). Other nests show different patterns of heat control (Section 8.4.1.1.3.2).

As explained by Lane and Skaer (1980, pp. 155-184), the orientation of termite and ant nests is an influential factor in moderating the nest temperature. Even the shape of the nest affects thermoregulation. For example, fire ants build an oval-shaped nest with the majority of the long axes extending from south to north. In some species, the alignment of the nest slope to the sun's rays facilitates maximum solar heat absorption. The orientation of the nest entrance also affects the range of temperatures inside it.

b) ***Orientation:*** Some animals use orientation as a strategy to control heat gain. This makes animals capable of conserving their body temperature by altering their body orientation either to minimize or maximise exposure to sunshine (Kevan & Shorthouse, 1970; Penacchio et al., 2015).

c) Movement

- ***Shuttling:*** Another thermoregulatory strategy is a type of rapid movement known as shuttling. Using this method a desert lizard called *Uromastyx aegyptia microlepis* behaviourally regulates its body temperature by rapidly moving between sun and shade and so between cold and hot microenvironments (Withers & Campbell, 1985).
- ***Moving along a thermal gradient:*** Brattstrom (1979) notes semi-aquatic amphibians do not have prominent behavioural thermoregulation and this is because they are restricted to aquatic habitats. To control heat gain they move to a warm or cool area of their watery habitat, however, the oxygen might diminish in these areas and this affects the species which are partly dependent on cutaneous respiration, so a balancing act is required. This strategy has been also called predictive thermoregulation when referring to the predictable characteristics of natural habitats (Davenport, 2012, p. 55).

8.4.1.1.2.3 Decreasing heat gain

a) Movement

- ***Sidewinding:*** Some species show specific behaviour in their movement. For example, snakes do 'sidewinding' as a way of enabling them to move rapidly over hot surfaces. This type of movement minimises both the duration and the area of surface contact
- ***Climbing:*** Several lizards also climb to avoid heat uptake and increase heat loss by evaporative cooling. Snails have also been reported as climbing to reduce heat uptake by increasing the distance from the heat source (Dittbrenner et al., 2008).

b) ***Colour reflectance:*** As argued by Ghassemi Nejad et al. (2017), there is evidence for the indirect influence of coat colour on absorbing or reflecting solar radiation. While the impact of coat colour on decreasing heat gain is almost negligible, a high reflectance coat colour has been argued to reduce radiative heat absorbance significantly (Stuart-Fox et al., 2017).

c) ***Posture:*** Some animals (e.g. sheep) change the duration of their lying and standing positions to control heat transfer (Mannuthy, 2017). Similarly, a type of desert lizard changes the heat flux in its body through posturing, and this is known as an intelligent alteration of the exposed body surface.

- **Stilting:** Some species such as locusts have an extra ability to survive high temperatures by *stilting*. Standing minimises the heat transfer from the ground as the area of contact is significantly smaller. If the temperature continues to rise, the locust climbs the local vegetation to increase the distance between it and the hot surface (Seeley, 2010). Many insects employ stilting behaviour in which all or some of their legs are extended. This behaviour is also seen in animals (Dean & Milton, 1999, p. 151). For example, some geckos lift their bodies away from the hot surface of a rock so that a breeze can pass underneath as a means of cooling, as well as reducing their surface contact.

8.4.1.1.2.4 Increasing heat gain

a) ***Posture*** (see 8.4.1.1.2.3, Posture)

- **Basking/heliothermy:** Basking or heliothermy is "The regulation of the body temperature of an ectothermic animal by behavioural adjustments of its exposure to solar radiation" (IUPS Thermal Commission, 1987). Basking is mainly accompanied by the intelligent orientation of the body so as to facilitate absorbing the maximum heat when it is required and reducing it when the body temperature has reached its optimal level (DeWitt et al., 1967).
- ***Thigmothermy:*** Thigmothermy is mostly used nocturnal species as they have limited access to solar radiation. Here the animal draws heat into its body from something that has been previously warmed by the sun. There are some nychthemeral species living in forest environments that practice thigmothermy as in forests the tree canopies block most direct solar radiation but as the canopy warms the animal can make use of this heat (Garrick, 2008).

8.4.1.1.2.5 Avoiding heat gain (in place)

a) ***Shading:*** Shelter seeking behaviour occurs when animals need a different microclimate because the ambient temperature is not favourable. For example, animals that live in the deserts use shade from rocky areas to avoid heat gain and those living on farms seek the shade of trees and farm buildings if the temperature increases. Shade seeking behaviour is one of the behavioural strategies that farm animals use to cope with high temperature (Ratnakaran et al., 2017).

b) ***Burrowing:*** The main strategy for surviving cold temperatures is to keep a low-level metabolism (Barnes, 2012). For example, bears hibernate (multiday torpor) during the winter to avoid heat loss. Some mammals and reptiles either burrow, find shade, or become nocturnal (Wilms et al., 2011). Burrows as a thermal refuge play an important part in the acclimatisation of animals to the environment. Burrows, in other words, are the thermally buffered microclimates animals use to survive (Milling et al., 2018). The orientation and morphology of burrows affect their ventilation (Ganot et al., 2012). The underground microclimate (temperature and humidity) is influenced by vegetation cover, soil porosity, and the depth, length, diameter, and shape of the burrow. Soil heats up by solar radiation and its colour influences the level and speed of heat absorption. The thermal conductivity of the soil also determines the temperature fluctuation cycle. Generally the temperature in a burrow is more constant as its depth below ground level increases. The depth, diameter, length, and shape of burrows also have an impact on ventilation, as in interconnected tunnels the greater difference in depth causes better ventilation (Burda et al., 2007).

Basically, air advection in burrows can be achieved by three mechanisms: a wind-induced pressure gradient along the burrow, the piston-effect movement of the burrow inhabitant, and thermal conductive venting (TCV), through which the temperature gradient induces air flow (Ganot et al., 2012). The morphological classification of burrows (Figure 8-3) might suggest innovative strategies for ventilating spaces in buildings given their complex geometrical patterns. A comprehensive study conducted by Knaust (2012) has categorised the morphology of burrows.

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Figure 8-3 Morphological variations of burrows (Frey et al., 1978)

c) ***Migration:*** Migration to other microclimates has been practised by some animals as a thermoregulatory behaviour. For example, Transantarctic Bluefin tuna show a high migratory behaviour (Block et al., 2001; Campana et al., 2011). Likewise, birds fly to cooler microclimates during the hot period (Newton, 2010, p. 145).

8.4.1.1.3 Controlling heat loss

8.4.1.1.3.1 Decreasing heat loss

a) Posture

- ***Hunching:*** Animals change their body postures to decrease heat loss. For example, piglets crouch to keep warm (Monteith & Mount, 1973, p. 98). Many mammals also reduce their surface to volume ratio by hunching in a ball-like posture (Sultan, 2015, p. 75). Examples of organisms who use this thermoregulatory behaviour are monkeys, lemurs, rodents, and seals and the behaviour is usually seen when the ambient air temperature falls (Terrien et al., 2011).

8.4.1.1.3.2 Increasing heat loss

a) Movement

- ***Climbing*** (see 8.4.1.1.2.3)

b) Nest building: The structure of termite mounds can allow both open and closed ventilation. In the former, the air can stream in and out of the nest through a series of holes in the walls (Korb & Linsenmair, 2000). This happens due to the difference in the wind velocity as the height at which holes are made are different, producing a temperature gradient. In closed ventilation systems instead of holes, peripheral air channels or cavities extend from the bottom to the top.

c) Saliva spreading: The spreading of saliva on the body surface is usually a deliberate (behavioural) thermoeffector action to cool the surface by evaporation (Needham et al., 1974). Sometimes this is inaccurately termed grooming.

d) **Wallowing:** "The thermoregulatory increase in evaporative heat loss by spreading an aqueous fluid (e.g., water, mud, urine) on the body surface" (IUPS Thermal Commission, 1987). For example, buffaloes spend more time wallowing midday when the sunshine reaches its maximum level (Mannuthy, 2017). As another example, the desert iguana Dipsosaurus wriggles its abdomen in the sand to keep it cool. The desert locust Schistocerca gtegaria shows the same behaviour.

8.4.1.1.3.3 Avoiding heat loss

a) **Burrowing and Migration** (see 8.4.1.1.2.5)

b) Torpor: *"A state of inactivity and reduced responsiveness to stimuli"* (e.g. hibernation during winter, hypothermia, or estivation often during summer).

- **Estivation***:* Estivation (Aestivation) is a prolonged torpor and takes place when ectotherms suffer from a lack of energy specifically during the summer. Estivation is not exclusively applied to ectotherms. In large-bodied species the number of daily torpors increases during the estival period. This happens as the environmental conditions are more restrictive in terms of water availability and ambient temperature (Valera et al., 2011). Estivation in some species could be linked to their specific morphology. For example, observation of snakes shows that their limpness morphology is the main reason behind their high body temperature compared to animals that are capable of controlling heat gain through posturing. This is why these animals show more tendency towards estivation (Seigel et al., 1987).
- ***Hibernation:*** Hibernation is a multiday torpor in heterothermic mammals (those that vary between self-regulation of body temperature and allowing the external environment to affect it) and is seen as a strategy to conserve energy.

8.4.2 Biological autonomic mechanisms for thermal adaptation

8.4.2.1 Controlling heat

8.4.2.1.1 Generating heat

Even though ectotherms mostly change their body temperature in response to the environment it might still be impossible for them to survive if the latter gets too cold or too hot. This is suggested as the reason why some have mechanisms for changing their body temperature irrespective of the environmental thermal condition (Davenport, 2012, p. 6). For example, the high temperature in the bodily muscles of a tuna fish happens through a countercurrent blood circulatory system. Also, several species of flying insects, and large crocodilians and turtles use muscular thermogenesis to maintain their body temperature above the ambient temperature.

Generally, heat generation in animals can be categorised into the two groups of non-shivering and shivering thermogenesis.

a) **Thermogenesis, non-shivering:** "[is] the increase in non-shivering thermogenesis in response to acute cold exposure. The principal effector organ is the brown adipose tissue which may adaptively increase its capacity for heat production in the course of acclimat(isat)ion and adaptation to cold stress" (IUPS Thermal Commission, 1987). Brown adipose tissue or brown fat has a heat-generating capacity and is more common in animals with smaller body size and also new-borns of large species (e.g. humans). It also seems to be restricted to mammals.

b) **Thermogenesis, shivering:** "[is] an increase in the rate of heat production during cold exposure due to the increased contractile activity of skeletal muscles not involving voluntary movements and external work" (IUPS Thermal Commission, 1987).

8.4.2.1.2 Controlling heat gain

8.4.2.1.2.1 Decreasing heat gain

a) ***Permanent insulation***: Mammals use fur, fat, or feathers to insulate their bodies and decrease heat loss. In some mammals, fur acts as a barrier to reduce heat gain from the environment. Most mammals use hair or fur to trap a layer of air close to their bodies, which functions as an insulating layer in heat transfer. Marine mammals (e.g. whales) use blubber as an additional thick layer of fat. Insulation in birds is improved by their having feathers (Thomas & Fogg, 2008, p. 13).

Compared to species living in lower latitudes, polar terrestrial invertebrates, microbes and plants are less sensitive to low temperature. One of the most significant adaptation strategies in this climate is used by the arctic fox that despite its small size possesses the most effective fur insulation (Barnes, 2012, p. 95). Polar bear fat and fur have a much enhanced insulation capacity, around seven times more than that of humans improved by clothing. In addition, the specific properties of polar bear fur such as transparency to short-wave radiation and colourlessness, with a dark skin, allows this animal to absorb heat (Thomas & Fogg, 2008, pp. 27-28).

8.4.2.1.3 Controlling heat loss

8.4.2.1.3.1 Decreasing heat loss

a) Permanent insulation (see 8.4.2.1.2.1)

b) Temporary insulation: Some animals are capable of insulating their body by using temporary methods.

- ***Waterproofing:*** A type of frog called *Phyllomedusa* that lives in the desert controls heat loss simply by waterproofing its skin by spreading lipid secretions all over its limbs. With this protection, water loss decreases significantly when the animal is basking in the sun.
- ***Preening:*** This is a strategy used by birds living in Antarctic latitudes. During preening, the oil transfers from the preen gland to the feathers. The oil acts as a waterproofing layer and reduces heat loss by trapping the air next to the body (Davenport, 2012, p. 23).
- **Piloerection** (see 8.3.1.3) **and ptiloerection:** These are the "involuntary bristling of hairs or ruffling of feathers; in thermal physiology, an autonomic thermoeffector response often associated with behavioural (e.g., postural) adjustments." To reduce heat loss, birds fluff their feathers and animals raise their fur. This helps by thickening the insulating layer.

***c)* Hidromeiosis**: This is explained as "the swelling of keratinized layers of the skin, due to prolonged exposure to water or sweat, which blocks sweat ducts and reduces sweating rate."

d) Body shrinkage: An example is the shrinkage of the body surface of the water bear (*tardigrade*). When the humidity level drops in alpine regions the body surface of this animal desiccates to reduce heat loss through its skin (Wharton & Brown, 1991).

e) Countercurrent heat exchange: This is used by many birds and mammals enabling them to transfer heat to cooler parts of their bodies. For example, the legs of some wading birds possess an artery that allows warm blood to be carried from the heart towards the foot. As the returning blood from the cold foot ascends through the veins it reduces the heat of the blood in the arteries and when the blood reaches the foot it is at a minimum temperature. This permits a significant decrease in heat loss as the temperature difference between cooled blood in feet and the surrounding environment is considerably reduced while the body core is still warm.

Some ectotherms also regulate blood flow to the skin as a way to conserve heat. For instance, iguanas reduce blood flow to the skin when they go swimming in cold water to help retain the heat they soaked up while on land.

The amount of heat transferred and carried through blood depends on the blood velocity, vessel diameter and thickness of blood, heat transfer coefficient of blood, and also the temperature of surrounding tissues (Sinha et al., 2016).

f) ***Circulatory heat transfer:*** In addition to generating heat, a series of ectotherms and all endotherms are capable of controlling heat loss through physiological means, for example, dilation and vasoconstriction of blood vessels. The former happens during basking in the sun (Davenport, 2012, p. 5). Circulatory heat exchange occurs due to a series of interrelating factors the combination of which allows the heat to circulate in the body. These are 1) the flow through superficial body tissue in capillaries, 2) the blood flow through veins, and 3) the respiratory ventilation mechanism rate. Reducing or increasing heat basically happens through widening or contraction of blood vessels which is called vasodilation and vasoconstriction.

- ***Vasoconstriction:*** In vasoconstriction the diameter of blood vessels shrinks to decrease heat loss. This process takes place as the blood follows another path to return to the heart or in other words, the blood vessels bypass the skin surface. For example, heat loss is slowed by peripheral vasoconstriction when an iguana dives into the water to forage. To compensate for this heat loss, the iguana basks in the sun on coming out of water.

8.4.2.1.3.2 Increasing heat loss

a) ***Circulatory heat transfer***: see 8.4.2.1.3.1

- ***Vasodilation:*** This enables increasing heat loss, as the blood leaving the heart moves towards the capillary bed in the skin surface. Some species of mammals are furry and benefit from a specific network of blood vessels in places without fur for heat exchange. For example, the large furless ears of jackrabbits facilitate rapid heat loss due to their extensive network of blood vessels. This is how jackrabbits can survive in hot desert environments.

- **Selective brain cooling:** This comes under the vasodilation category and has been defined as "lowering of brain temperature, either locally or as a whole, below arterial blood temperature. Cool venous blood returning from the cephalic heat dissipating surfaces acts as a heat sink, either for brain tissue directly or for arterial blood supplying brain tissue. Special vascular arrangements, e.g., the ophthalmic or carotid retia mirabilia, support arterio-venous heat exchange underlying selective brain cooling. Its existence in many species has been proven, but the situation in humans is still debated."
- **Menopausal hot flush (flash)**: This has been described as "an abrupt heat dissipation response, occurring in hypoestrogenic women. The response typically consists of peripheral vasodilation, sweating and reports of intense warmth."

b) Evaporative mechanisms: Evaporative heat loss is the only way through which animals behaviourally lose heat when their body temperature is above the ambient temperature (Blatteis, 1998, p. 4). The different types of evaporative heat loss mechanisms are categorised below.

- ***Sweating:*** Sweating is only seen in mammals and is an autonomic mechanism through which the skin releases water. For humans, sweating has been recognised as the most significant heat loss mechanism (Shibasaki & Crandall, 2010) and is under sympathetic cholinergic control (cholinergic neurons affect brain processes), while in the animal kingdom sweating is under adrenergic control. Heat loss mechanisms in humans and animals have been referred to as somatomotor and vasomotor responses respectively (Blatteis, 1998, p. 5). Thermosensitive neurones respond to any changes in the temperature by sending signals to the hypothalamus which has been assumed to act as a set point manager similar to the thermal management system of a building.
- ***Panting:*** Many mammals use panting to increase evaporative cooling and hence heat loss. Panting is a low energy demanding thermoregulatory mechanism, through increasing evaporative loss from the mouth area. Water evaporation from the skin is called cutaneous evaporative heat loss (CEHL) and is the "*Rate of heat dissipated by evaporation from the skin.*" Birds and mammals pant but might use slightly different strategies. For example, in some species such as dogs panting is combined with a counter-current heat exchanger. This is developed in animals so they can keep their brain from overheating. Panting can be categorised into the following groups:

- ***o*** **Thermal hyperpnea:** "An increase in tidal volume associated with an increase in alveolar ventilation occurring during severe heat stress which has caused a large rise in core temperature." In animals, thermal hyperpnea is typified by slow and deep breathing, also called second phase panting, while typical or first phase panting is accompanied by rapid, shallow breathing.
- ***o*** ***Thermal tachypnea (Synonym: thermal polypnea*)**:** "A rapid respiratory frequency accompanied by an increase in respiratory minute volume and, commonly, a decrease in tidal volume, in response to a thermoregulatory need to dissipate heat."
- ***o*** **Gular fluttering:** "...a characteristic form of thermal panting in some birds during exposure to high ambient temperature, by which means air is moved across the moist surfaces of the upper respiratory tract." As discussed by S.-A. Richards (1970), the respiratory parameters, air sac properties, and cooling efficiency of panting in birds affect their panting mechanism.

8.4.2.1.3.3 Avoiding heat loss (in time)

The two strategies of freeze avoidance and freeze tolerance enable organisms to survive in cold climates. In both strategies organisms need to control ice formation. Freeze tolerant organisms deal with controlling ice formation in extracellular fluid spaces that preserve the intracellular from freezing. The freeze avoidance mechanism is an adaptation strategy for surviving intracellular freezing, which usually happens due to a spontaneous decrease in temperature. In this strategy, organisms reduce the supercooling point of their body fluids to decrease the possibility of intracellular ice formation, as intracellular crystallisation is lethal. This mechanism is used in the normal winter when organisms suddenly experience nucleation.

a) Freeze tolerance: Ectotherms are vulnerable to freezing but some species such as barnacles, mussels, intertidal gastropods, and overwintering insects can survive the freezing of extracellular body fluids. Likewise, many plants species employ freezing in extracellular fluid spaces to survive (Wisniewski et al., 2014).

b) Freeze avoidance: Freeze avoidance is a physiological or biochemical adaptation. Supercooling can be recognised as a conforming mechanism (see 8.3.1.6.1). In an Antarctic environment where the most noticeable feature is the low temperature, arthropods rely on supercooling as a freeze avoidance mechanism so they can survive the sub-zero temperatures. For example, the supercooling mechanism of the Antarctic mite *Alaskozetes Arcticus* relies on accumulating glycerol and removal of ice-nucleating particles from the gut (Young & Block, 1980). Another example is the development of antifreeze proteins in fish (Barnes, 2012, p. 40). A number of insects have a high level of cryoprotective glycerol in their haemolymph (circulating fluid in an arthropod), and Antarctic Icefish have the same chemical substance in their blood. This chemical acts as antifreeze. Despite these examples, most ectotherms use behavioural adaptation mechanisms to avoid freezing (Davenport, 2012, p. 6).

8.4.3 Heat exchange mechanism: complementary aspects of thermoregulation

In endotherms metabolism, circulation, and respiration work together to keep homeostasis. However, most ectotherms do not generate heat within their bodies. For these organisms, circulation and respiration are required to work together. For plants also, complete photosynthesis is defined as the combination of the physical and chemical aspects of photosynthesis. The fact systems have to work together has parallels with HVAC systems in buildings (see 8.5.3).

In animals the cardiovascular system is responsible for transferring oxygen to different parts of the body. It also supports thermoregulation and circulatory mechanisms. The main function of the circulatory system is the gas exchange between blood and tissues. Blood absorbs oxygen and releases carbon dioxide. This means circulatory and respiratory systems work together.

In the respiratory system, inhalation creates a negative pressure and makes the lung inflate. The air passes through the nasal cavity getting warmer and more humid. Then the air moves through the throat towards the lung and in the lung from the primary bronchus to the tertiary and respiratory bronchi to which alveolar ducts are attached. The gas exchange occurs in the ducts that are in direct contact with the capillaries of the circulatory system. This intimate contact enables oxygen to be diffused from the alveoli and to be absorbed by blood capillaries and carbon dioxide to be diffused by blood and absorbed by alveolar ducts. Given this, the two influential factors in the gas exchange process are the diffusion distance and the surface to volume ratio of the alveoli. Diffusion is a passive transport process occurring in cells through which the material travels from a high to a low concentration region and this becomes feasible only through a thin cell membrane. For this reason in unicellular, simple organisms such as cnidarians and flatworms, and organisms with a highly-flattened body which produces a higher surface to volume ratio, diffusion is effectively the gas exchange mechanism that serves the respiratory system (Reece et al., 2015, p. 942).

In larger animals, other respiratory tissues are required to compensate for the ineffectiveness of gas exchange through diffusion. This is the reason larger animals such as earthworms, and adult amphibians use their skin as a respiratory organ, and those that live in water such as cnidarians (including corals, sea anemones, and jellyfish) have evolved gills. The highly branched and folded aspects of gills facilitate gas exchange as both aspects provide a larger surface area to volume ratio. The respiration system developed by terrestrial vertebrates (amphibians and reptiles) and marine animals are called cutaneous respiration and branchial respiration respectively.

In insects, respiration is independent of the circulation system and in their bodies a highly-specific circulatory system known as the tracheal respiration system manages the gas exchange mechanism. This means blood does not play a role in gas exchange. Instead, a network of small tubes in the tracheal system enables the process. The oxygen comes into and leaves the body through small openings called spiracles that are connected to these tubes. The fluid flowing in tracheoles is called haemolymph.

Reptiles, birds and mammals use their lungs for respiration. This is called pulmonary respiration.

All respiratory surfaces either cell membrane, skin, gills, or lungs, should have

1) a large surface area to allow entry of gases
2) a thin permeable surface to increase the rate of diffusion
3) a moist exchange surface to allow gases to dissolve
4) a concentration gradient in blood vessels

Table 8-2 presents the characteristics of examples of respiratory systems.

Table 8-2 Specification of respiratory systems in human lungs, fish gills, and leaf cells

SYSTEM	LARGE SURFACE AREA	SMALL DISTANCE	CONCENTRATION GRADIENT
Human lungs	600 million alveoli with a total area of 100m²	each alveolus is 1 cell thick	constant ventilation replaces the air
Fish gills	feathery filaments with secondary lamellae	lamellae are 2 cells thick	water pumped over gills counter-current to blood
Leaves (tree)	- SA of leaves =200m²; - SA of spongy cells inside leaves = 6000m².	gases diffuse straight into leaf cells	wind replaces air round leaves

The two types of circulatory systems are known as open and closed. The basic components of each are a network of interconnecting vessels, a pump, and a fluid for transporting substances.

In an open system, which can be seen in arthropods such as grasshoppers and some molluscs, the contraction of the heart creates a pressure causing the circulatory fluid (*haemolymph*) to be pumped and sent into the interconnected sinuses. When the heart returns to a relaxation state, the blood comes back to the pores. Valves enable the pores to open and close repeatedly as they control the sending out of the haemolymph from and drawing it back into the vessels.

The fluid in a closed circulatory system is the blood that is pumped from one or more hearts and is sent into large and small branches of the blood vessels until it penetrates the organs. Annelids (including earthworms), cephalopods (including octopuses and squids), and all vertebrates belong to this group.

8.5 Parallels in building design

After this review of thermal adaptation mechanisms, this stage introduces a series of possible parallels in buildings so as to suggest appropriate strategies that might be used to improve building thermal performance and energy efficiency.

Passive and active design strategies (Energy Efficiency Design Parallels or EEDP) for designing energy-efficient buildings are located on the right-hand sides of Figure 8-6 and Figure 8-7. This list suggests energy-efficient building design has already benefited from imitating many thermal adaptation mechanisms that nature employs for survival, except for those shown in the white cells. In other words, these empty white cells suggest a series of thermal adaptation mechanisms imitation of which remains a challenge to designers, since as yet they have no identified parallels in building design.

The following section briefly discusses the application of biological mechanisms in buildings so as to facilitate the development of the ThBA framework. The ThBA should be able to connect the thermal challenges of buildings to relevant biological strategies. This, however, is achieved through finding the mechanisms used by organisms that have been or have the potential to be used in energy efficient building design as either passive or active design strategies.

8.5.1 Passive strategies

This section introduces passive design strategies used by architects for improving the energy efficiency of buildings, and that are comparable to behavioural thermal adaptation mechanisms in nature. Figure 8-6 shows the latter (left-hand side) and their equivalent building design strategies (right-hand side). The central grey column sets out the major functional and morphological principles of each individual strategy. In the context of bio-inspired design (BID), these principles need to be extracted independently of biological systems to facilitate the development of design solutions.

8.5.1.1 Controlling heat

8.5.1.1.1 Generating heat

a) Interior heat gain

Internal heat gain in a building comes from heat from occupants, electrical equipment, and lights. Regarding occupancy as a parallel to clustering, people can move within buildings and there is a tradition of gathering in one heated room in winter in buildings in cold climates. For example, in northern medieval monasteries only the caldarium was heated.

b) Space organisation

Clustering might suggest strategies for space heating as the heat generated by clusters from their movement and amalgamation patterns can be paralleled by HVAC systems moving heat around a building. As discussed earlier, the aggregation of animals in herds, flocks, and swarms has inspired engineering design as animals group to optimise heat generation, and swarm optimisation has been used as an evolutionary computational technique for designing heat sinks (Alrasheed, 2011). In the context of swarm intelligence (SI), the self-grouping of animals has the potential to inform thermal optimisation through adaptive and decentralised HVAC operation management so as to control heating and cooling systems efficiently.

Stigmergy (an action that leaves a trace that leads to the next action) in insects is a cognitive behaviour, but is similar to SI, which is a reactive behaviour. This has inspired the naming of major algorithms developed for data management (Awad & Khanna, 2015), such as artificial immune system, bacterial foraging optimization, artificial bee colony, particle swarm optimization, and ant colony optimisation.

The collective behaviour of insects (e.g. clustering of bees) in response to high and low temperatures and the movement pattern in their hives and when swarming have the potential to be emulated in space arrangements in architectural design (Ocko & Mahadevan, 2014). The parameters that affect heat transfer in a bee swarm (Ocko & Mahadevan, 2014), suggest ideas for improving the energy efficiency of buildings. For example, the density of bees in different parts of the swarm could inspire space planning or HVAC distribution. Consequently, a mathematical heat transfer equation of the movement of bees within a cluster might be useful (Figure 8-4). The variables in the study by Ocko and Mahadevan (2014) for calculating heat generation based on a cluster with a spherical boundary were:

- Schematic of interior (Ω),
- (δΩ) boundary mantle–core structure,
- Ŝ and Ž are radial, vertical directions in polar coordinates,
- R is the cluster radius.

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Figure 8-4 Heat generation in a bee cluster (Ocko & Mahadevan, 2014)

The collective structure of army ants also has the potential to suggest guidelines for building plans and HVAC distribution. As an example, Anderson et al. (2002) found at least four self-assemblage structures made by ants that have a thermoregulatory effect (Table 8-3).

Table 8-3 Social insect self-assemblages classified by structure (Anderson et al., 2002)

Self-assemblage	Structure		
	Chain (1D)	Mesh (2D)	Cluster (3D)
Bivouac	✓	✓	✓
Curtains		✓	
Swarms			✓
Thermoregulatory			✓

8.5.1.1.2 Controlling heat gain

8.5.1.1.2.1 Increasing and decreasing heat gain

a) Solar heat gain

- ***Static building envelope:*** The building envelope corresponds to nest building in organisms and as with nests the orientation of a building can influence the amount of heat received by the building envelope. The size and shape of a building could be seen as being similar to the body of animals as the level of heat gain can be controlled by adjusting these. At a smaller scale, a conceivable parallel of nests in building design could be the apertures and glazing systems installed in the building envelope, including skylights, as the orientation, shape and size, material, and type of these are influential factors in heat gain.
- ***Kinetic building envelope:*** A building that moves with the sun, such as the Heliotrope house in Freiberg (Ramzy & Fayed, 2011) is an example of the kinetic approach. A simpler example would be moveable blinds and shutters through which the level of solar gain can be controlled.

The similarity between moving architecture and organisms may not seem obvious as most buildings are static and generally almost all of their elements are in a fixed position. This contrasts with the dynamic ability of animals enabling them to move to appropriate microclimates to control heat gain. This suggests kinetic architecture may not be a useful approach (Fox, 2016), although many efforts have been taken to incorporate movement into design. The energy used for these movements has come from integrating human movements, environmental kinetic forces such as wind, air, and water, and machines where movement is achieved by mechanical motors (El Razaz, 2010). The cost and benefits of all these approaches need to be taken into account.

8.5.1.1.2.2 Decreasing heat gain

a) Cool roof: The roof material needs to have a high solar reflectance or high solar emittance for a cool roof in order to reduce solar heat gain (Roberts, 2008). For a well-insulated building with no cool roof, cooling energy is expected to increase. Nikolaou et al. (2015, p. 199) state the overall thermal resistance of the roof material and temperature difference between the inner and outer surface of the roof affect the roof energy balance to give the following equation:

- $Q_{in} = (T_s - T_c)/ R$ where:
- R is Overall thermal resistance of the roof material (m^2K/W),
- T_s is Temperature of the outer surface of the roof (K),
- And T_c is Temperature of the inner surface of the roof (K).

8.5.1.1.2.3 Avoiding heat gain

- ***Shading:*** Many studies have analysed the effectiveness of solar shading systems on the cooling energy requirements of buildings (Tzempelikos & Athienitis, 2007; Pino et al., 2012; Bellia et al., 2013). Fixed external solar shading can be composed of single or multiple vertical or horizontal blades. Shades can be either fixed or moveable. Seasonal heat gain has traditionally been prevented by whitewashing all-glass buildings like conservatories in the summer months and removing this in the other seasons.
- ***Underground architecture:*** This corresponds to a burrowing strategy that seeks a favourable microclimate for organisms avoiding harsh environments (X. Yang et al., 2014). An example would be the underground rooms found in some Iranian traditional houses (Beigli & Lenci, 2016).
- ***Portable building:*** Migration links to portable buildings but most nomadic cultures are to do with finding pasture rather than migrating to find a more suitable microclimate. In the European Alps, people would move to live in huts high in the mountains in summer so they could look after their flocks, which also migrated up the mountain to take advantage of the new grass growth.

8.5.1.1.3 Heat storage

a) Thermal mass: This is a strategy of passive solar design in which the construction material buffers heat gain and heat loss to keep the internal temperature more stable. Thermal storage can be achieved through either conventional mass or phase change materials that form sensible and latent heat storage systems respectively (Khudhair & Farid, 2004).

8.5.1.1.4 Controlling heat loss

8.5.1.1.4.1 Decreasing heat loss

a) Compact building form: One of the functions of building morphology is the control of heat loss through building envelopes. An energy analysis by Ratti et al. (2005)

sought to determine the most energy efficient building geometry in terms of surface-to-volume ratio. While such investigations seek the best geometrical configurations as a means of decreasing heat loss through the building envelope, there are ongoing consequences of using this approach, as a reduced building surface area will limit opportunities for providing daylight and ventilation for internal spaces.

Comparing this strategy to the ball-like posturing used by mammals, it becomes obvious that there are limitations in regarding a building as a 'living organism'. Buildings that can be transformed might make use of this approach but as noted above the costs and benefits need careful assessment.

8.5.1.1.4.2 Increasing heat loss

a) ***Solar chimney (wind tower):*** A solar chimney is similar to the ventilation achieved by the structure of termite mounds and is a form of passive cooling in buildings. It is composed of an inlet, a cooling cavity, and an outlet. The wind is captured, flows into the cooling cavity and then enters the room (Aboulnaga, 1998). A number of design parameters influence the effective performance of a solar chimney.

1) Length and width of the chimney
2) Air gap dimensions
3) Inlet-outlet distance
4) Area of the inlet, outlet and the cavity (Aboulnaga, 1998)

b) Green roof/wall

Green roofs can be incorporated into building design to control heat transfer through the building envelope. Green roofs can improve the microclimate, minimize the urban heat island effect, and reduce energy consumption both at building and urban scales (Morakinyo et al., 2017). They generally consist of a vegetation layer, waterproofing, and insulation, depending on the location and building requirements.

c) Cooled soil

The cooled soil strategy is to some extent similar to wallowing, as the building is raised over constantly moist soil. Even though this strategy does not involve underground heat exchange pipes, it has potential for functioning as a cooling source during the summer in arid regions (Givoni, 2007).

8.5.2 Active strategies

In this section energy-efficient building design strategies have been characterised as analogous to the physiological thermal adaptation mechanisms performed by organisms. Referring back to section 8.4.2.1, Figure 8-7 follows the same structure of Figure 8-6 to demonstrate the comparability of active biological solutions to similar strategies in architectural design.

8.5.2.1 Controlling heat

8.5.2.1.1 Generating heat

a) ***Non-renewable resources:*** The operation of HVAC systems could be a parallel to non-shivering thermogenesis carried out by brown fat, as the energy used for running HVAC equipment is not necessary renewable. Intelligent control of HVAC systems could also be seen as analogous to involuntarily thermogenesis in animals (Parameshwaran et al., 2012).

b) ***Renewable energy resources:*** The following mechanisms could be interpreted as shivering thermogenesis in which the shaking muscles are responsible for generating heat. This is an iterative mechanism which makes it similar to heat generation through renewable sources of energy, such as the sun and wind.

- ***PV solar systems and wind turbines:*** Hybrid photovoltaic/thermal (PV/T or PVT) solar systems consist of PV modules coupled to water or air heat extraction devices, which convert the absorbed solar radiation into electricity and dissipate the heat, which would otherwise reduce the efficiency of the PV panels. In wind turbines, the rotating energy is converted into electrical energy. Saying there is an analogical link between non-shivering thermogenesis as a physiological thermal adaptation strategy and both PV solar systems and wind turbine is weak.

8.5.2.1.2 Controlling heat gain

8.5.2.1.2.1 Increasing heat gain

a) ***Ground cooling and heating:*** using the ground capacity as a passive means of cooling and heating is a design strategy for controlling heat gain and heat loss in buildings. For this, a heat exchanger system is buried in the ground. Such a system is similar to the counter current heat exchange mechanism in animals and is composed of a circulatory network of pipes that use air or water as the heat transfer medium (Florides & Kalogirou, 2007). In winter, the soil acts as a heat source but has the opposite function of a heat sink in summer. In this strategy the heat balance calculation uses the following input data: the geometrical characteristics of the system, the thermal characteristics of the ground and the pipes, and the undisturbed ground temperature during the operation of the system. These parameters seem analogous to the radius of blood vessels and their temperature, and the thermal properties of skin tissue.

The geometrical characteristics of heat exchangers determine whether the system is open or closed. The latter is grouped into the two categories of horizontal and vertical pipe networks with varied geometrical configurations (Figure 8-5).

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Figure 8-5 Different geometrical configurations of pipes for heat exchange

8.5.2.1.2.2 Decreasing heat gain

a) ***Static thermal insulation:*** Thermal insulation technology falls into the four major groups of bulk technology, reflective technology, nanotechnology, and vacuum technology (S. W. Lee et al., 2016). Irrespective of their specific types, thermal conductivity, thickness, and density of materials affect the effectiveness of each insulation technology.

8.5.2.1.3 Controlling heat loss

8.5.2.1.3.1 Increasing heat loss

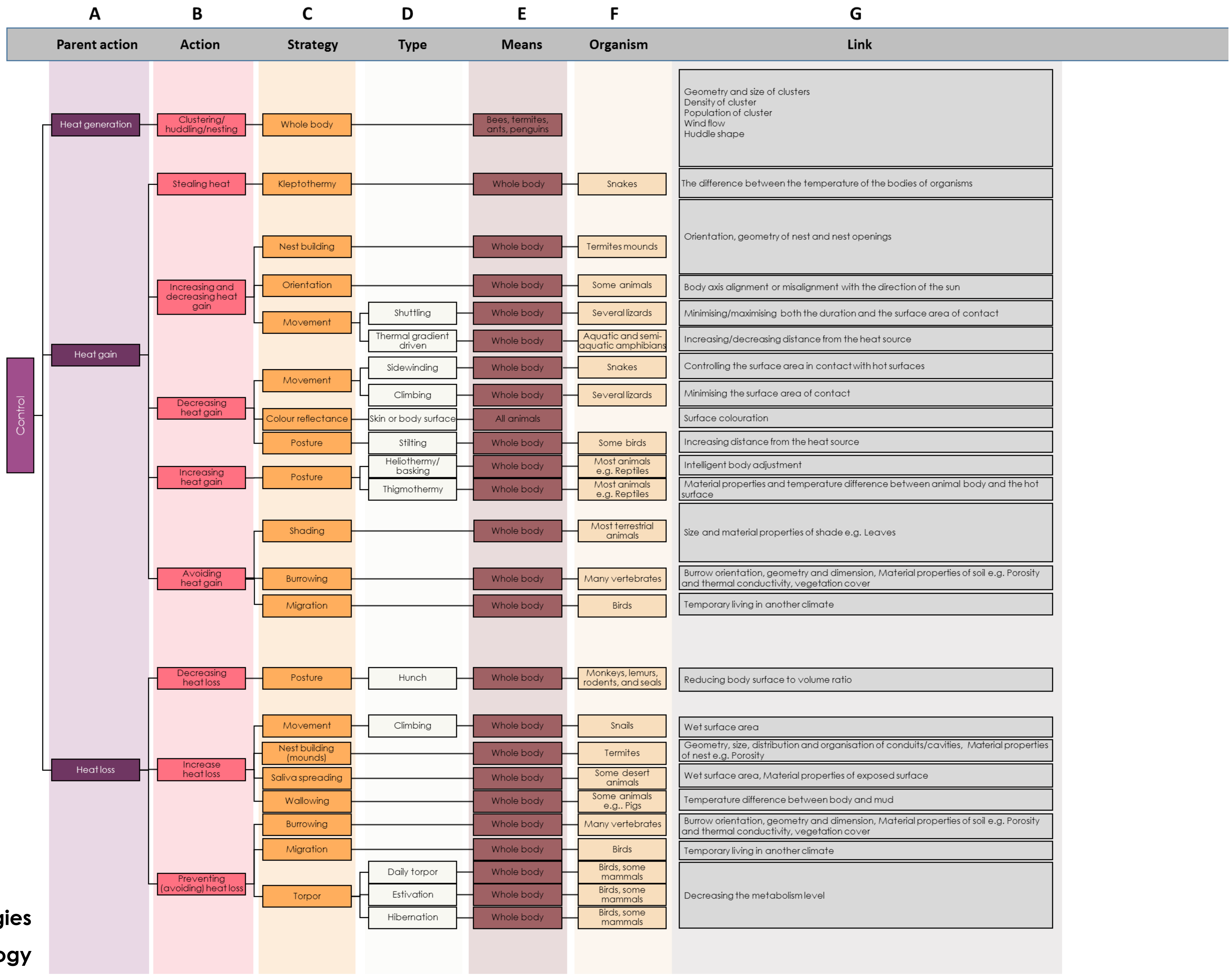
a) ***Ground cooling and heating***: see 8.5.2.1.2.1
b) ***Evaporative cooling:*** Evaporative coolers in buildings can be direct and indirect. In both types water is used for cooling the air, the only difference being how the air is cooled. In direct cooling, water is used as the cooling medium while in indirect cooling, the outdoor air is cooled by a precooled air flow (Al-Juwayhel et al., 1997). The two parameters of the mass (water) flow rate and packing thickness affect the thermal efficiency of this mechanism.

8.5.2.1.3.2 Decreasing heat loss

a) ***Static thermal insulation:*** see 8.5.2.1.2.2

8.5.2.1.3.3 Preventing heat loss

a) ***Air tightness:*** The aim here is to control unwanted air movement and consequently unwanted heat loss.



Passive strategies

Biology

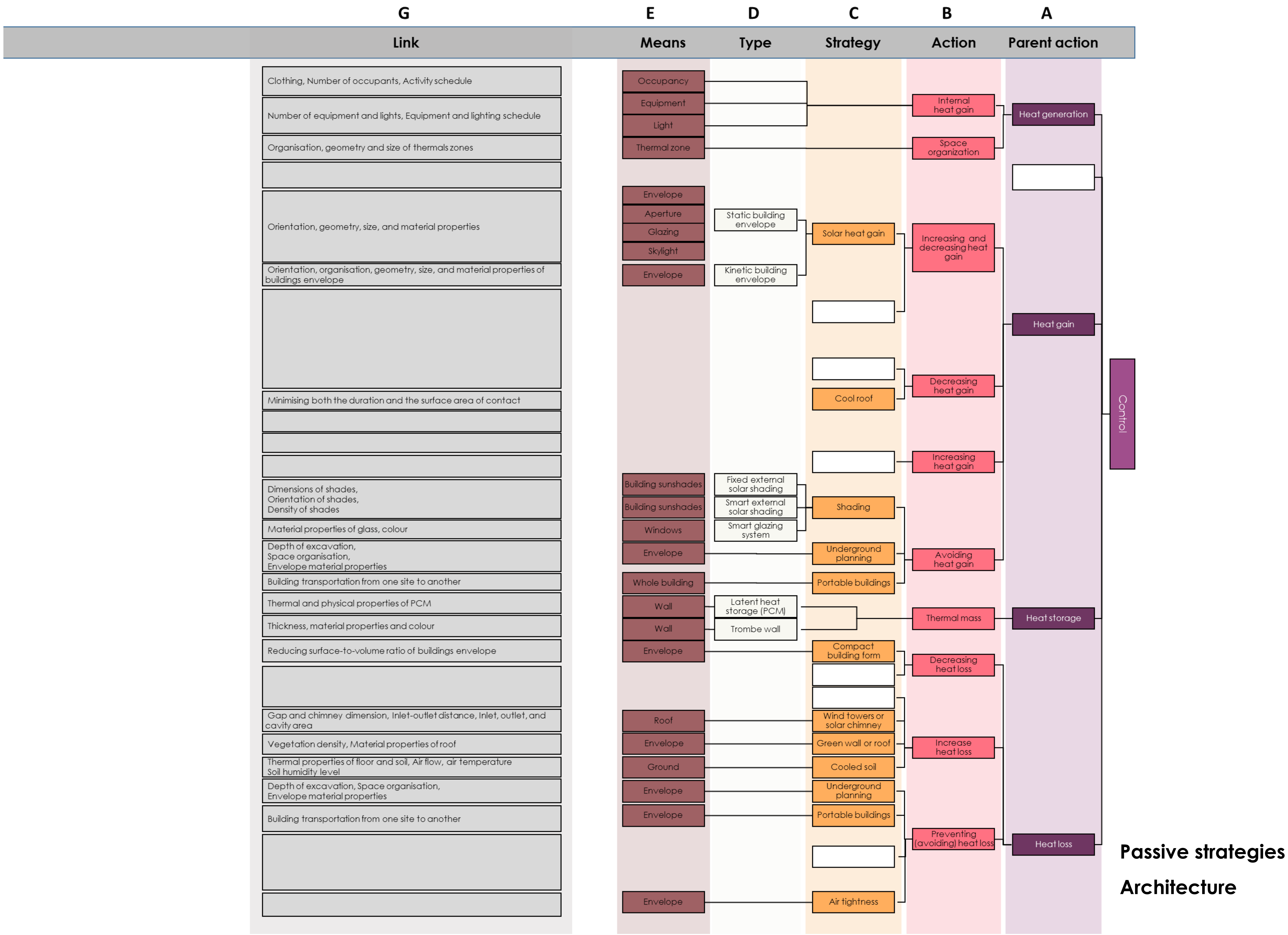
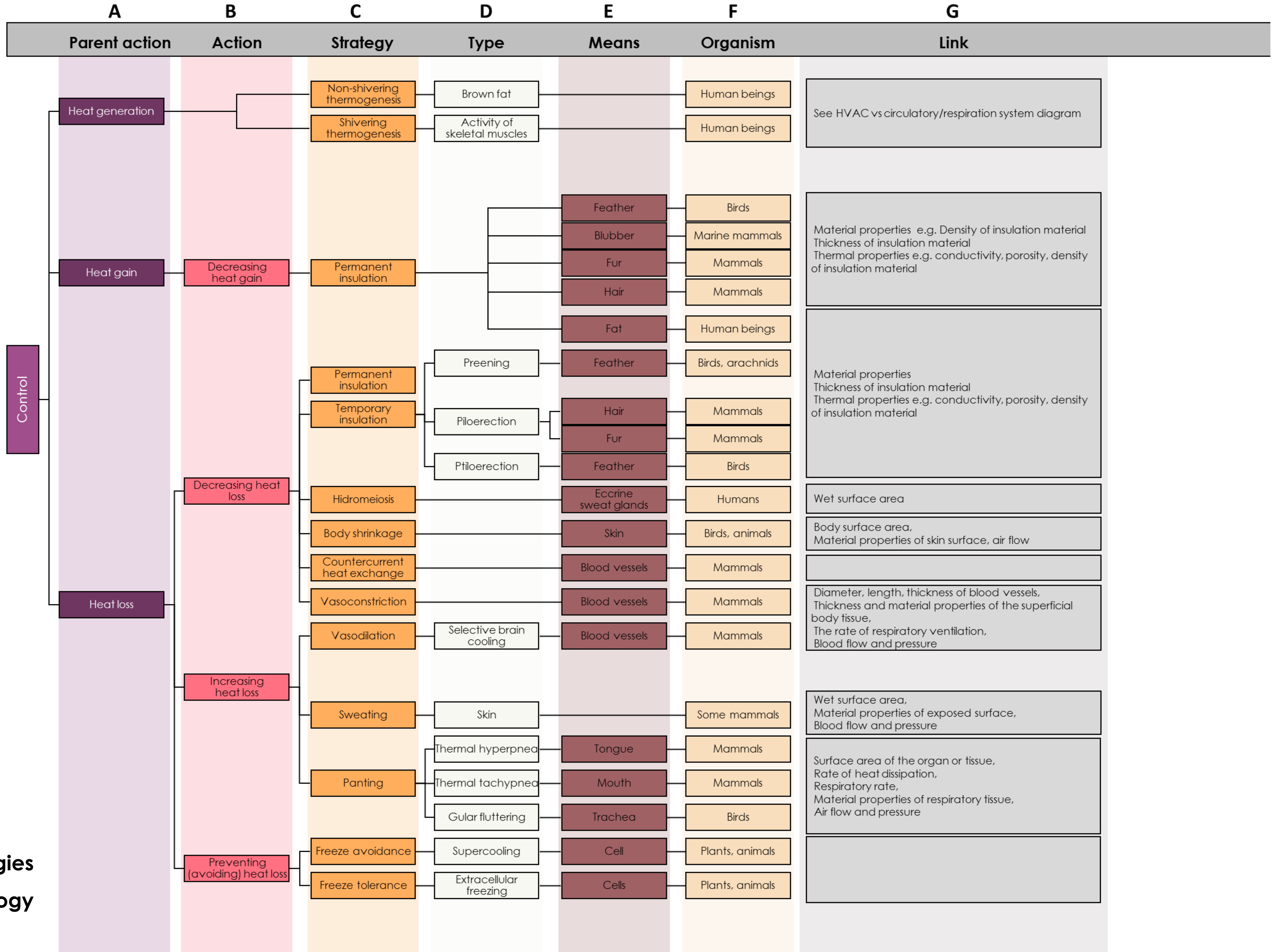
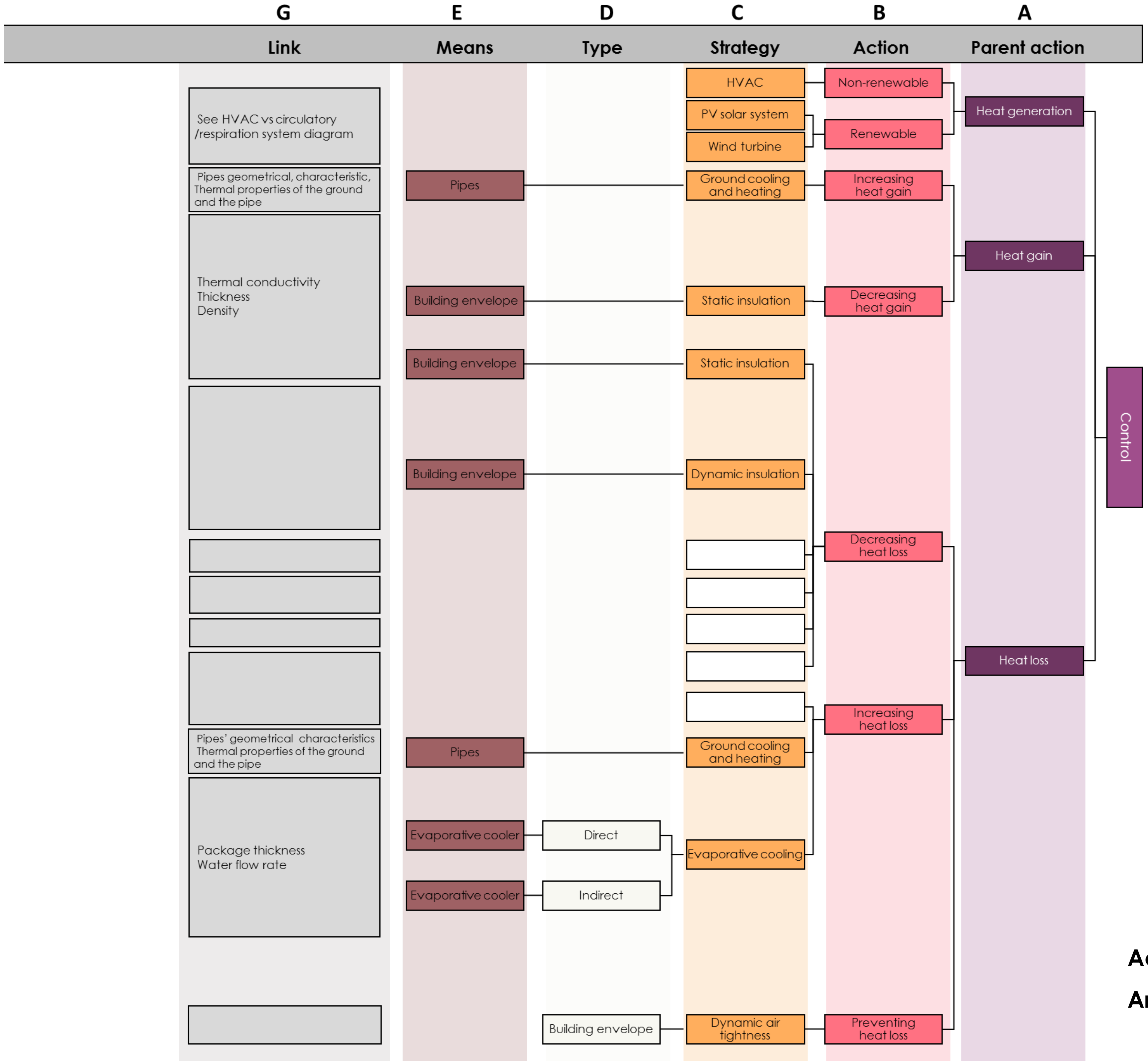


Figure 8-6 Autonomic thermal adaptation mechanisms in nature and their parallels in architectural design (passive strategies) Version 01 Part a



Active strategies

Biology



Active strategies

Architecture

Figure 8-7 Autonomic thermal adaptation mechanisms in nature and their parallels in architectural design (active strategies) Version 01 Part b

8.5.3 HVAC in buildings and circulatory and respiratory systems in organisms

Circulatory and respiratory systems in animals are comparable to the principles of thermodynamics, fluid mechanics, and the heat transfer mechanisms of HVAC systems in buildings (Figure 8-8). Non-ducted systems such as split air conditioning and window air conditioning resemble the gas exchange mechanism of unicellular and simple organisms. Gas exchange mechanisms of this type are similar to that of a space that is simply ventilated by air coming through windows or is equipped with a ductless indoor or outdoor split system that is in direct contact with the outdoor air.

Cutaneous, pulmonary, and branchial systems correspond to ducted HVAC systems (Figure 8-8). Since the function of the cardiac system in organisms is comparable to that of a HVAC system, the two main types of ducted HVAC system—packaged air conditioning and central plant—can be linked to cutaneous, and pulmonary and branchial systems respectively. In the first, each package is positioned in a single zone and accordingly resembles individual hearts, such as the auxiliary hearts in earthworms, while in the second and third, the whole building circulation is achieved through one central unit connected to multiple zones and corresponds to a branchial system in fish gills connecting to the heart of the fish.

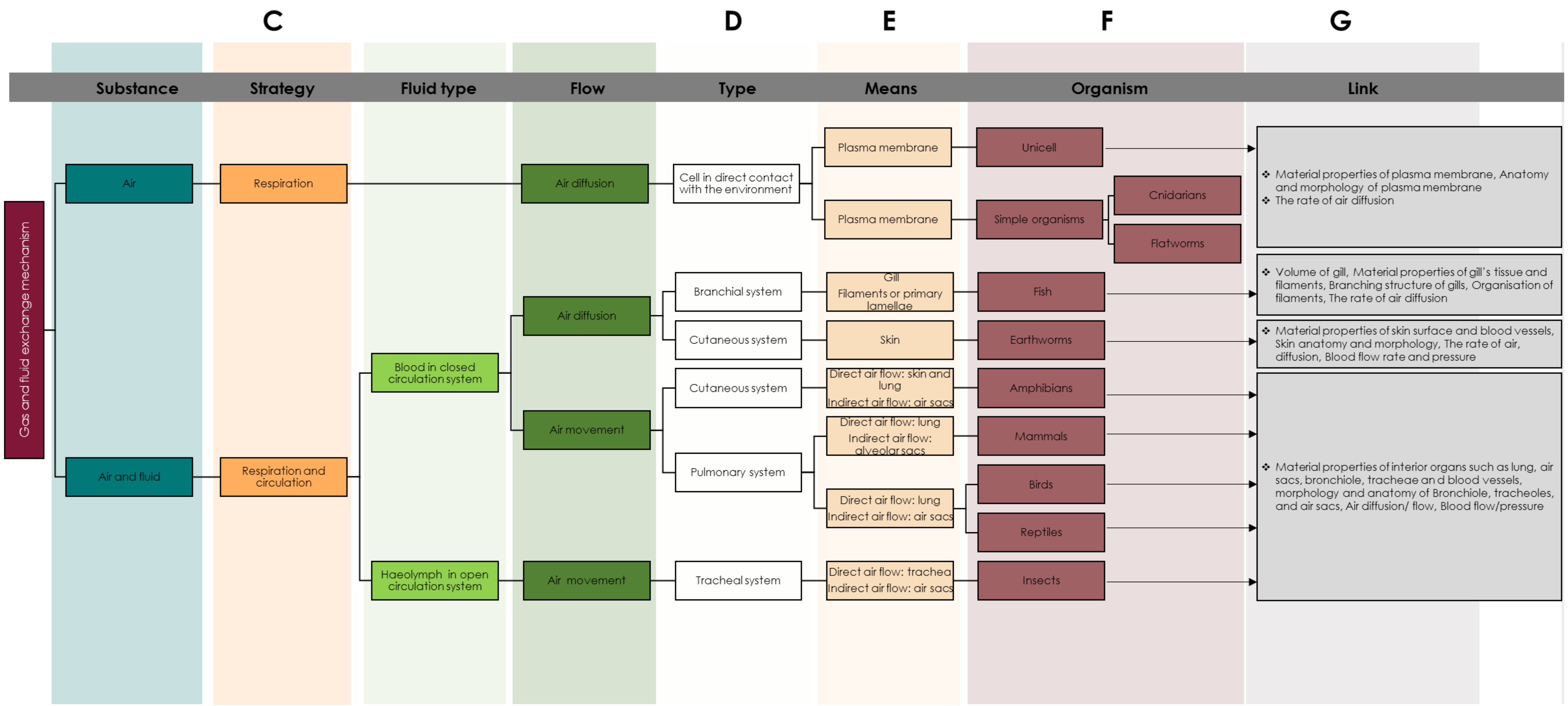
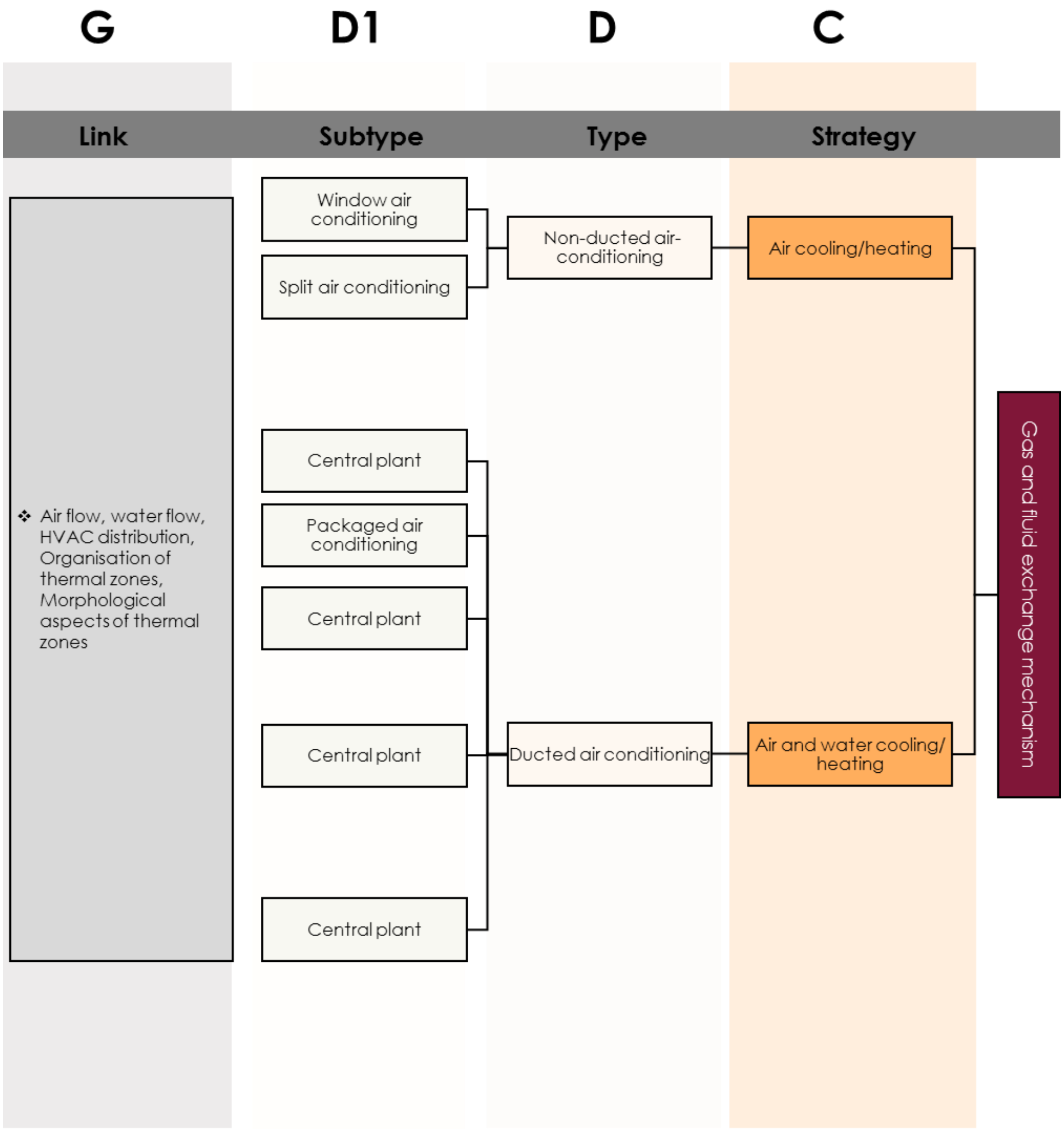


Figure 8-8 HVAC system in buildings vs circulatory and respiratory systems in organisms


G
D1
D
C
Link
Subtype
Type
Strategy
Window air conditioning
Split air conditioning
Non-ducted air-conditioning
Air cooling/heating
Central plant
Packaged air conditioning
Central plant
Central plant
Ducted air conditioning
Air and water cooling/heating
Central plant
Air flow, water flow, HVAC distribution, Organisation of thermal zones, Morphological aspects of thermal zones
Gas and fluid exchange mechanism

Both water and air cooled systems use air for heat transfer through or out of each thermal zone in a building. In view of this, and considering the principles of heat distribution and storage, gas exchange in unicellular and simple organisms (respiration system) can be viewed as analogous to air cooled HVAC units. Cutaneous, pulmonary, branchial, and tracheal systems are all equivalent to water cooled systems in which water plays the same role as that of blood or haemolymph in circulatory systems in organisms. The other difference is that in circulatory and respiratory systems in animals the purpose is to transfer oxygen to the cells while in buildings heat needs to be sent to or sucked out of each thermal zone.

The air and fluid transfer in circulatory and respiratory systems is similar to that of an air or water cooled air conditioning system (Figure 8-9).

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Figure 8-9 Left) gas exchange mechanism in tissues (Lumen, 2017); Right) HVAC systems in a building (Brown Technical, 2018)

The manner in which the transfer of heat in the living human body takes place is somewhat complicated, owing to the fact it is a combination of thermal conduction, convection and metabolic heat production. Conduction and diffusion take place in tissues, while convection occurs in blood and other body fluids.

8.6 Thermal adaptation in plants

At this stage it was decided that the ThBA would not be complete without also looking at thermoregulatory systems in plants and then looking for architectural parallels.

In hot deserts where high temperatures and radiation levels form the environmental challenges, tall plants control light absorbance by the orientation of their leaves so these are not perpendicular to the sun's rays (Barnes, 2012, p. 199). The reflectance of a leaf can also affect light absorbance. In plants with leaves oriented from east to west, more light is absorbed in the early morning and late evening. This accordingly protects the plants from the midday sunlight. Another barrier to light absorption is depostion of the hairs and wax on the surface of leaves. Whitish, silver, and greyish colours are other evolutionary adaptation mechanisms developed by plants in hot deserts (M. G. Holmes & Keiller, 2002).

Like microbes, plants basically use one or a combination of the following strategies to survive in the cold:

1) Avoid freezing, and/or

2) Tolerate freezing.

In the former state, a chemical similar to antifreeze is found and in the latter, a carefully controlled ice-creation mechanism prevents intracellular freezing (Barnes, 2012, p. 95).

The adaptation mechanisms plants use to cope with high temperature can be one or a combination of physiological, morphoanatomical, and biochemical alterations. The physiological and biochemical adaptation processes in plants might not be directly useful for building design, but studying the influence of these alterations on the morphology and structure of plants either at macro or micro levels might suggest innovative ideas.

Physiological thermal adaptation in plants can produce an increase in the rate of photosynthesis. Physiological and biochemical mechanisms in plants can be seen in their morphological alterations. These mechanisms include reduction in cell size, closure of stomata, increased stomatal and trichrome densities, and larger xylem vessels. Biochemical mechanisms are induced by protein production and are out of the scope of this research (Waraich et al., 2012).

A similar approach to that for organisms was taken to classifying the thermal adaptation mechanisms of plants. For many plant strategies, the boundary between passive and active strategies was unclear, which restricts their separation into passive and active categories. It was therefore decided a diagram without this classification would be presented to biologists for their evaluation (Chapter 9). Figure 8-10 is the ThBA framework developed for plants. At this stage it was not possible to prepare the architectural side related to plants before the date set for the focus group. However, it was felt this would not affect the outcome of the panel discussion as the biology experts would only be asked to comment on the biological side of the framework.

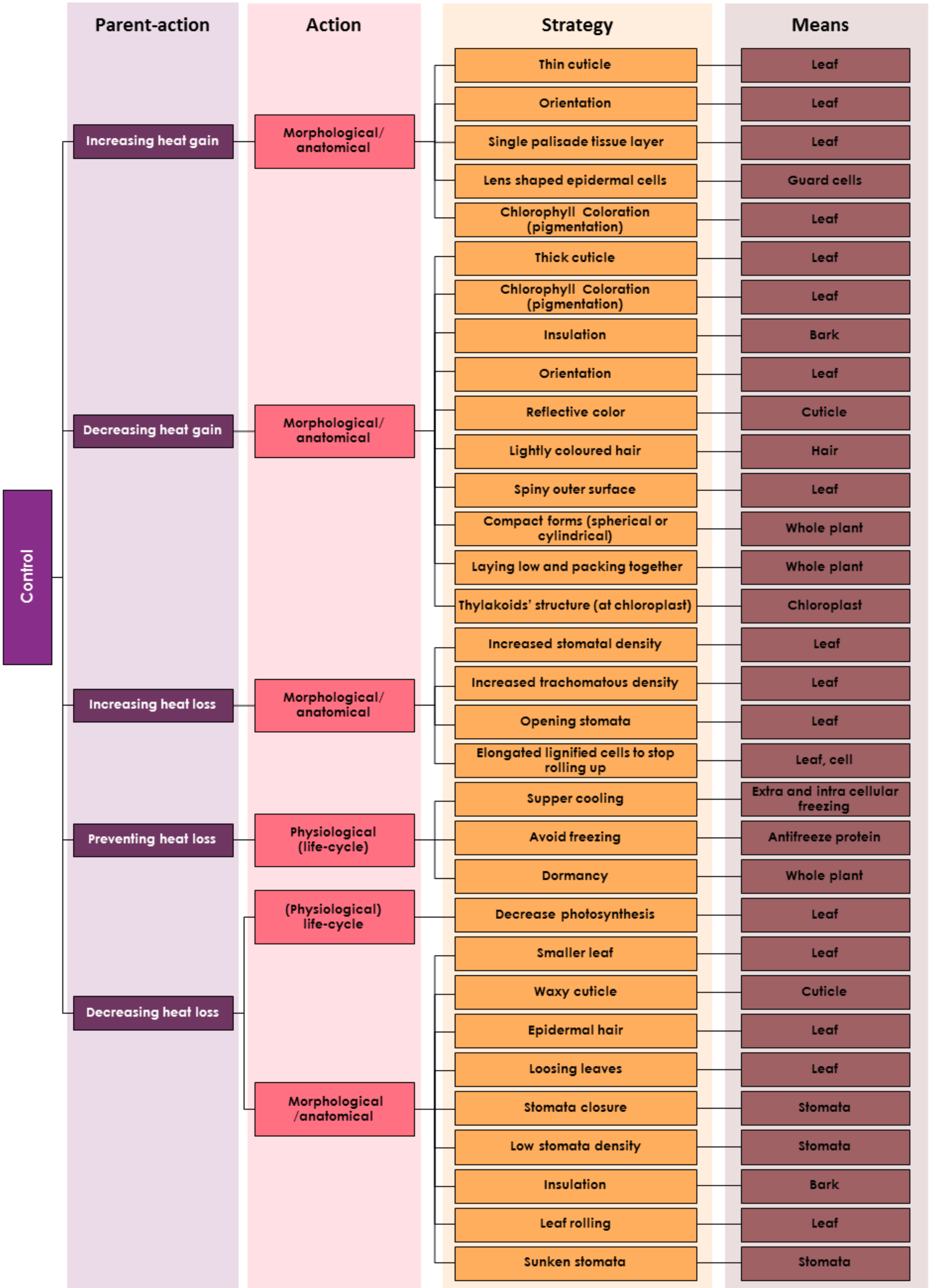

Figure 8-10 Behavioural and autonomic thermal regulation strategies of plants

8.7 Biology to architecture transfer

In a design by analogy process, once the retrieval phase of appropriate solution(s) is accomplished, a mapping stage is needed to facilitate transferring knowledge between domains (Gust et al., 2008). This is the stage in which the biological solutions should be abstracted to basic principles in order to assist designers in distinguishing feasible and appropriate ways for their architectural application.

The following three items inform the hierarchical structure of mapping links between biological mechanisms and architectural design strategies. Considering thermal adaption as a process in biological organisms, there is always a hierarchical connection descending from

1) The whole body of the organism to

2) The ultimate organ or tissue (the organ or tissue in contact with the environment), and/or the multiple organs/tissues/cells in an interaction, and

3) Ultimately between organs, tissues or cells.

Thus, these three hierarchical components can be abstracted for any mechanism of active thermal adaptation such as sweating or panting. Figure 8-11 shows the levels at which the generalisation could occur for passive and active strategies.

Even though the adaptation mechanism happens in a hierarchical order, some principles seem to play a primary role in homeostasis for each thermal adaptation mechanism. For almost all active strategies the ultimate organ/tissue is central to the adaptation mechanism while for passive strategies, the principles related to the interaction of the whole body of an organism with its surrounding environment seem to be the governing factors in thermal adaption. For the three levels of 1) organism, 2) ultimate or interrelated organ/tissues, and 3) between organs/tissues/cells, the following form the principles on which links were established (Figure 8-11).

1) morphological, spatial (location/position), and material properties for whole body
2) morphological, spatial (spatial interrelation of internal structure), and material properties for the ultimate or interrelated organs or tissues or cells
3) fluid and gas properties between organs/tissues/cells

For example, shape and size as the two morphological characteristics of an animal body affect thermoregulation in mammals. Body mass and the area of body surface influence the dissipation of heat or the convective heat transfer coefficient, and the ratio of the former to the latter changes inversely with body size. Accordingly, a large mammal with a low surface area would dissipate much less heat than a mammal with a higher surface area.

The size of animals can change dynamically during their lifetime. For example, some terrestrial species lose their body water to an extent the skin becomes totally dehydrated (Crowe, 1972);(Horikawa et al., 2006) as cited in (Horikawa et al., 2008). The contracted animal is called a tun and does not show any symptom of being alive but the animal resumes activity once rehydrated. This non-metabolic state is termed anhydrobiosis (Keilin, 1959).

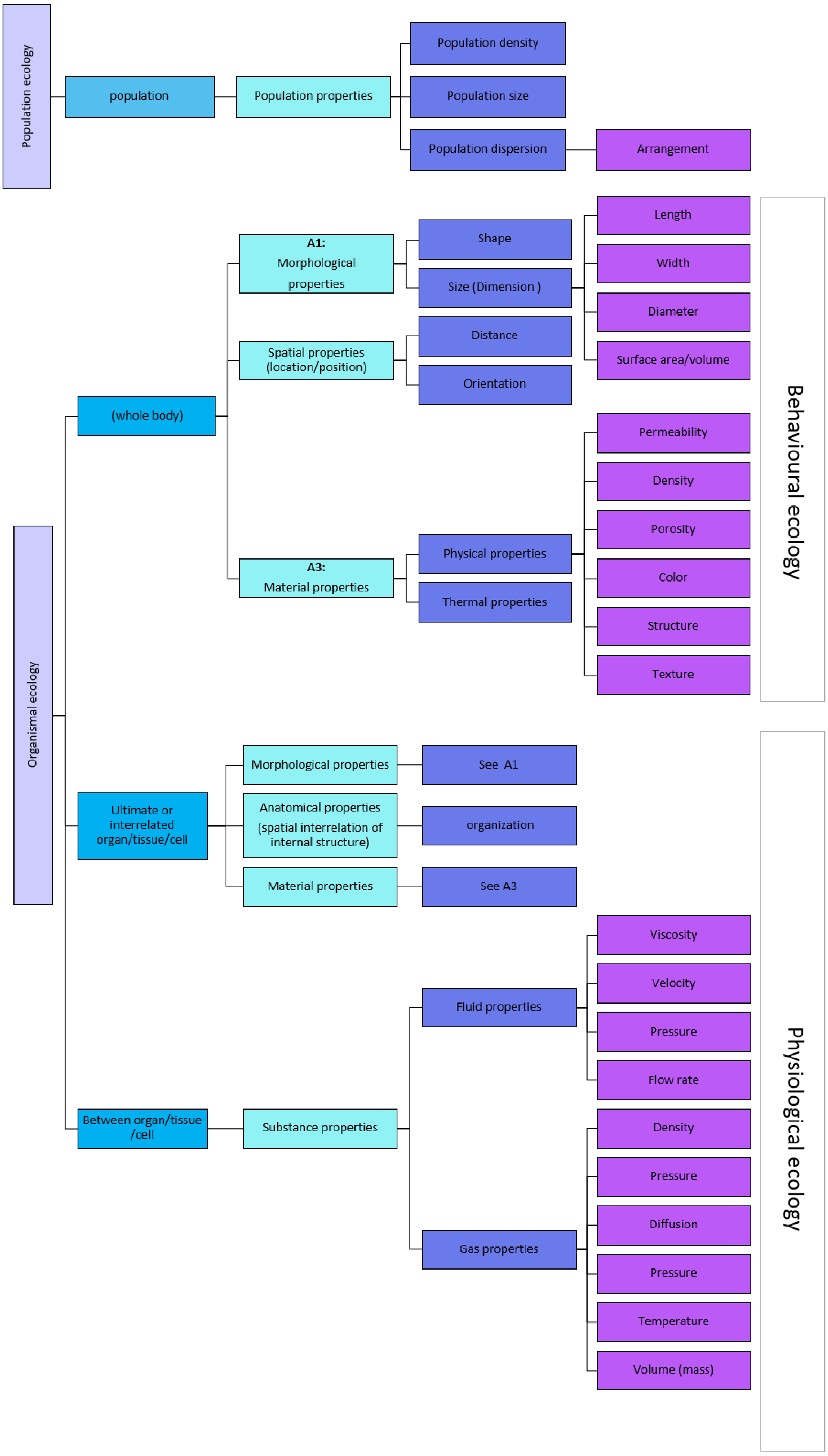

Figure 8-11 The hierarchical structure of mapping links between biological mechanisms and architectural design strategies

8.7.1 Discussion

Looking at Figure 8-6 and Figure 8-7, and as discussed in section 8.5, the white cells represent the areas in which the potential for architectural design to imitate the corresponding thermal adaptation principles in nature remains undiscovered. Most limitations in transferring biological principles to architectural ones seem to be about the physiological thermal adaptation mechanisms used by organisms. In other words, these limitations emerge as the dynamic responses of organisms to environmental thermal stresses that are stimulated by chemical interventions and supported by a complex system in terms of synchronising intricate changes in chemically provoked physiology, morphology and behaviour. However, this is inevitable to some degree as human expectations of dwellings are more in line with their static and constant properties. Moreover, humans cannot shut the whole building off for a long period of time on a seasonal basis, which is what animals do by dormancy. Likewise building surfaces are required to be in most parts unmoving and motionless and consequently, the building envelope cannot dynamically shrink back temporarily in order to decrease heat loss or expand to increase it as required.

Given this, imitating thermal adaptation mechanisms, where the mechanisms are involved with the whole body of organisms (e.g. torpor, body shrinkage, migration, locomotion) in building design will be difficult due to the inherent characteristics of buildings as unmoving structures. For thermal adaptation mechanisms that use a part(s) of the body (e.g. feather and fur insulation and piloerection), there are emulation possibilities and consequently potential applications in building design, as some parts of a building could show dynamic behaviour, such as sun shades. The conventional methods of building, however, restrict the imitation of some of these. For example, currently wall and roof insulation layers are positioned between constructional layers. This limits the ability to show dynamic behaviour similar to that carried out by organisms (e.g. piloerection). Only with the development of new insulation materials might piloerection be imitated, though adding additional insulation seasonally, such as putting up extra window sashes in winter, could be seen as a pseudo imitation of piloerection.

According to Willmer et al. (2009, pp. 14-15), the basis of physiological thermal adaptation mechanisms is at the molecular level. However, the manifestation of these mechanisms can be seen either at the sub-cellular, cellular, or organ level. They note that the adaptive acclamatory response of these three levels is associated with intracellular fluid, extracellular fluid, and circulating fluid respectively. From these three levels, the last one uses skin as the medium surface for adaptation which is comparable to the building envelop. This thesis does not cover extracting principles of thermal adaptation mechanisms reflection of which is not manifested through the skin or a tissue (e.g. blood vessel), such as supercooling.

As discussed in section 2.4.1.2 and section 2.4.1.3, different tools have been developed to facilitate BID which designers can use to bridge between biology and technological design. These tools have been developed for both solution seeking processes and analogical transfer phase.

In general, as shown in , the BID process consists of the following steps (Fayemi et al., 2017):

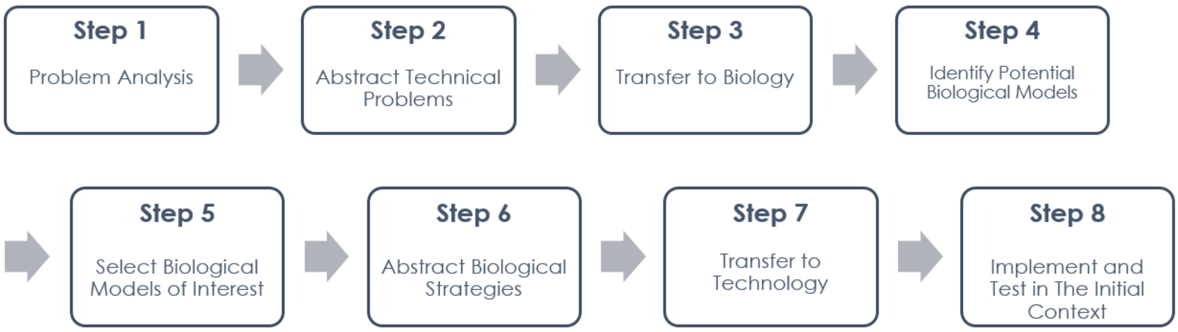

Figure 8-12 General processes of bio-inspired design adapted from Fayemi et al. (2017)

In moving from step 1 to step 4 and from step 5 to 8 the same process repeats. The first four steps are related to the solution seeking phase of BID while the next four steps need to be taken for transferring biology into design. The BID tools are developed for each step. These tools can be categorised into four different groups each related to the types of task that are required to be performed in that specific step.

1) analysis tools used for steps 1 and 5
2) abstraction tools used in steps 2 and 6
3) transfer tools used in steps 3 and 7
4) application tools used in steps 4 and 8 (Fayemi et al., 2017)

In this research, a series of heat transfer mechanisms (e.g. generate, gain, and prevent heat gain) are used (step 1) to abstract and describe the technical problems (thermal issues) in buildings (step 2). As the heat transfer terminologies are similar in building science and biological science, the same terms were used (step 3) to search the biological literature to identify biological solutions (step 4).

In this research there is an extra step between steps 4 and 5 (step 4-1) (see Chapter 9). This step involves consultation with experts in biology to confirm that the ThBA is as comprehensive as possible. Steps 5 and 6 go back to the thermal issues identified in step 2 and uses the ThBA to seek for appropriate biological models (Chapter 10). Step 7 was considered in Chapter 10 but implementation (step 8) was beyond the scope of the thesis.

Referring to section 2.4.1.2 and section 2.4.1.3, all abstraction tools lead to a functional model of the biological system. For example, *SAPPhIRE* (see 2.4.1.1) describes the biological system through state-action-part-phenomenon-input-organ-effect or, as another example SBF (see 2.4.1.3) represents any biological system through its structure, behaviour and function. The purpose of all functional models is to extract principles from the living organism. Accordingly, this research describes all thermal adaptation mechanisms by breaking them down into morphological (structural or anatomical), spatial and material properties.

Given these points, it seems that this research, at the current stage, has developed the small scale so called 'exploration model' created by Badarnah and Kadri (2015). However, this research has also examined the generalisability of thermal adaptation mechanisms. This has been done as a step towards the generalisation of thermal adaptation strategies for the purpose of creating BID office buildings.

Looking at Badarnah and Kadri (2015)'s model , there seem to be flaws in terms of classifications. For example, the pinnacle column of Figure 8-13 includes dark pigment, rock, and organism species and all are considered to fit in the same level. This seems to be an inappropriate categorisation as dark pigments are one characteristic of the organ of an organism and rock is not a living being. These flaws can also be seen in the Factors column (Figure 8-13).

In addition, the most significant result in the first round of developing the ThBA, shows that in contrast to Badarnah (2012)'s work, different species do not seem to use different mechanisms to adapt to the environment. Consequently, if the result of the focus group supports the same hypothesis, the investigation of additional species would not make significant changes in the systematic branching structure of the ThBA framework.

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Figure 8-13 Badarnah (2012) exploration model

8.7.2 General discussion

This chapter investigated thermal adaptation mechanisms in nature followed by looking for comparable energy efficient solutions in architecture. Overviewing the contents of this chapter, the following highlights emerge.

- When comparing thermal adaption mechanisms in nature to architecture, it seems organisms use a tight feedback loop in response to thermal challenges. This means, where organisms cannot adapt their body temperature to the environment through using a certain thermal adaptation mechanism, they intelligently switch into another one and this keeps repeating until thermal comfort is achieved. However, in buildings the same systems might not be possible. A poor analogy in the context of thermal control of buildings, is the use of thermostat. However, the on/off switching behaviour of a thermostat is not the same as the biological switching patterns that intelligently enable transition from one strategy into another. The latter is the tight feedback loop used by living things to respond to thermal stressors.

- It seems that thermal adaptation strategies do not vary from species to species or in other words there is not an infinite number of adaptation strategies in nature. This, accordingly, might suggest the irrelevancy of assuming nature to be the infinite source of intelligent ideas at least in the context of thermal adaptation. If the result of the focus group supports this claim, this research will respond to the fundamental question(s) addressed and considered by previous researchers regarding the generalizability of thermal adaptation principles. The goal would be focusing on the approaches the ThBA includes. Comparing the architectural parallels to biological ones might also suggest gaps where buildings have fallen short of emulation or at least proper imitation.
- The ability of organisms to respond to thermal stresses by using a hierarchy of thermal adaptation methods does not seem to have a parallel in buildings. While thermal adaptation in buildings can be also achieved through using a hierarchy of strategies such as openable windows, insulation, and sunshades, this is not comparable to biological systems in which there is a smart and automated connection between different levels of the hierarchy.
- If the focus group affirms the comprehensiveness and generalisation of biological thermal adaptation strategies, it also suggests that other aspects of biology with possible applications in building design, such as structural solutions, could be used in a systematic way by researchers if they follow the same approach.

Bearing in mind these highlights, and based on the discussion in Chapter 6 on finding the most appropriate approach for getting inputs from biologists, the next chapter concerns the semi-structured focus group.

8.8 Chapter summary

This chapter details the development process of the ThBA with the resultant document for later assessment by expert biologists the next stage. The development process began with the basic heat transfer mechanisms in biophysics. This was followed by reviewing the principal thermal regulation terminologies, which then enabled classification of the thermal adaptation strategies into the two categories of passive and active strategies.

The next chapter will explain how the focus group was conducted and the results analysed in order to determine the effectiveness of the ThBA as a vehicle for bio-inspired design for improving the thermal performance of buildings.

9 Evaluating the ThBA Version 01 by Experts in Biology

9.1 Introduction

This chapter details the qualitative data collection procedures and data analysis results related to the research stage of evaluation of the thermo-bio-architectural (ThBA) framework by biologists. This was achieved through means of a focus group discussion. Before using the ThBA in a bio-inspired design process (see Chapter 10), it was important that biologists evaluate the framework. The focus group provided an opportunity for biologists to assess the quality, inclusiveness, and applicability of the framework.

Focus groups have been used as a technique for evaluating user-centered tools. Usually, evaluation of a tool such as the ThBA investigates the usability, and applicability of the relevant applications or systems (Wright, 1998). Also, in some Human-Computer Interaction (HCI) research, the key point has been identified as the user's full comprehension of the tool and its structure (Mazza, 2006), so ensuring biologists understood the ThBA was thought to be important, as well as checking that nothing was missing from it. Since the ThBA was developed to be used by architects, only its biology side needed to be evaluated at this stage. A comprehensive understanding of the ThBA's configuration could enable a valid evaluation of the logic behind the classification scheme of the biological solutions, which in turn would create a mental map for the experts. With a clearer mental map, the intention was it would be easier for biologists to comment on any missing information and the appropriateness of the hierarchical structure.

9.2 Pre-evaluation of the focus group outcome

At an earlier stage, this research was presented on Thursday 26th April 2018 at a seminar in the Ecology and Evolution seminar series 2018 in the School of Biological Sciences. All staff members in the school were invited to attend this event via the email they would normally receive for the monthly seminar series. Around ten people attended, most being PhD students. The ThBA framework was not developed at that time.

The purpose of having a presentation was to check whether the research question would communicate well to biologists, and to ensure the language that was planned to be used for the explanation of the ThBA interdisciplinary framework was appropriate. It was important as confusing biologists could have affected the research results. Similar to other interdisciplinary research, successful communication between disciplines increases the chance of receiving trustworthy and useful results. Thus, the language should be tested to avoid the ambiguity which can occur involuntarily when people from different disciplines want to share their ideas.

The seminar presentation consisted of a number of slides showing the results of the energy simulation and the thermal challenges identified for one of the case studies. Audience comments suggested the research question was well-worth investigating, and a number of those attending were interested in taking part in any future focus groups.

9.3 Recruitment process

Participants in the focus group were identified by their area of expertise as explained on their university web page. They were invited to the focus group through an email sent by the lead researcher (Appendix B). Around 50 emails were sent. Almost all the invited experts replied to the invitation email, even those who said they could not take part. Twenty experts were interested in taking part but had limitations with their schedules. Around 80% of those who expressed an interest in participating were either professors or associate professors. Eventually seven participants agreed to take part with one pulling out at the last minute because of a schedule change. Doodle poll was used for selecting the most appropriate day on which all participants could come.

Participants were given a 10-dollar coffee voucher. This incentive was used as a means of increasing the likelihood of participants attending the focus group on time and ensuring their undivided attention. Refreshments were also provided during the session.

9.4 Description of the focus group

The focus group was conducted to evaluate the effectiveness of the ThBA in systematically finding biological strategies and corresponding information. Participants were greeted and then advised to read the ground rules and sign the consent forms (see Appendix B) before starting the discussion. Then they were provided with the list of questions and a ten minute introduction that included a brief explanation of the ThBA structure, and the motivation behind its development, as well as guidance on how to use it.

The focus group was not planned as the first in a series of multiple focus groups but it was decided there might be a need for a second focus group if the results of the first session were inconclusive. There were three potential concluding conditions for the first focus group:

1) The framework has many substantial problems and cannot be fixed quickly as modification of the framework would be either time consuming or impossible.
2) The framework is almost comprehensive and successful but still needs some modifications that need to be confirmed by biologists in an extra focus group.
3) The framework is quite inclusive and only minor changes are required. This means the researcher can make amendments independently.

In the case of outcomes 1 or 3 there would not be a second focus group as a second focus group was foreseen only if outcome 2 happened.

At the focus group of six people each pair of participants (see 9.4.1) shared the two frameworks (active and passive strategies) printed on A1 pages (Figure 8-6, Figure 8-7 and Figure 8-10), on which information was mapped in a hierarchical order. Each framework consisted of the architectural and biological parts located on the left and right-hand sides of the page respectively. An empty box for notes was also included on the sheets in which participants were asked to write down their comments on issues arising, or suggestions, in case the time limit for discussion of each question was reached before these thoughts were voiced.

One of the researcher's supervisors was present in the focus group but did not sign the agreement and hence was not a member of the panel. This supervisor was only there as an observer but occasionally contributed to the discussion when asked to do so by the participants.

9.4.1 Sampling and group composition

It has been argued that there is no limit to the number of participants in a focus group and the sample size is determined based on the aim of the project (Kitzinger, 1995). Others say the size of the ideal focus group is limited, and can vary from 4 to 14 (Dilorio et al., 1994), although Morgan (1996, p. 34) and Bloor et al. (2001) suggest between 6 and 10.

Initial thoughts were to conduct only one focus group with six to eight participants. This was because the purpose was to evaluate the ThBA rather than elicit diverse set of opinions on a topic. The only problem was having sufficient knowledge of all biological fields. Research suggested there were up to eight different fields of biology that could generate different approaches to the assessment of the ThBA framework. These were the fields of Zoology including Entomology (the study of insects), Herpetology (the study of reptiles and amphibians), Ichthyology (the study of fish), Malacology (the study of molluscs), Mammalogy (the study of mammals), and Ornithology (the study of birds) as well as Botany and Microbiology.

The group of volunteers consisted of three PhD students, and three academics none of whom had a supervisory relationship. The group covered a diverse range of expertise including botany, and marine and terrestrial animal biology. The group's fields of specialisation covered almost the whole of the system of animal classification as there was an approximately equal distribution of expertise between those working on vertebrates and invertebrates in different biological scales from cells to tissues, organs, and single organisms.

The focus group session was conducted on 30th November 2018 at Victoria University of Wellington, Kelburn Campus, after approval was obtained from the Victoria University Human Ethics Committee (ref 26789). The whole session was audio recorded to capture what was said during the meeting. The School of Architecture provided an audio recorder for the focus group, and the recorded file was later transcribed. Participants agreed to be approached and asked for their permission later if there was a need to attribute a quote to their particular background or expertise. This option was added to the consent form in case that necessity arose.

The session was confidential, and participants agreed not to share any details of it with anyone outside the group, even family members and friends. It lasted for 90 minutes including the welcome, organisational information, signing off, and refreshments. This aligned with what has been suggested in the literature where the recommended time for a focus group should never exceed two hours (Morgan & Krueger, 1993; Plummer-D'Amato, 2008; Doody et al., 2013). After the introductory 10 minute session the five main questions were asked (see Appendix B), and discussion of each took around 15 minutes. The session was closed 5 minutes at the end of the discussion of the last question. The chairs and tables were organised in a circular pattern.

9.4.2 Analysis

One of the methods for analysing qualitative research is through use of Computer Qualitative Data Analysis Software (CAQDAS), which can store and organise a large amount of data. Despite being powerful in terms of systematising the research analysis, such software is not a panacea for solving the problems linked to the identification of themes and interpretive strategies (King, 2008; Gale et al., 2013). It has been argued that CAQDAS causes analytical distance, meaning it does not allow the researcher to see the big picture as the automation of the analysis process seems to induce overuse of coding (Gilbert, 2002; Johnston, 2006). However, the increasing popularity of such software highlights its benefits in fracturing and reassembling data compared to the traditional methods of data analysis. One of the key advantages of CAQDAS is its high speed (Carvajal, 2002; Blismas & Dainty, 2003; L. Richards, 2014, p. 127). It also provides researchers with a variety of analytical options through which researchers can test their assumptions rapidly.

This research used *NVivo 12 plus* and latent content analysis for coding and theme identification. The qualitative content analysis can be either focused on manifest or latent content. The former is the obvious components of the text while the latter involves interpretation of the hidden layers under the text (Downe- Wamboldt, 1992; Kondracki et al., 2002). The audio record was transformed into text using Trint. The transcription involved verbatim meaning reproduction of every single word of the verbal data. This has also been claimed as a crucial phase in data analysis as all the interpretations are generated based on the text (Lapadat & Lindsay, 1999). To assure the precision of the tool (*Trint*) in transcribing the entire dialogues, the researcher listened to the audio for a second time and matched what was heard to the transcript to check the accuracy of the text generated by the automated transcription tool.

Analysis of the text requires knowing the purpose of the research as the purpose drives the analysis (Rabiee, 2004). The text was abstracted and codes, themes, and categories were used to aggregate the data. Abstraction means "*grouping together under higher order headings*" (Burnard, 1991, p. 462) and as suggested by Graneheim and Lundman (2004) abstractions are associated with a higher logical level of description and interpretation.

Codes are the condensed meanings that have been assigned a label. A thematic approach was used for the data analysis based on the questions and the narratives of participants. To create a basis for the most common themes, transcriptions were read several times, and the text was then imported to *NVivo* for further coding and more detailed analysis. Codes were grouped into different categories, and all clustered in a category shared commonality, and finally themes were created to link similar categories. Themes have been referred to as threads of meaning (Baxter, 1991, p. 264) and recurring regularities between categories (Polit & Beck, 2004, p. 734).

The following sections introduce the themes identified including their categories and subcategories.

9.4.2.1 Development of themes and sub-themes

The main reason for this focus group was to evaluate the applicability, usability, and inclusiveness of the data categorised and aggregated in the ThBA framework. Accordingly, the main themes were to some extent predictable due to the purpose of the focus group. The focus group process, as well as the question list, highlighted the possible emergence of a distinctive set of themes.

The themes were derived out of the concerns raised during the research. The focus group was set up to ensure

1) the participants understood the framework,
2) they had evaluated the ThBA and;
3) the framework was valid.

Given the first theme, it was important for the participants to understand fully both the framework and the purpose behind its creation. This was targeted in the parts of the discussion where the participants showed their understanding by asking questions or talking about the framework. However, no question was directly asked to confirm whether the participants had understood the ThBA.

For the second theme, the main reason for the focus group was to examine the contents of the ThBA. Accordingly, the second theme was focused on evaluation of the framework.

In the context of thermal adaptation principles, a series of concepts seemed to play a critical role in the understanding of the nature-biology relationship. These concepts were revealed during the exploration of the ThBA structure. Consequently, the third theme was centred around the validity of the ThBA. It was not only important to evaluate if the researcher had a good grasp of the necessary knowledge of how thermal challenges are dealt with in nature, as this formed the basis of the ThBA, but also to examine the extent to which this knowledge had been successfully incorporated into the structural organisation of the ThBA. The third set of questions provided a chance for the researcher to learn whether these goals had been achieved.

The analysis showed that the ThBA could perform properly in its current configuration without the need to add extra layers to its structure. Furthermore, the understanding of the biological concepts was confirmed as valid and it was not thought that a rearrangement of the ThBA framework was necessary. One suggestion for change was raised but it was made clear that this could be added to the framework in the next stage of this research (see 9.4.2.7).

Given these three themes had to be addressed the text was analysed against them. The coding process was performed using the whole text rather than scanning through the answers given for individual questions. Initial lists of codes were created based on the topics brought up by biologists (Braun & Clarke, 2006). The codes achieved through descriptive coding were then reviewed and grouped under a category heading. These groupings were based on their similar patterns and commonalities as well as their relationship to the themes. The categorisation of codes was repeated multiple times, each iteration being labelled with an analytical code. The process of re-categorisation continued until the remaining categories no longer shared any commonalities and hence could not be merged into a new group or labelled with an analytical code. The last sets of codes were the subthemes falling under the main themes.

Those codes that did not fit into any of the themes were saved for further analysis. Almost all codes fell into at least one theme, and only five were identified as emergent topics unrelated to any of the themes. These codes were amalgamated under a new theme labelled 'suggestions'.

Figure 9-1 shows the different stages in which the codes were generated and grouped under the second theme of framework evaluation which is shown in blue in Figure 9-2. A similar approach was used to derive the sub-themes of the first and the third themes. The light blue boxes represent the initial codes and the blue gets darker each time the codes group under a new category. This continues until the themes and sub-themes are defined.

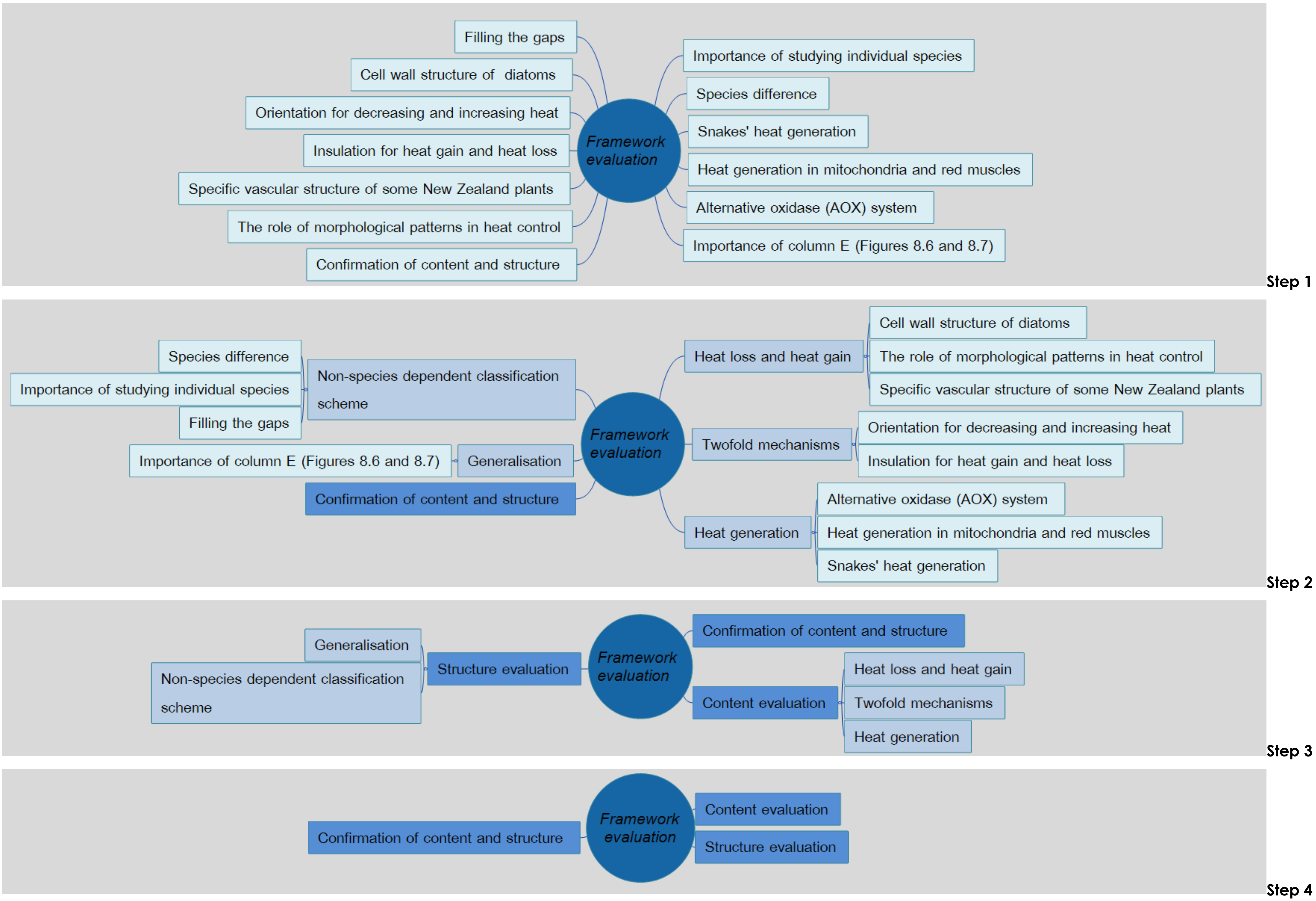

Figure 9-1 Different stages of coding based on the second theme 'framework evaluation'

9.4.2.2 Coding structure

Figure 9-2 shows the hierarchical structure of data with the highest level showing the four main emergent themes of:

1) Understanding the ThBA,
2) Framework evaluation,
3) Framework discussion
4) Suggestions

These are shown branching into sub-themes and their corresponding subcategories. The sub-theme layer is set within the rectangular boundary.

In Figure 9-2, the themes are shown in different colours. The colour gradient represents the hierarchy as it gets lighter in each level from the top (main themes) to the bottom (sub-themes and sub-sub-themes).

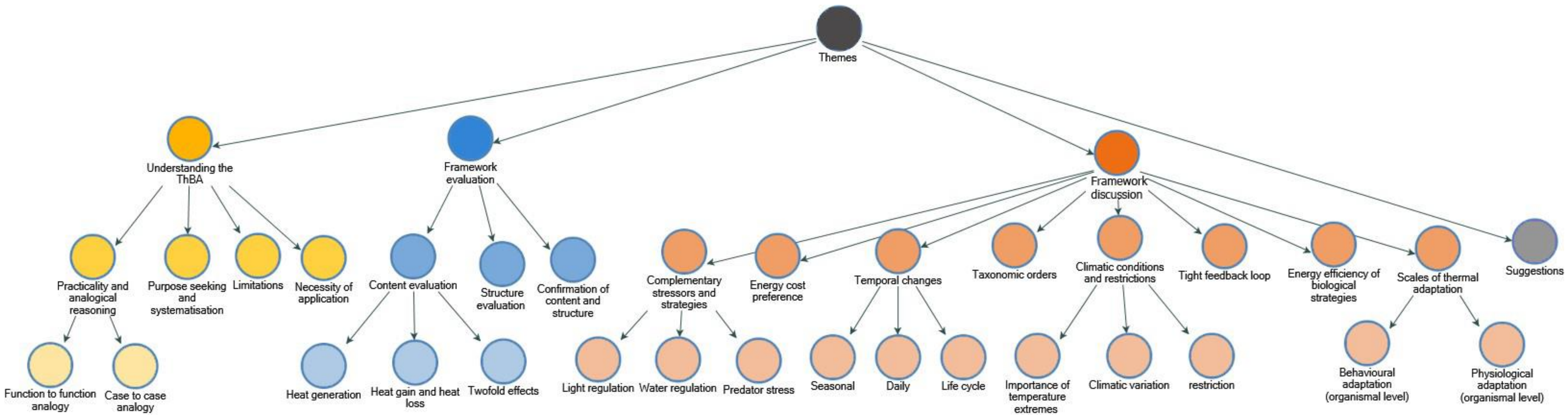

Figure 9-2 The coding structure including the main emergent themes and sub-themes

9.4.2.3 Visualisation of the participants' contribution

Although this stage of the research is a qualitative investigation, the use of *NVivo* introduces a quantitative aspect. As a result, Figure 9-3a, 9-3.b, and 9-3.c show the distribution of the references used to generate the themes based on the expertise of participants and the biological scale under focus. For example, Figure 9-3.a breaks the references down by specialism, 9-3.b by whether the participant worked at the scale of organism or cells, and Figure 9-3.c indicates the contribution made by each participant to the emergent themes. The percentages are useful in showing the distribution of responses, for example in 9-3.c it is apparent that A1 made a very small contribution and A2 was the only person who made additional suggestions.

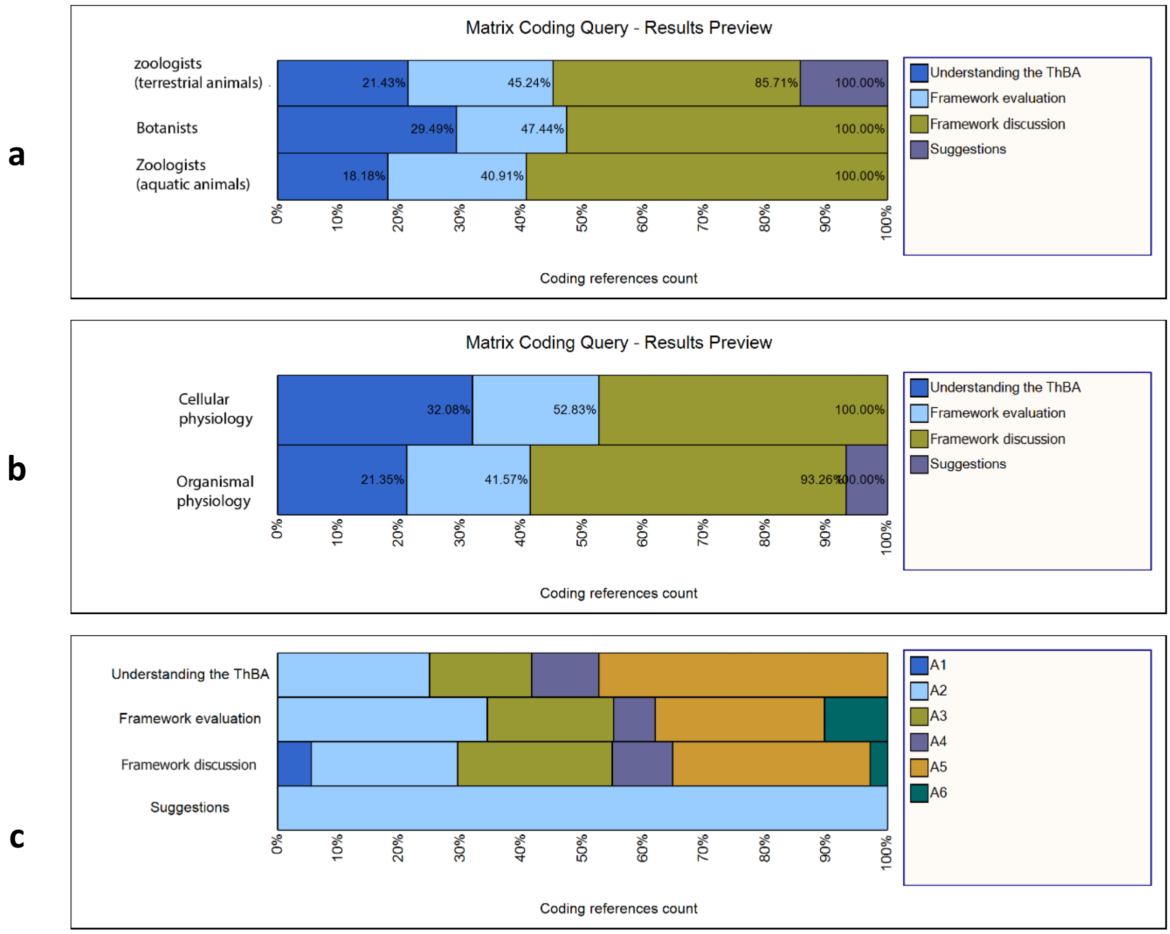

Figure 9-3 Distribution of the references a) based on participant expertise, b) based on biological scale under focus, c) contribution of participants to the emergent themes

The size of the rectangles in Figure 9-4 represents the total number of references coded for the four main themes. It shows that almost half of all codes was related to the framework discussion theme. In other words, the diagram represents a balance between the two parts of:

1) Evaluating what the researcher had developed (the ThBA) and;
2) Evaluating the analogical relationship between nature-architecture discovered during the development of the ThBA.

The dominance of the framework discussion theme not only underlines the successfulness of the ThBA, as the time spent on participant understanding and approval of the ThBA was noticeably short, but also highlights the quality of the learning process, the validity of the concepts, and the level of biological knowledge and its use within the ThBA to make it appropriate for architects and building designers.

Figure 9-4 Proportional representation of all references coded for the main themes

Figure 9-5 shows the data in a visual hierarchical format as an *NVivo* output. Themes are shown in different colours, and the size of the rectangles represents the number of coding references at those nodes (themes), with sub-themes shown within themes in a lighter shade.

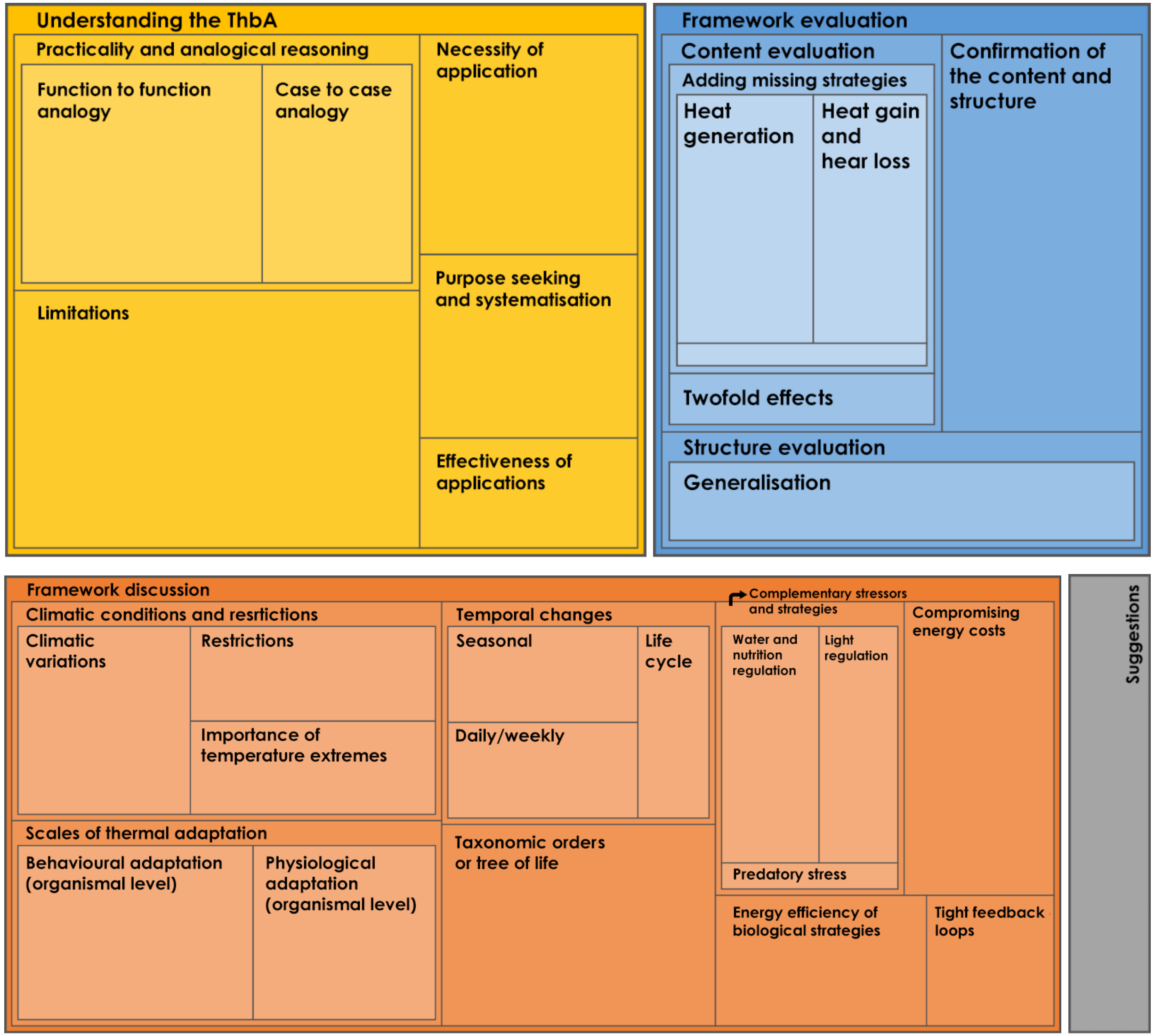

Figure 9-5 Hierarchical representation of the themes, sub-themes, and sub-categories

9.4.2.4 Understanding the ThBA

The following categories that emerged from the focus group discussion showed the ThBA was understood by participants. There was evidence suggesting the research question was also understood. In general, the participants' understanding of the ThBA framework was manifested in a hierarchical perception level proving they knew:

1) why the ThBA has been developed (purpose seeking) and that a bottom-up approach to the BID process could be a system for designing energy-efficient buildings (systemisation of the BID process);

2) why the ThBA should be used (need for its application);

3) how the ThBA could be utilized (practicality and analogical reasoning) and;

4) where the ThBA might not be useful (its limitations).

Figure 9-6 shows the contribution of the participants to this theme. Although A1 and A6 did not say anything at this point they made it clear they agreed with the points the other participants made. For example, the arrows drawn from 'limitation' to A4, A5, and A2 show that only these three participants contributed to this sub-theme.

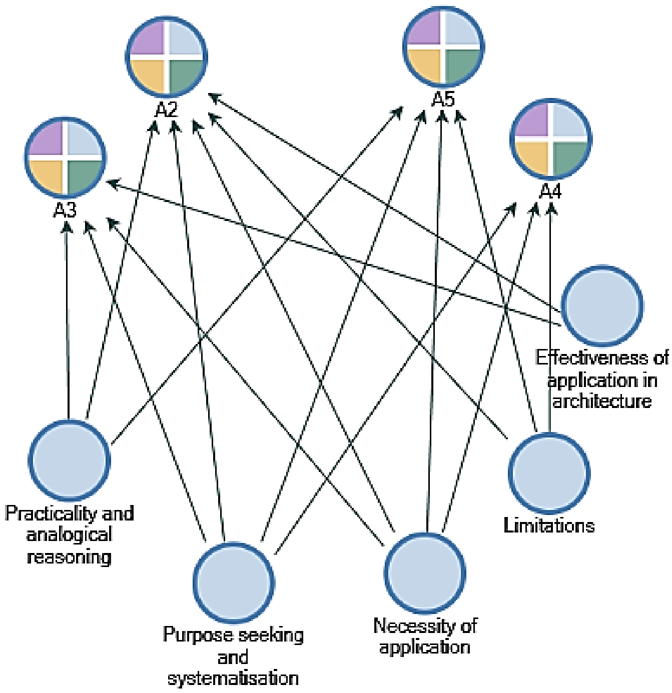

Figure 9-6 Contribution of the participants to the "understanding the ThBA" theme

9.4.2.4.1 Purpose seeking and systematisation

The participants perceived the rationale behind developing the ThBA framework. They were aware of the limitations of numerous metaphoric uses of biological functions and processes in the fields of architecture and design under the notion of biomimicry. A5 stated, "*...yeah, you can attach it [a metaphoric description] to a photo and it looks nice.*" Participants became aware of the importance of a system like the ThBA, and the purpose behind its development as A2 confirmed how "*...the gap analysis*" could be used for identification of future technological improvements for designing bio-inspired energy efficient buildings. A4 added, "*...the purpose of the system is to identify the feasibility of [biological] methods [in building design] and the gaps [empty boxes].*" Participants were informed about some of the empty boxes in the architecture side of the ThBA framework that highlighted the apparent absence of parallels in biology. However, it was not expected the biology experts would be able to fill these gaps. A3 noted that where the existing biological knowledge failed to offer a practical solution for architectural thermal challenges, designers could seek deeper "*...in biology, finding a spot on earth or in the ocean [for a solution] is [always] in prospect.*"

In response to the question of whether The BID process could be a system for finding appropriate solutions in nature to improve the thermal performance of office buildings, A5 asked "*It seems you have a building site and a purpose [thermal challenge] in mind, you have a list of goals and restrictions, so you would want a list of organisms with the same conditions and restrictions, right?... making [an] encyclopaedia of creatures and their thermal acclimations.*" A5 continued "*...there is nothing like that existing, right? I think it could be a system.*"

9.4.2.4.2 Necessity for application

The group members pointed out some existing thermal challenges in New Zealand's buildings based on their personal experience of using these, and noting that residential and office buildings do not seem to be well adapted to New Zealand climatic conditions. A5 was unhappy with New Zealand houses and asserted "*...in Wellington, we don't go downstairs in the winter [to stay warm].*" A2 referred to TeToki a Rata (TTR) a new building located on the Victoria University campus and claimed that architects as amateur biologists "*...have got enough of [biological knowledge]*", for example, using "*glass for light and temperature*" but they do not consider both ends of a strategy as large windows bring in more light to interior spaces but can also make them extremely hot. Like A5, A2 was unsatisfied with the TTR building and continued "*...the weird thing about TTR is the* *massive glass, it is cool but too warm."* A5 explained the experience of living in a building with an attic and added "...*in winter all the heat goes up to the attic*." Likewise, A1, A3, and A4 echoed criticism of the thermal comfort conditions of buildings in New Zealand especially in winter. A3 joked about the concept of acclimation in existing buildings and declared "...*acclimation basically says the person in the house is just hardy enough*." A1, A5, A4, and A6 agreed and continued "*yes, by [using] more blankets*." A5 continued "...*the houses in Wellington should not be in Wellington*."

9.4.2.4.3 Practicality and analogical reasoning

The group members confirmed there is a logical link between nature and architecture. They comprehended this analogy at two scales. At the larger scale, participants recognised the analogy between buildings and organisms regarding adaptation to the environment (see 9.4.2.4.3.1). Following this, they dug deeper into the concept investigating the possible applications of biological intelligence in buildings (see 9.4.2.4.3.2). They understood the ThBA to the extent that in some cases they were curious about finding parallels between biological and thermal adaptation strategies in architectural design.

9.4.2.4.3.1 Case to case analogy: buildings to organisms

The following quotes show the participants could see the similarity between a building and its environment. Participants discussed whether buildings could be recognised either as endotherms or ectotherms or as plants or animals. There were contrary opinions.

Several analogies were related to the notion of envisaging buildings as either plants or animals. The debate started when A3 pointed to the part of the ThBA framework developed for animals going on to say "…*in my opinion animals are much more clever in an evolutionary sense of solving these problems, but buildings are structurally more like plants*." A3 brought this topic up again almost 20 minutes after the start of this discussion and after the group had confirmed the inclusiveness, effectiveness, and applicability of both the animal and plant parts of the framework by saying "*I was just curious…architects gravitate to animals which would be intuitive, or plants which maybe is a little bit less intuitive but more structurally similar*."

The discussion about heat generation was linked to the broad classification of animals into endotherms and ectotherms. As part of this discussion, the researcher pointed to heat generation in buildings as the reason for having to find a way to provide thermal comfort for the occupants and said "*heat generation is a characteristic of endotherms and* *maybe that is the reason architects are more interested in animals."* A3 agreed with this and declared *"I guess you're right…endothermic animals might be the best."* A2 did not agree and believed *"...endothermy is the problem"*, and proposed buildings should be *"…treated like the ectotherms."* A2 referred to the characteristics of ectotherms in terms of keeping their body temperature at the same level with the environment explaining how this feature makes them free of needing to generate heat and added *"…if you could not use energy in a building and keep it at a stable temperature then that would be more optimal than other ways."* A2 believed in harsh climates *"…ectotherms and plants can survive."*

The dialogue about the ability of some organism to generate heat led to a new discussion about the weakness of one category compared to another. The researcher questioned A2 to confirm if being endothermic was a weakness compared to being ectothermic. For the second time, this was confirmed by A2 noting *"…[an] ectotherm minimises its energy and to be able to be active, [an ectotherm] stops and eats once a week."* A3 seemed to want to refer to the point that humans cannot stop working and wondered if the situation would arise where *"…it's far too cold to come to work today."* A2 mentioned the importance of the end goal in designing energy efficient buildings and asserted *"…if the end goal is to reduce energy use, then the way that ectotherms and plants do it might be a good thing."*

9.4.2.4.3.2 Function to function analogy: building adaptation strategy and organism adaptation strategy

Almost all participants tried to find a parallel in building design when explaining a thermal adaptation strategy. A5 described the heat generation and melting capability of the skunk cabbage and noted the skunk cabbage *"…from an architectural standpoint… [is like]…turning on a heater."* On the topic of multiple environmental stressors, A2 claimed the light distribution mechanism of the orchid flower *"…is a cool idea for architecture if you can reflect the light [within the space]."* A5 was not sure if the daily behaviour of reptiles and the lifecycle of seeds could have a meaningful translation to or a parallel with buildings, stating *"I do not know what [its] architectural equivalent might be."* A1, A2, and A5 suggested how architects might deal with the changing temperatures in winter and summer. A4 wondered whether *"…you can expand the house during the summer?"* A2 added it would be good *"…if you could just raise up the ceiling [in summer] like a heat trap."* This was confirmed by A5 stating *"I feel that the ceiling can [deal with] it."*

9.4.2.4.4 Limitations

There was agreement between participants in terms of identifying a number of limitations in applying the ThBA to building design. All participants agreed the constraints in architecture as well as the requirements of construction often fall short of the ideal espoused by biomimicry. They discussed current buildings that have not been built so that they could behave and function like organisms. The discussion then focused on the necessity of adopting temporal changes so an organism could acclimate to its surrounding environment. A5, A6, A2, and A1 claimed "*…we cannot shut down a building [at certain times]*." A2 explained this further with an example "*…an ectotherm can stop and eat once a week if [it] has a [long] road [to go] and needs to stay warm enough to be able to be active*." A5 mentioned that "*…some organisms do not exist in certain conditions*" and added "*…it might not be the whole organism [that undergoes temporal changes]*" as in some cases only one part of an organism gets involved with the latter. A5 stressed the sudden failure of a living organism in harsh climates when the climatic conditions go beyond its capability for adaptation, and added "*…some plants do not try to acclimate to winter conditions, they die*." A4 stated "*… [a] sponge changes its shape based on temperature*" and was curious how a temporal change could occur in architecture, continuing "*I wonder how an architectural setting can change shape and size.*" A5 stated "*…in biology if something does not fit [to the environment] it dies.*" Later A5 linked this claim to the concept of the connection between buildings and the environment, "*…we should take it into account…if a building does not fit…[it] just stays there [unused]*."

9.4.2.4.5 Outline

With respect to the first theme (understanding the ThBA), Figure 9-7 and Table 9-1 show the spread of the generated codes by the expertise of the participant. Expertise was broken down into three categories based on the classifications/levels/scales of the organisms in which participants specialised. These categories were labelled:

a) Terrestrial and marine zoology, and botany,
b) Organism and cellular physiology; and
c) Vertebrates and invertebrates

Figure 9-7 presents the participants' proportional contribution based on b and c. As can be seen the codes generated covered cellular and organism physiology almost equally while that linked to invertebrates was more dominant. However, what Figure 9-7 does demonstrate is that all fields were covered.

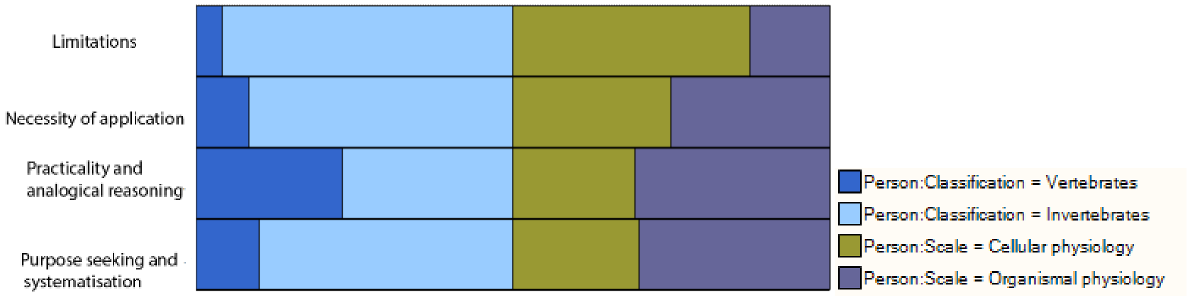

Figure 9-7 Spread of the codes generated across the expertise of the participants

It is apparent from Table 9-1 that most of the codes were related to practicality and analogical reasoning. Botany had the highest contribution with the most codes generated for the limitations theme (Table 9-1). This is interesting regarding the discussion that arose later over whether building were plants or animals (see 9.4.2.4.3.1). Again Table 9-1 shows all themes were covered by all biological specialties.

Table 9-1 Spread of the codes based on field of expertise

	A Limitations	B Necessity of application	C Practicality and analogical reasoning	D Purpose seeking and systematisation
Zoology (terrestrial)	1	1	6	1
Botany	9	4	7	3
Zoology (marine)	2	1	0	1

9.4.2.5 Framework evaluation

The evaluation of the ThBA framework had two main parts:

1) Content assessment and

2) Structure assessment.

Confirmation of the validity of the whole framework was achieved in a very short time (Figure 9-4) as most of the discussion was not focused on the evaluation issues. This created extra time and allowed the group to make a number of suggestions. The participants believed extra layers could be added to the framework in the future as complementary levels. The following sections explain the minor changes they felt could be considered in both the content and the structure of the ThBA framework.

It can be seen from Figure 9-8 that almost all participants are quoted at least once in this section.

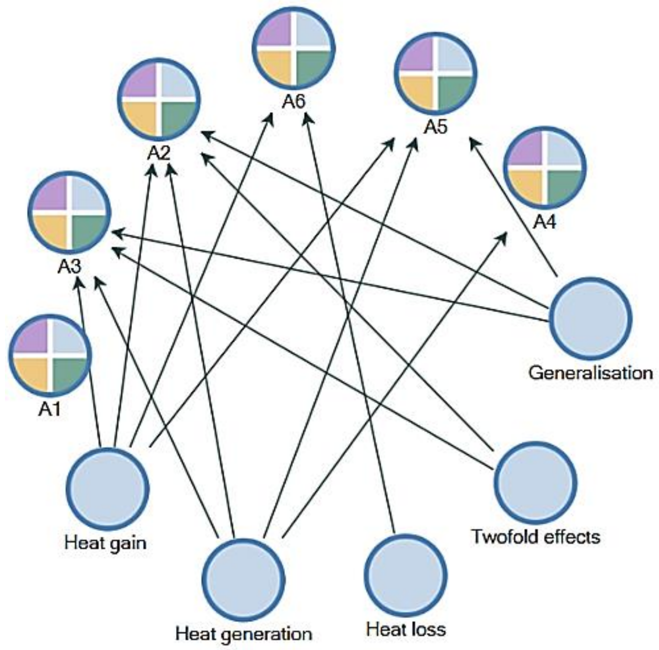

Figure 9-8 Contribution of the participants to the framework evaluation theme

9.4.2.5.1 Content evaluation

Reflecting on the content, comments from the discussion have been organised based on column A in the ThBA with the addition of twofold effects which emerged as an issue in the discussion Figure 8-6, Figure 8-7 and Figure 8-10.

9.4.2.5.1.1 Heat generation

Only a few strategies related to heat generation mechanisms were missing. In some cases, the strategies suggested by participants existed in the framework but were categorised differently. This could be reflected in the fact that thermoregulatory terms have been changed (see 8.3.1.3, IUPS). For example, A2 referred to shivering as a heat generation mechanism in snakes for "…*increasing the temperature of their clutches…the snake is curled up around that clutch and [the heat] is transferred to the eggs to increase development in the egg.*" A2 suggested this when group members were asked to evaluate the passive strategies while shivering was already classified under the active strategies. A5 explained another heat generation mechanism that was basically "…*an alternative oxidase (AOX) system that skunk cabbage [uses] to melt the snow around their flowers.*" This mechanism was described by A5 as "…*an electron transport*" activity in which the enzyme causes the electrons to move quickly through the AOX pathway. The short circuit transportation of electrons does not allow energy to be conserved *"in the mitochondria for respiration [as] all the energy gets dumped really fast to generate heat in the process."* This thermoregulation strategy occurs at the cellular level and is a biochemical activity which is not within the scope of this research. Orientation was mentioned by A3 as a temperature regulation strategy for increasing heat gain. A4 explained a type of heat generation in swordfish which was confirmed later by A2 as a strategy that deals with *"mitochondria and red muscles."* This strategy was similar to the heat generation process in brown fat. Brown fat heat generation as non-shivering thermogenesis was documented in the active strategies sheet but as it is carried out in cells and through metabolic reactions it was hence not the focus of this research.

9.4.2.5.1.2 Heat gain and heat loss

Colour was suggested by A2 as an effective strategy for increasing heat gain in reptiles. A3 described the specific vascular architecture of some New Zealand plants as a means of retaining heat between the leaves. A3 referred to some recent research and indicated that *"[the] distinctive architecture [of the plant]…during the day, the air heats up inside the lattice of branches, and it's more slow to cool down at night."* A5 suggested *"…a lot of stationary organisms, especially [those] underwater can't control their temperature."* The discussion partly clarified why thermal adaptation in some organisms should be carried out at a cellular level (physiological adaptation) as A5 confirmed *"…it's all about cellular level acclimation."* The participants proposed only one additional heat loss strategy. A6 suggested the morphological patterns on the shells of *"…some intertidal bivalves act as a radiator when sea water is left on them".* A6 stated *"…the cell wall structure of some diatoms is supposed to be involved in focusing light for photosynthesis, and hence increasing the temperature at some points."*

9.4.2.5.1.3 Twofold effects

As shown in the ThBA, a number of thermal adaptation strategies have double applications in terms of a heat regulation mechanism. This was brought up and confirmed by A2 and A3 when they referred to orientation and insulation respectively. A3 explained how orientation of leaves towards or away from the sun leads to increasing or decreasing heat gain. A2 described how the burrowing of ectotherms provide insulation for survival during both the cold and hot parts of the year.

9.4.2.5.2 Structure evaluation

Confirmation of the ThBA framework structure (step 3 of stage 3, Figure 6-4) would be achieved if the main characteristics of

a) the generalisation, and

b) the non-species dependent classification scheme

were accepted by the participants.

The concept of generalising strategies was raised multiple times during the discussion. A2 stated the ThBA "…*is a really good in depth information and tells [users] where it comes from and how general it is.*" All the experts also explained that climatic variation might trigger the evolution of some different species from endotherms and ectotherms. A2 believed the general features are more likely to be used by endotherms and ectotherms but in different climates "…*there might be species differences.*"

Furthermore, A2 referred to column E in the framework (Figure 8-6 and Figure 8-7) stating "*I wouldn't go down to the detail [and] to the gene…I like column E, because it shows the levels of organisation or scale.*" Given the ThBA classification system, confirmation of whether the generalisation of the thermal adaptation strategies was preferable to investigation of adaptation mechanisms in individual species was achieved through documenting participants' quotes according to the contexts in which the discussion occurred. The importance of the species was discussed as part of the bioprospecting concept in biology where, as explained by A3, researchers study the biochemistry of small and nondescript marine animals to find pharmaceutical antibiotics. This is the situation in which hundreds of species get examined simultaneously. A5 added "…*it is a massively parallel searching.*" There was another situation where the experts believed architects could look for species in particular. A3 claimed architects could set off looking for species where the existing documented knowledge in biology does not support an equivalent mechanism. A3 believed the white boxes that indicated the gaps in the architecture side "…*could be targeted by the architects*" as they might be able to "…*find a spot on earth or in the ocean in prospect*" wherein a specific species has responded to the stressor in a manner that matches what building designers are seeking.

9.4.2.5.3 Confirmation of the content and structure

Regarding the legitimisation of having developed a systematic process for finding appropriate solutions in nature, A5 felt *"It's pretty fair."* All participants believed the ThBA was inclusive as they claimed almost all of the biological thermal adaptation strategies were included. They also confirmed that the terminologies were used correctly and few mechanisms were missed. The missing strategies are explained in section 9.4.2.5.1. A3 said, *"It's startling."* A2 said *"I think you have done a great job."* A5 added *"…actually [it is a] really impressive classification."* At the end of the discussion, group members emphasised the high quality of the research for the second time by saying it was *"…very impressive"* (A4) and *"…it's a very well researched framework"* (A5). A1 was really impressed by the ThBA framework and asked if it were possible to receive a copy. Overall, the participants supported the proposed ThBA framework, and no one could think of a different or more appropriate classification system.

9.4.2.5.4 Outline

Table 9-2 illustrates the breakdown of the Nvivo codes generated for the content and structural evaluation of the ThBA according to expertise. An observation to emerge from the data comparison was that the academics made more quotes related to the structure of the ThBA, while PhD students were more active in the content analysis.

Looking at the structure evaluation column, fewer codes were linked to cellular physiology while the trend was the opposite in the content evaluation column, where organism physiology was recorded fewer times. Structural evaluation did not receive input from marine zoology. Both the content and the structural evaluation were endorsed by expertise related to terrestrial zoology and botany. The percentages in Table 9-2 are there for guidance.

Table 9-2 Percentage breakdown of the Nvivo codes generated for the content and structure evaluation

	Content evaluation	Structure evaluation	
Zoology (terrestrial)	50%	50%	100%
Botany	60%	40%	100%
Zoology (marine)	100%	0%	100%

Cellular physiology	85%	15%	100%
Organism physiology	55%	45%	100%

9.4.2.6 Framework discussion

This section explains the experts' opinions about a number of issues that materialised during the development of the ThBA. The following themes highlight the validity of the issues that emerged as well as evaluating their importance for the future development of the ThBA.

The left hand side of Figure 9-9 illustrates the contribution of participants to the sub-themes while the data related to the sub categories of the sub-themes is shown in the right hand side diagram. From the data in Figure 9-9 it is apparent that there was a balance between codes assigned to the sub-themes, with around four participants contributing to each. There were more examples given for the link between water and light as abiotic stressors, and only one example was related to the biotic stressors.

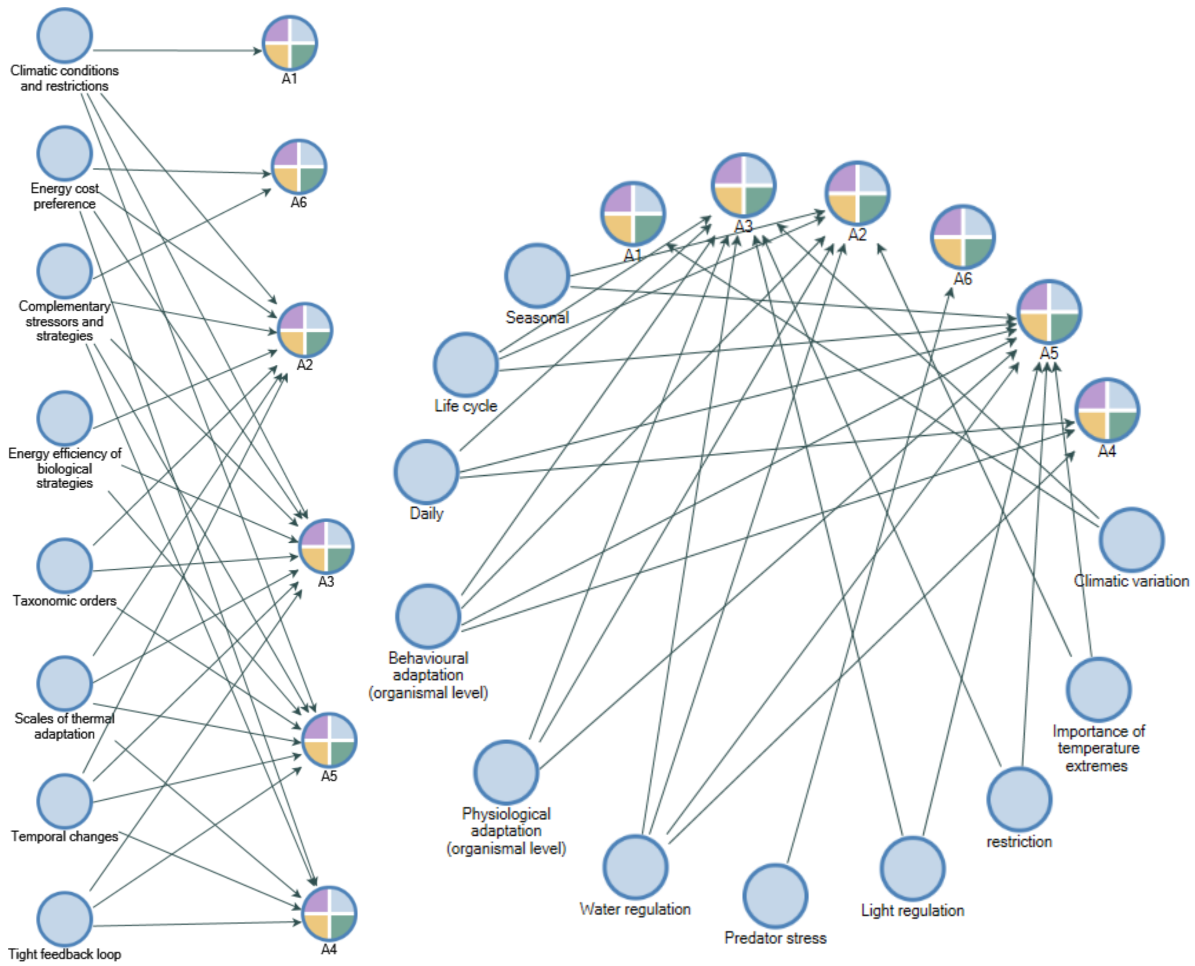

Figure 9-9 Contribution of the participants to the framework discussion theme

9.4.2.6.1 Complementary stressors and strategies

One of the concepts that emerged during the ThBA development process related to the multiple use of adaptation strategies. The focus group questions were formulated to examine the two possibilities of:

a) a combination of thermal adaptation strategies (morphological, physiological, and behavioural) in response to thermal stressors, and

b) responding to thermal stressors through regulation of other environmental stresses.

Responses to these two possibilities are set out below.

9.4.2.6.1.1 Light regulation

As discussed by A3, light regulation in some species of orchids controls the intra-floral temperature. A3 referred to this mechanism for "...*attracting pollinators in cold environments*" through "*lens-shaped epidermal cells that decrease heat gain*" by reflecting the light. This specific cell structure enables light harvesting, as the multiple reflections between the surfaces of the petals increases the transmittance of energy and hence the temperature between the flower petals. A3 added "…*so you can lose heat but also gain heat.*" A3 also explained how, in some species of plants, the response to the biotic environmental stressors contributes to thermal regulation. A3 noted the branching structure of some plants is assumed to have evolved for functioning as a heat trap mechanism (see 9.4.2.4.3.2). Participants alluded to other specific cellular structures that are used by marine organisms for light regulation. A5 used the light regulation mechanism in coral structures as an example, saying "…*if you point a red laser pointer at the coral skeleton, the whole coral skeleton will glow and produces a homogeneous light environment, but it doesn't have anything to do with temperature*."

9.4.2.6.1.2 Water and nutrient regulation

A recent discovery has shown that plants communicate with each other to survive under environmental stresses. A3 explained how plants cope with thermal stressors "...*through fungi transportation running across the root systems*" as this regulates photosynthesis and nutrient uptake. A2 stated "...*there is a close relationship between temperature and water regulation.*" A5 explained how responding to climatic restrictions such as having no access to light and nutrients as a consequence of living deep in the ocean currents might affect thermal regulation in corals as they change their structure and "...*become stubby* *and robust to handle currents while they also need that surface area to volume ratio to feed and collect light."* A6 felt this strategy "...*might not be thermal but I guess directing the current in a useful way would be beneficial."*

9.4.2.6.1.3 Predatory stress

A6 referred to another case in which the defence response in organisms induces heat generation: "…*if [a] mammal is trying to escape from the predator a lot of heat is going to be produced unintentionally."*

9.4.2.6.2 Temporal changes

It was agreed that organisms can be temporarily active and then deactivate, especially during periods of torpor, dormancy, and hibernation. A number of questions targeted the significance of this criterion. The importance of temporal changes was explained as a critical aspect of some thermal regulation strategies. The focus group text analysis revealed temporal changes were discussed as occurring over a day, a week, or a year. Furthermore, temporary morphological changes during the life cycle of some organisms were seen as necessary to enable them to survive under harsh climatic conditions.

9.4.2.6.2.1 Seasonal

A5 stated "...*sometimes the plant dies and only leaves behind a seed…the whole organism does not [become] dormant; they just have different phases in their life cycle*." A3 added, "…*they do not try to acclimate to winter conditions, they make seeds and die*."

9.4.2.6.2.2 Daily/weekly

A4 pointed to the concept of plasticity in animals and declared "…*some sponges change their shape every week based on the temperature…in summer they go down to tiny little dots, and then they grow back*." A2 believed in some climates not only is the range of daily temperature extremes wide, but also there is "...*the temperature seasonality and unreliability of the seasonality*" that needs to be considered. A2 continued "…*temperature regulation is a challenge in New Zealand [as] you cannot bank on it*." A3 pointed to the temporary morphological changes of New Zealand plants in response to wind as this was the dominant environmental stressor in this climate. However, the daily biomechanical response of native plants was not believed to be associated with thermal regulation purposes and was explained only to clarify how some responses to environmental stressors (biotic and abiotic) might happen in random but repeating periods.

9.4.2.6.2.3 Life cycle

In addition to A5 referring to the temporary death of plants during their life cycle, A2 and A3 explained how reptiles and some plants cope with thermal stresses. A3 stated, "…*sometimes when a plant is small, [it] makes filaments [in] leaves that reduces drag in flowing water, but once [the water] hits the top of the water column, the [filament] switches and makes a lily pad.*"

9.4.2.6.3 Climatic conditions and restrictions

During the ThBA development process, one issue was whether classification of the framework based on climatic distinctions would offer a more appropriate systematisation technique. To this end, a series of questions were formulated to investigate the legitimacy of the ThBA structure. The following themes highlighted the significance of taking the climatic variation/classification, the extreme ranges of temperature, and habitat restrictions into account. Participants talked about extreme temperatures in a scattered pattern during the discussion. However, the classification of the ThBA based on the factors mentioned above was not seen as useful, as the collective opinion of the group members and participants did not recommend grouping strategies according to the temperature ranges in which the strategies were employed. Only one participant felt climatic classifications needed to be included in the ThBA structure. Considering the restrictions of the environments in which organisms live was also mentioned by one participant. This implies the aggregated opinion of the group was that changes to the structure of the ThBA as presented to the group were unnecessary. However, some suggestions for the future development of the ThBA were made, as discussed below.

9.4.2.6.3.1 Importance of temperature extremes

Participants mentioned multiple cases where temperature extremes led to certain strategies. A5 explained heat generation in the skunk cabbage occurs in extreme circumstances when the plant needs to receive light (see 9.4.2.4.3.2). A2 stated architects might need to find one or two "...*cost-effective adaption strategies that would have multiple ends of extreme temperatures.*" A5 asserted "…*all organisms live at the edge of their envelope.*" A2 confirmed "…*temperature has a steep drop off in the extreme [that] will affect [organism] performance and reproductive ability.*" Later during the discussion, A2 claimed one of the best options for building designers is to look for the extremes as "…*animals have to survive extreme [conditions]*."

9.4.2.6.3.2 Climatic variations

A1 believed "...*the range of the environment organisms live in*" should be added to the framework and later during the discussion A1 seemed to have been seeking confirmation of this from the rest of the group members by asking "...*do you mean any adaptation plasticity depends on the locality situation?*" Later on, A1 emphasised focusing on the proper adaptation of native organisms and stated "…*I think [architects] could try to look in the local environment to investigate how animals and plants adapt with the local situations, not only temperature but also humidity and light…the environmental affability.*" A3 indirectly highlighted how climatic conditions trigger the evolution of specific thermal adaptation strategies by referring to the particular reflective characteristics of the surface of petals in a cold environment (see 9.4.2.6.1.1).

The researcher questioned the inclination of some designers interested in biomimicry to restrict their research to native species. However, participants believed strategies used in a different climate might be useful in the one in which the building was to be located. A3 explained "…*biologists always work on an organism's fitness in one environment versus another one*" going on to give an example "…*some [e.g. invasive] species [when moving to the new environment] reproduce and distribute everywhere while some wither away.*" A2 also referred to the significance of looking at native species by pointing to the biomechanical capability of New Zealand plants in response to wind pressure (see 9.4.2.6.2.2).

9.4.2.6.3.3 Restrictions

Only one participant stressed the restrictions from the habitats in which organisms live on response strategies to environmental stressors. A5 repeatedly alluded to the limitations of marine organisms living in the depth of the oceans. A5 stated "...*stationary organisms especially those underwater cannot control their temperature and the acclimation happens at the cellular level. Even if they could, the water around them would not carry the heat away immediately.*" A3 also mentioned the substantial morphological changes from soft to hard of corals are imposed on them by their being restricted in movement. A3 mentioned a similar phenomenon referring to "*seawater barnacles*".

9.4.2.6.4 Taxonomic orders or tree of life

Another question raised during the development of the ThBA was the importance of systematising biological data based on the taxonomic orders. The concepts of phylogeny and genealogy seemed to cover this area of inquiry. However, the group felt rearrangement of the framework according to the taxonomic orders was not necessary, as this criterion was properly embedded in the proposed classification scheme of the ThBA. A2 stated, *"…by analogy, biologists [would] call taxonomy phylogenetic conservation to figure out if [the species] was evolved in the environment or in the past."* A2 continued "…*biologists struggle [with] current selection or past selection of ancestors to some degree.*" A3 added the common patterns among organisms (e.g. mammals) "...*might be because of the evolutionary history*" or phylogenetics, as the environmental specifications might trigger "*species weirdness*" (see 9.4.2.6.3.2). A3 explained how species might come from a different genus and referred to phylogeny and genealogy as "...*plasticity versus something that has [a] hard-wired trait." A5 felt this was "…genotype versus phenotype.*" A3 believed photogenetics and genetics could have implications for building design. A2 stated "…*an example of plasticity [is] the [distinctive] species of corals growing in different locations*" (see 9.4.2.6.3.3). A2 brought up an example of phylogenetic variation, declaring "…*New Zealand reptiles are not able to get to the temperature they would like to live in, so their physiology is adapted for being in cooler environments.*"

9.4.2.6.5 Tight feedback loops

Reviewing the fields of biological science in developing the ThBA, highlighted the possible capability of an organism to switch between thermal adaptation strategies. The concept of a tight feedback loop in organisms was, therefore, a question raised for discussion. A3 believed behaviour is more related to animals as they have a brain and said: "…*without a brain, organisms cannot have [these] sort of things*" referring to the tight feedback loop mechanisms. A2 added "…*burrowing animals might decide it is too hot*" and switch to another strategy. A4 added "…*like selecting a better place as habitat.*" However, A5 seemed to have the opposite opinion as rather than associating switching the strategy with the behavioural level, A5 claimed feedback "...*is tightly controlled at the cellular level and the changes are very fast.*"

9.4.2.6.6 Scales of thermal adaptation

The concept of active and passive strategies or behavioural and physiological adaptation was used as the basis for developing the ThBA. The focus group discussion also highlighted the importance of this as almost all the participants suggested it. A5 noted "…*behavioural and cellular adaptation are basic principles and probably applicable to architecture.*" A3 declared "…*there are three scales in biology…the same question asked* *in different scales, more likely is [to] receive different answers…biologists usually focus on one scale at a time."*

9.4.2.6.6.1 Behavioural adaptation (organism level)

Referring to the limitations of corals and marine invertebrates in thermal adaptation, A5 stated it had been proposed but not proved that "...*there is not a lot of behaviour invertebrates can do, [so] they adapt at the cellular level*" (see 9.4.2.5.1.1). At the beginning of the session, A5 questioned if the researcher had split behavioural and physiological strategies. Right after A5 was informed by A2 that passive and active categorisation was part of the ThBA, leaving A5 to state "*Ah, you have done it.*" A5 claimed some animals "...*might try to minimise the thermal stress by their behaviour but the cell itself has [to] deal with it.*" A3 stated "…*behavioural switching is in the core of animal behaviour.*"

9.4.2.6.6.2 Physiological adaptation (organism level)

Many references were made to cellular activities such as "...*electron transport in the mitochondria*" (A5 and A2) (see 9.4.2.5.1.1). A5 referred to enzymology as an area of knowledge dealing with molecular levels of thermal adaptation, going on to note that thermal adaptation strategies occurring at different scales (cells, organs, and tissues) "...*do not work with each other [at other scales] when they are reporting on their [thermal adaptation] status.*" The discussion went into greater depth focusing on the multiple responses to several environmental stressors at the cellular level. A5 continued "…*a lot of stress pathways intersect at certain points at the cellular levels and often the heat chakras are the proteins that respond [to the stress]…so sometimes different stressors meet at the same point to change the proteins.*"

9.4.2.6.7 Compromising energy costs

Almost all participants talked about the energy costs of thermal adaptation mechanisms. On the subject of burrowing and insulation, A2 stated "*I guess reptiles compromise*." A4 continued "…*it's always a cost-benefit for [choosing between] thermal adaptation strategies and some organisms struggle with that.*" A2 noted organisms consider the energy costs at all times and said this "...*would not be just thermal, it might be the risk of being [attacked by] a predator.*" A3 noted "…*trade-offs are everywhere in biology…you make a decision relative to one variable [but] it might not be an affordable variable…so [organisms] have to find some common grounds for making decisions that minimise two different costs that are running in opposite directions…one [variable] almost never fits all.*"

A2 confirmed and added *"… [the variable] might become additive and take [the organism] faster in the other direction…so both ends are important."*

9.4.2.6.8 Energy efficiency of biological strategies

There seems to be no general discussion evaluating the efficiency of biological thermal adaptation strategies in terms of energy use in the literature and whether applying these mechanisms to building design would be reasonable. A few research studies have done a comprehensive analysis to examine whether bio-inspired design strategies have reduced building energy consumption (see 4.2.4). This raised a question of whether all thermal adaptation strategies are inherently efficient. In this context, the participants agreed there was energy wastage in some cases. A5 described "*…alternative oxidize systems in some cabbage generates heat but it is very wasteful [and] from the plant's energy use perspective, it's expensive and not efficient.*" A2 stated, "*…in some cases, the adaptation might not be optimising.*" A3 confirmed this stating "*...biology is filled with poor solutions.*" A2 named an enzyme called *Rubisco* and continued "*…the most common enzyme on planet earth is poorly designed and inefficient.*" This raised an issue about whether looking to biology for solutions to man-made problems would be a sensible strategy, thus questioning the basis for biomimicry. This will be explored in Chapter 10 where the ThBA will be implemented.

9.4.2.6.9 Outline

Looking at the colour coded gradients (Table 9-3), the sub-themes related to climate, complementary stressors, scales, and temporal changes were more discussed. The highest number of codes generated for these sub-themes might indicate their significance in thermal adaptation. Discussion related to 'energy efficiency of biological strategies' was not particularly prominent in the focus group data.

For column C 'energy cost preference' in Table 9-3, discussions were more frequent between those working on vertebrates, organism physiology, and zoology. Looking at column E 'scales of thermal adaptation' in the same table, more codes were linked to cellular physiology when the participants were asked to comment on the importance of the scale of exploration. It seems that botany did not figure in the discussion of 'energy cost preference' as almost all the codes were associated with zoology, organism physiology, and vertebrates. Overall, the subtheme of climatic conditions (A) contained more codes while only a few were pinned to the sub-themes of E 'scales of thermal adaptation' and H 'tight feedback loop'.

Table 9-3 Percentage breakdown of codes generated for the sub-themes A to H grouped under the theme of 'framework discussion'

	A : Climatic conditions and restrictions	B : Complementary stressors and strategies	C : Energy cost preference	D : Energy efficiency of biological strategies	E : Scales of thermal adaptation	F : Taxonomic orders	G : Temporal changes	H : Tight feedback loop	
Zoology (terrestrial)	18%	12%	24%	6%	12%	18%	12%	0%	100%
Botany	21%	13%	2%	8%	23%	15%	15%	4%	100%
Zoology (marine ecology)	31%	15%	23%	0%	8%	0%	15%	8%	100%
Vertebrates	18%	12%	24%	6%	12%	18%	12%	0%	100%
Invertebrates	23%	13%	7%	7%	20%	11%	15%	5%	100%
Cellular physiology	20%	10%	3%	10%	30%	7%	17%	3%	100%
Organism physiology	23%	15%	15%	4%	10%	17%	13%	4%	100%

9.4.2.7 Suggestions

None of the three main categories of themes introduced above concerned significant modification of the ThBA framework. One participant discussed including climatic classification within its structure (see 9.4.2.6.3.2) but felt there was no need to either rearrange or modify it. A2 believed the ThBA should not be changed, but did see a layer that could be added to the framework in the future, stating "*…there is an interaction between some of these strategies*", and adding "*…in dinosaurs, a combination of [factors] like posture, the colour of coatings, and blood vessels of the spines contributes to thermal adaptation…so you should consider the interconnectedness of some of the strategies.*" A2 continued, "*…however, I think in a lot of cases interconnectedness might be not as simple as [in] dinosaurs.*" A2 believed the proposed ThBA Version 01 should be kept "*...because I think that's a great foundation for thinking about coverage [comprehensiveness] and special needs [specific heat gain/loss].*" However, A2 did think another layer could be added in the future stating "*…now that you have some strategies* *here, you can start thinking about lumping some of those things to achieve multiple goals."*

9.4.3 Study findings

The focus group results proved the initial hypothesis that developing a systematic process for designing energy efficient bio-inspired buildings was possible. Reviewing the results against the themes revealed the participants had a good understanding of the ThBA and its application in building design. The framework contents and structure were approved, and a few missing strategies were added. Also, the concepts that had emerged from the development of the ThBA were confirmed as valid and relevant. One suggestion for improvement was made but was advised not be implemented into the framework at present but saved for future development. Below the findings of the focus group study are summarised:

- Participants gave examples and were able to link nature to architecture by referring to a series of analogies. They discussed how buildings could be seen as more like plants than animals.
- All participants agreed there is a limitation in building design if the aim is to imitate thermal adaptation strategies found in nature. Buildings cannot shut down temporarily. This is in contrast with the temporal changes in organisms that might occur on a daily, weekly, or annual basis.
- Participants believed that many buildings in New Zealand are not environmentally well-adapted. They also mentioned organisms die if they do not fit their environment, but it is not energy efficient to destroy buildings which do not adapt to their surroundings.
- The ThBA was confirmed as including almost all thermal adaptation strategies, and all those that could be immediately useful.
- Generalising thermal adaptation mechanisms was seen as possible by the experts as they believed such strategies are usually common for endotherms and ectotherms, although they also said climatic variation might lead to the evolution of different species.
- Searching for non-documented species was suggested if architects could not find a solution in nature from the existing database. Otherwise, the proposed ThBA Version 01 coverage and structure should support queries related to heat control.
- Exploring individual species or bio-prospecting was mentioned as something recently used for producing pharmaceutical products.

- The structural hierarchy and the classification scheme were seen as useful by all participants, and no reconfiguration of the data in the ThBA was advised.
- The participants agreed thermal adaptation strategies take place at different scales. They also believed what happened at different scales was not necessarily linked and looking into each scale would reveal a different solution.
- The group referred to other environmental stressors being in close relationship with thermal stressors to the extent that responding to one of them would result in thermal adaptation. The stressors mentioned were light, water, nutrients, and predators.
- Two participants highlighted the importance of temperature extremes when looking for relevant solutions, but the rest of the group did not comment on this.
- It was felt organisms native to one climate might offer strategies in another climate, meaning that building designers should not limit themselves to the local environment.
- The participants pointed out tight feedback loops were a common aspect of all organisms.
- The participants emphasised not all biological thermal adaptation strategies are energy efficient.
- The group agreed there is an energy cost for thermal adaptation strategies and organisms compromise over this all time.

9.5 Chapter summary

This chapter has explained the focus group process, composition and analysis (see 9.4). The significance and relevance of the focus group is highlighted in section 6.9.1.4.1. The CAQDAS used for the analysis was *NVivo 12 plus*, and thematic coding was used as the method of analysis allowing both deductive coding (derived based on the focus group questions) and inductive coding (emerging themes from the participants' discussions). The steps of the analysis were explained for one representative theme. The selected theme had more layers of codes in its hierarchical structure, which made it a useful example for explaining the similar processes used for deriving all the subthemes. Finally, the main four themes and their sub-categories were described.

Having the ThBA confirmed in this chapter as well as the thermal issues identified for the office buildings in Chapter 7, the next chapter will provide the details on designing energy efficient bio-inspired office buildings. It will elaborate how from one or multiple thermal issues, building designers can use the ThBA to find relevant solutions in biology to improve the thermal performance of office buildings and to reduce the whole building energy consumption. Furthermore, the next chapter will reveal whether the ThBA has the potential to assist designers in the first phase of the architectural design process.

10 Testing the ThBA through Redesigning the Case Studies

10.1 Introduction

This chapter presents the fourth stage (Figure 10-1) of the research process 'testing the thermo-bio-architectural (ThBA) framework Version 01 (Figure 6-4 and Figure 6-5). Referring back to the research question, the main objective of this study was to investigate the possibility of generalising thermal adaptation strategies in nature and developing a system for connecting thermal challenges in office buildings to relevant biological solutions in order to improve the thermal performance of the former. The research also sought to confirm the comprehensiveness of the generalised thermal adaptation strategies as classified in the ThBA framework version 01 (Chapter 8, Figure 8-6, Figure 8-7, and Figure 8-10). This chapter explains how designers could find inspiration in nature either based on the thermal challenges identified for an existing building or to make energy efficient decisions at an early design stage.

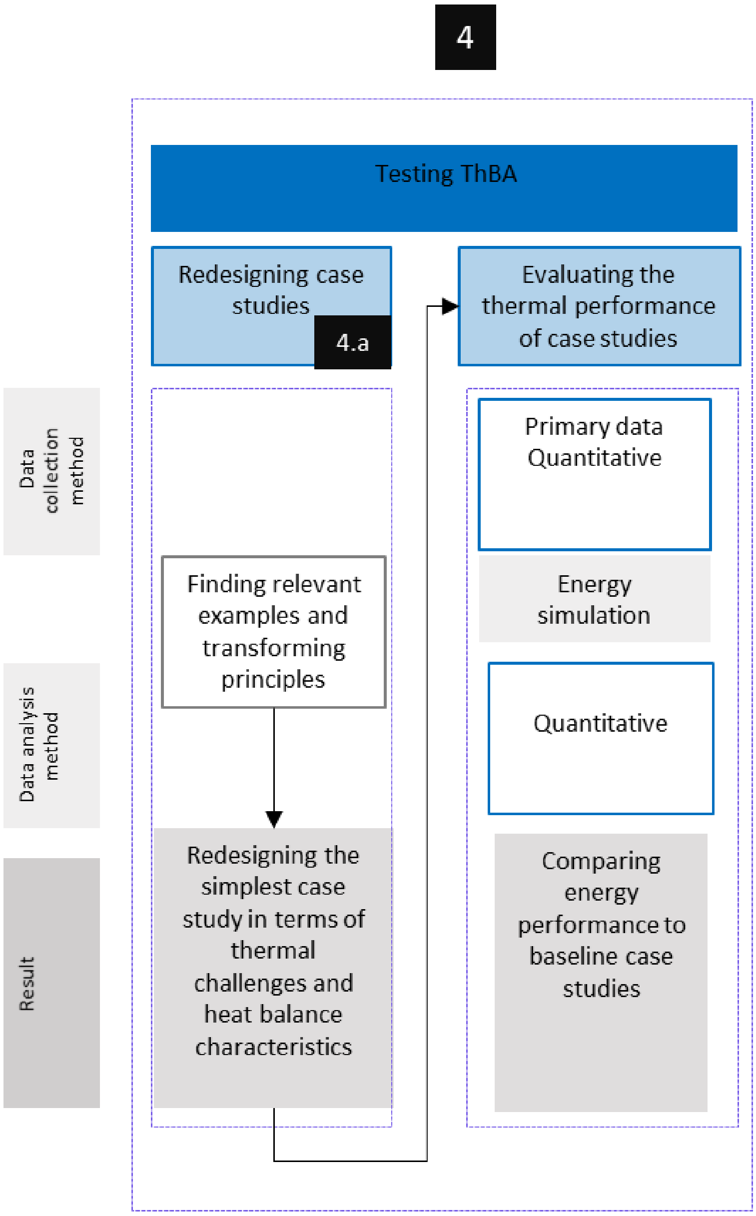

Figure 10-1 The fourth stage of the research process

This chapter also details how designers can use first the thermal issues and, secondly the thermal characteristics of a building to search the ThBA for finding relevant solutions. These two would determine the relevant actions which would then be used as input to the ThBA. The vast range of biological strategies within the ThBA would be searched for suitable design opportunities.

To be able to find an analogy in biology, a column named 'link' was generated in the first draft of the ThBA (Chapter 8, Figure 8-6, Figure 8-7, and Figure 8-10). In the grey columns of the ThBA Version 01, links have been developed to provide useful snippets of information for architects in order to translate natural thermal adaptation mechanisms into architectural design principles. The links suggest an outline of where and how a design parameter could be modified in order to improve the energy efficiency of a building. Selecting different links leads to distinct design approaches. While it might be possible to classify bio-inspired building design strategies into a dataset for designing energy-efficient office buildings, further research is required to create an inclusive list of such design approaches, which is not the aim of this research. The intention in this chapter was that two case studies with identifiable thermal challenges would be redesigned to show the process architects could use to design or redesign office buildings. The aim in doing this was to test how relevant biological thermal adaptation mechanisms could be identified in the ThBA and translated into architectural design principals.

As discussed in section 7.4, running energy simulations for R0017 and R1586 in Auckland and Dunedin generated four options namely R0017 in Dunedin, R0017 in Auckland, R1586 in Dunedin, R1586 in Auckland (Table 7-8 and Table 7-9) from which, as explained in section 6.7 and Figure 6-5, the simplest case study needed to be used for testing the ThBA Version 01. Also, redesigning was planned to happen twice to assess the robustness of the ThBA. The aim was to set up a testing process with the following order:

1. To use the ThBA Version 01 to redesign the simplest case study in the original climate (test 01).
2. Then, to redesign the simplest case study in a different climate (test 02).

So, the proposed inputs to the ThBA framework were related to the simplest case study in Auckland and Dunedin. For each, the inputs were:

1) the thermal issues identified and, and

2) their heat balance characteristics (Table 7-9).

Testing in a second climate would be done to investigate whether the same building would still perform in different parts of New Zealand. If the results were negative, the intention was to use the ThBA repeatedly for finding relevant natural thermal mechanisms that would produce a building that did perform well in the different New Zealand locations.

10.2 The hierarchical structure of the first draft of the ThBA

In the first draft of the ThBA, the main categories were heat gain, heat loss, and heat generation. The sub-branches of these were renamed ‘actions’ (column B), and heat generation, heat gain, and heat loss were also renamed ‘parent actions’ (column A). In the ThBA 'actions' branch into 'strategies' (column C) and then into 'types' (column D). For each 'type', there is a 'means' that refers to the parts of animals or plants responsible for thermal adaptation.

As explained in Chapter 8, active thermal adaptations happen in a hierarchical order meaning that any changes in organs are triggered by physiological and chemical reactions in deeper layers (see 8.7). Column E gives the 'means' which are either the ultimate organ or tissue in active strategies or the whole body of organisms in passive strategies.

For some strategies and types, only cells deal with thermal adaptation while the rest of the body of the organism is not involved. In the ThBA related to animals, an example is introduced for each strategy (column F). Column G lists the contributing factors to the thermal regulation strategies. Figure 10-2 shows the structure of the first draft of the ThBA, however, columns D and F corresponding to 'types' and 'organisms' were not developed for the ThBA related to plants.

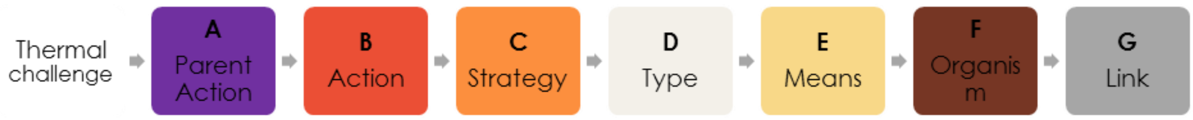

Figure 10-2 Biological information provided in columns A to G in the ThBA framework

10.3 R0017 in Dunedin (using the ThBA Version 01, test 01): the need to redesign the ThBA

R0017 in Dunedin was selected as the most straightforward case study (Table 10-1) as there was only one thermal challenge (heating). Although R1586 in Auckland also had one thermal challenge (cooling), it was not selected as it was a larger building. It also had more challenging thermal zones being a four-storey building with high energy use in January, February, March, April and May.

As discussed in chapter 7, R0017 in Dunedin was a skin-load dominated building as conductive and radiative heat gains through the windows were more significant than internal heat gains. There were also heat losses through the opaque surfaces and the windows with the former being nearly three times that of the latter.

As shown in Table 10-2, for R0017 in Dunedin, heating energy was the thermal challenge which meant that a great amount of energy was needed to keep the interior environment warm in winter (**Error! Reference source not found.**). Given this, the next step was to identify he relevant actions from the ThBA to overcome this challenge.

From the heat balance characteristics for R0017 (Table 10-2, see 7.4), both 'increasing heat gain' and 'decreasing heat loss' could reduce heating energy in winter. Looking at the 'actions' column in the ThBA, 'preventing heat loss' and 'stealing heat' seemed similar to 'decreasing heat loss' and 'increasing heat gain'. 'Generating heat' was also considered to be relevant. Hence, the ThBA framework related to animals and plants was used to search for these actions.

Having identified heating as the only thermal challenge for R0017, and the four relevant actions mentioned above, the first step was to go to the ThBA and look for the thermal adaptation mechanisms each action suggested. The first action selected was 'increasing heat gain'. However, in doing this step, it soon appeared that the ThBA was not as well-organised as it might be to aid this process. Despite the comments made by biologists, the ThBA organisation was not useful for architectural application. Therefore, it was decided to reorganise the ThBA before looking for relevant strategies to overcome the thermal challenges. The following section details the steps taken to reorganise the ThBA. It also explains how starting with R0017 as the simplest case study revealed what was inappropriate about the ThBA organisation and how it should be changed.

10.3.1 The process of redesigning the ThBA Version 01

Given the thermal challenge, the first step was to select strategies related to 'increasing heat gain' from the ThBA Version 01 related to passive strategies for animals. These were selected and marked up in the ThBA with a black boundary around them (Figure 10-3). Strategies related to this action were then imported into a table (Table 10-3). Apart from the inputs of columns A-G (the labelling system of the first draft of the ThBA, see Figure 10-2), two more columns were added at the start of the table to show whether the data was related to animals (A) or plants (P), and if the mechanism was passive (PA) or active (AC), noting this table only deals with animals and passive mechanisms.

Table 10-1 Location and duration of thermal challenges

	R0017		R0017	R1586			R1586					
	Auckland		**Dunedin**	**Auckland**			**Dunedin**					
Thermal challenge	Cooling	Heating	Heating	Cooling			Cooling			Heating		
Season	Summer	Winter	Winter	Summer			Summer			Winter		
Floor	G	G	G	G	M	T	G	M	T	G	M	T
Zones	NE, NW	Peripheral Zones	Peripheral zones	All	All	All	All	All	All	SW,NW, NE,SE	SW,NW, NE,SE	All
Most challenging zones	NE					SW,NW, NE,SE	NE,SE, NEM, NWM	NE,SE, NEM, NWM	NE,SE, NEM, NWM	SE	SE	SW,NW, NE,SE
Month	Jan, Feb, Mar, Oct, Nov, Dec		Apr, May, Jun, Jul, Aug	Jan, Feb, Mar, Nov, Dec	Jan, Feb, Mar, Nov, Dec	Jan, Feb, Mar, Nov, Dec	Jan, Feb, Mar, Oct, Nov, Dec	Jan, Feb, Mar, Oct, Nov, Dec	Jan, Feb, Mar, Oct, Nov, Dec	Jun, Jul, Aug,	Jun, Jul, Aug	Jun, Jul, Aug,

Table 10-2 Heat balance characteristics

Auckland	Dunedin	Auckland	Dunedin
R0017	**R0017**	**R01586**	**R01586**
External heat gain	External heat gain	Internal heat gain and external heat gain	Internal heat gain and external heat gain
Conductive heat loss through opaque surfaces	Conductive heat loss through opaque surfaces	Conductive heat loss through windows	Conductive heat loss through opaque surfaces and windows
Infiltration heat loss through windows	Infiltration heat loss through windows		
Conductive and radiative heat gain from windows	Conductive and radiative heat gain from windows	Conductive and radiative heat gain from windows	Conductive and radiative heat gain from windows

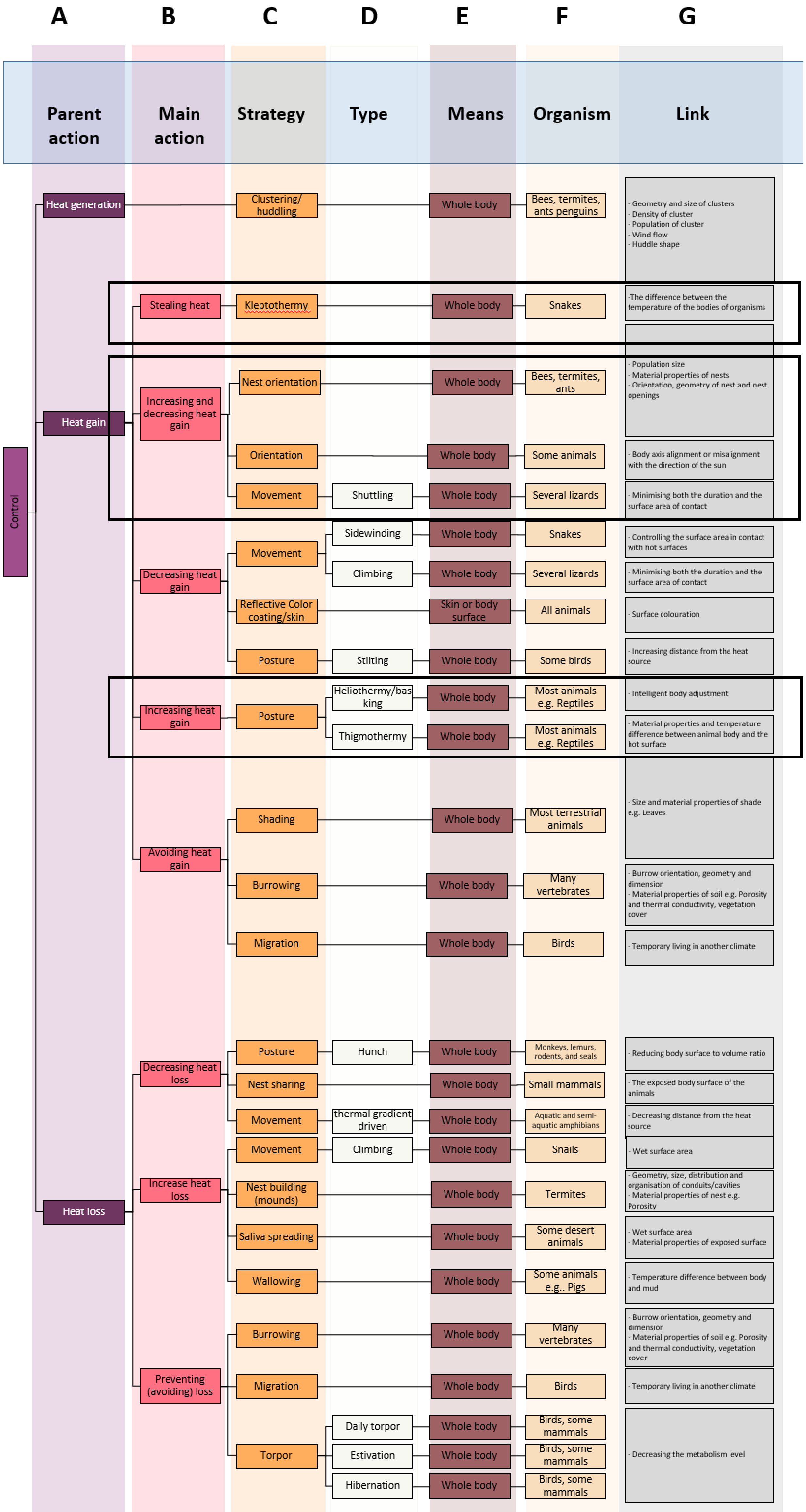

Figure 10-3 The ThBA Version 01 related to passive strategies in animals (used as an example)

Table 10-3 The ThBA Version 01 data for passive strategies of 'increasing heat gain' for animals

		A	B	C	D	E	F	G
A/P	**PA/AC**	**Parent action**	**Action**	**Strategy**	**Type**	**means**	**Organism**	**link**
A	PA	Heat gain	Increasing heat gain	Nest building	-	Construction	Bees, termites, ants	- Population size - Material properties of nests - Orientation, geometry of nest and nest openings
A	PA	Heat gain	Increasing heat gain	Orientation	-	Whole body	Soma animals	- Body axis alignment or misalignment with the direction of the sun
A	PA	Heat gain	Increasing heat gain	Movement	shuttling	Whole body	Several lizards	-Maximising both the duration and the surface area of contact
A	PA	Heat gain	Increasing heat gain	Posture	heliothermy / basking	Whole body	Snakes	- Intelligent body adjustment
A	PA	Heat gain	Increasing heat gain	Posture	thigmothermy	Whole body	Several lizards	- Material properties and temperature difference between animal body and the hot surface

Having studied Table 10-3, the following points emerged:

1) The 'parent action' column was removed as this broader category was not necessary at this stage.
2) To make the ThBA Version 01 a useful framework for architects its hierarchical structure was reordered. The 'strategy' and 'type' boxes were removed and their data was imported into a column labelled 'solutions'. This was done as many strategies had only one type. The strategy was moved to the 'solutions' column to condense the information but still facilitate interpretation of the data.
3) The 'means' column showed whether thermal adaptation happens by use of the whole body of an organism, or through its organs, tissues, or cells, hence the level at which thermal adaptation occurs. However, this did not seem important for architects and was removed. This information would remain in another version for users seeking the additional detail.

4) The ‘organism’ column also seemed to be unnecessary for architects, as seeking design options seemed more important than examples of animals or plants. Accordingly, column ‘F’ was removed at this stage (Column F in Table 10-3). Again, due to the possibility of the ThBA being used by other researchers, organism examples would be provided in another version to enable a more thorough investigation of biological solutions and organisms.
5) For each solution, the parameters affecting the thermal regulation mechanism were listed in the ‘Link’ column (Column G in Table 10-3). As discussed in chapter 8, links can be mapped into a hierarchical structure (see 8.7) as thermal regulatory mechanisms have a hierarchical connection which can be linked to more general categories (Figure 10-4). Even though the adaptation mechanism happens in a hierarchical order, some principles seem to play a primary role in homeostasis. Therefore, it was necessary to list the parameters central in each of the thermal adaptation mechanism. Determining the key thermoregulatory principles, Figure 10-4 was created.

To make the links useful, the parameters were reviewed to determine where they fitted within the general categories. The example below is for the ‘movement’ strategy from Table 10-3 and based on the hierarchical connection of thermal regulation shown in Figure 10-4.

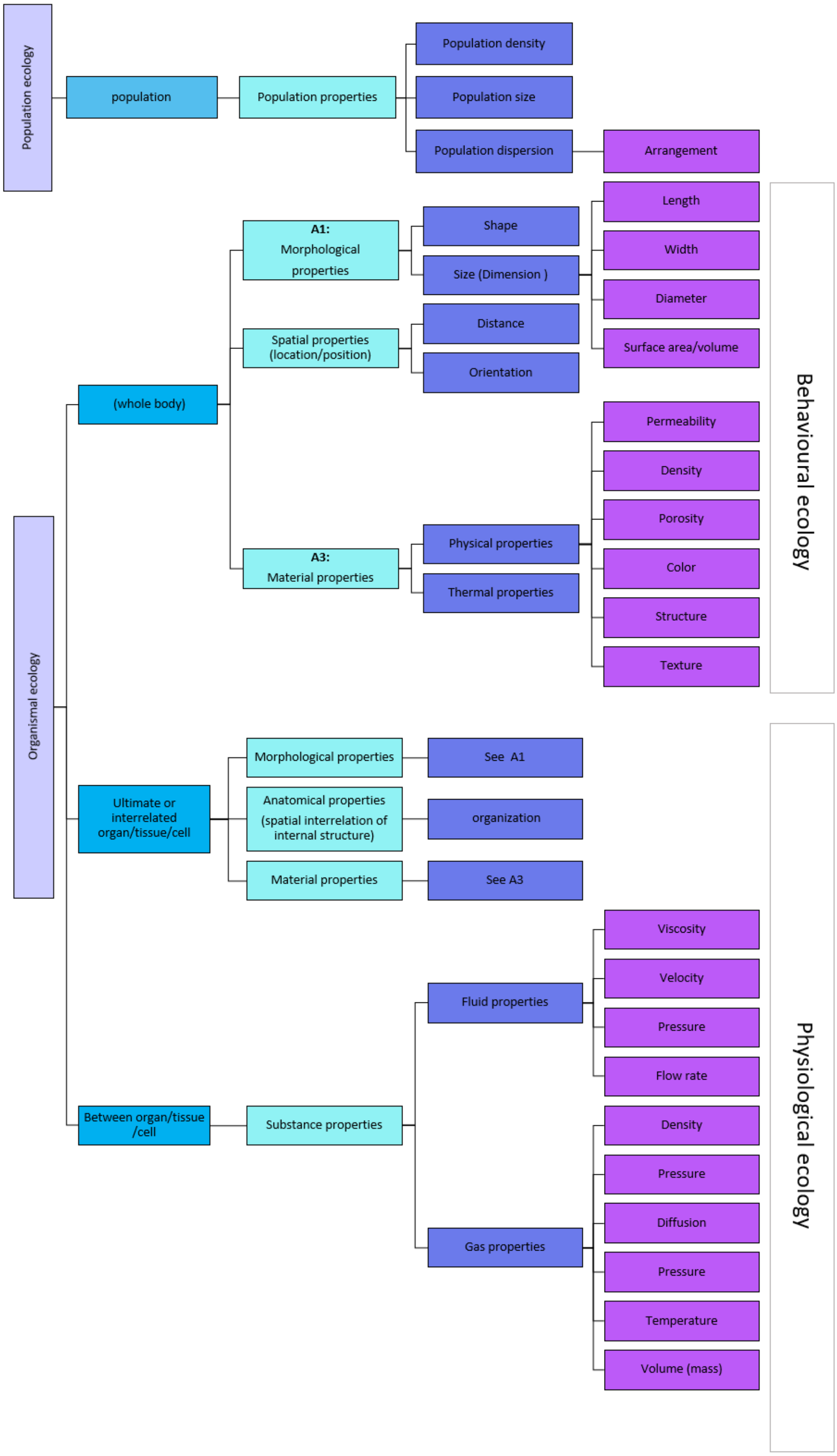

Figure 10-4 The hierarchical connection of thermal regulatory mechanisms in biology

For 'movement' the type was 'shuttling' and the links were:

a) maximising both the duration and,
b) the surface area of contact.

From the two parameters above, only 'b' seemed appropriate for a building designer and 'surface area' was sublimated to 'size' and then to 'morphological properties'.

In 'shuttling' the heat transfer is convective, that is heat is transferred from the air to the skin of animal. Given conduction, convection, and radiation are the three heat transfer mechanisms governing living things and building operation, it seemed to be important to document what method of heat transfer enabled homeostasis and what parameter was central in the heat transfer equation.

Convection is described by:

$$q = h * (T_1 - T_2) \qquad W$$

$$q" = h * (T_1 - T_2) \qquad W/m^2$$

where h is the convective heat transfer coefficient in Wm^2K, and As the surface area of convection in m^2. For 'shuttling', 'surface area' was both central to the thermoregulatory principle and the main parameter in the convective heat transfer equation.

While this was a solution with few thermoregulatory principles, some solutions in the ThBA seemed to have several of these out of which only some were central to thermal adaptation. To investigate how making the links productive might be done for a more complicated strategy, the ThBA charts related to animals and plants were searched again and 'Vasoconstriction' was selected from the ThBA related to active strategies for animals.

The example below is provided to explain how a similar approach was taken for more a complicated solution and how the main thermoregulatory principles were distinguished. This example is an active 'decreasing heat loss' solution for animals.

For 'vasoconstriction' the links are:

a) Diameter and length of blood vessels

b) Permeability, porosity, density, and thermal conductivity of the superficial body tissue (skin) and blood vessels

c) Pressure and blood flow

Table 10-4 shows the links for *vasoconstriction*. Using the hierarchical structure developed in Chapter 8 (Figure 10-4), item ‘a’ was generalised to size, item ‘b’ to physical properties, and item ‘c’ to fluid properties. These were linked for a second time, with ‘size’ being related to ‘morphological properties, ‘physical properties’ to ‘material properties’, and ‘fluid properties’ to ‘substance properties’. However, the main principle behind vasoconstriction was the change in the diameter of blood vessels, and consequent change in blood flow. This meant, the main vasoconstriction parameters were ‘a’ and ‘c’.

For a material there are several properties. There are the two broad categories of physical and chemical properties from which the former can be split into mechanical, thermal, electrical, magnetic, and optical, while for the latter there are the two categories of environmental and chemical stability (Aran, 2007).

Table 10-4 The links for vasoconstriction

Level of thermoregulation	Links		
Column 1	**Column 2**	**Column 3**	**Column 4**
Ultimate or interrelated tissues	Morphological properties	Size	Diameter of blood vessel
Between tissues	Gas exchange substance properties	Fluid properties	Blood flow rate

For this biological strategy, increasing the diameter of blood vessel seemed to be a primary principle and decreasing the blood flow rate, a secondary principle, since the latter depends on the former. For the former, the morphological properties and for the latter, gas exchange substance properties changed. Therefore, the links for 'vasoconstriction' were broken down into three levels (Table 10-4). A colour match was also used that related to the positioning of the principles in the hierarchical structure.

Convection involves the transfer of heat through the flow of a fluid over a solid boundary. For 'vasoconstriction', thermoregulation happens through convective heat transfer. Depending on how the convection is caused, the heat transfer coefficient will change. For a still fluid, the convection is 'natural' while it is 'forced' if the fluid flow is controlled by a pump. In these terms vasoconstriction is a forced convection since the heart pumps the blood into the blood vessels. The convective heat transfer coefficient varies depending on the fluid flow conditions meaning that fluid velocity, viscosity, and heat flux affect its value. For vasoconstriction the 'heat transfer coefficient' changes with the rate of blood flow to allow the heat transfer between the blood and the tissue, and so the main parameter in the equation is the 'heat transfer coefficient' (Table 10-5).

Table 10-5 The links and heat transfer method and variables for vasoconstriction

Solution	Links		Heat transfer method	Variable in the equation
	Column 4	**Column 2**		
What is the solution?	**What principle(s) is(are) central to thermal adaptation?**	**What properties of a living organism do central thermal adaptation principles belong to?**	**What method of heat transfer allows thermoregulation?**	**Which parameter in the heat transfer equation is changed?**
Vasoconstriction	Diameter of blood vessel	Morphological properties	Convective heat transfer	Convective heat transfer coefficient
	Blood flow rate	Gas exchange substance properties		

Having looked in detail at a complex thermoregulation solution, Table 10-3 was studied again to see if any other change was necessary to make the ThBA useful for architects. This led to the following:

6) Considering heating energy for R0017 was a temporary thermal challenge in winter, it was also important to document whether the solutions were employed temporarily or permanently by organisms.

Given the six points after Table 10-3 (part of the ThBA Version 01), the data in the ThBA was presented in another way to facilitate identification of relevant thermal adaptation solutions for architects (Table 10-7). This reorganising was part of developing the ThBA Version 02. Table 10-6 (Version 01) shows what columns were removed from or added to Table 10-3. Some columns however remained unchanged.

Table 10-6 Added, removed, and unchanged columns in Table 10-3

Added		Removed	Remained	Merged into 'solution'		Removed	Removed	Links for the main thermoregulation principles + 'heat transfer method' + 'variable in the equation' (see Table 10-6)	Added
		A	B	C	D	E	F	G	
A/P	PA/AC	Parent action	Action	Strategy	Type	Means	Organism	Link	Temporary/ permanent

Table 10-7 A part of reorganised version of the ThBA (ThBA Version 02): data from the ThBA Version 01: passive strategies of 'increasing heat gain' for animals

Animals/ Plants	Passive/ Active	Action	Solution	Links for the main thermoregulation principles		Heat transfer method	Variable in the equation	Temporary/ Permanently
				Column 4	Column 2			
A/P	PA/AC	What change in the heat exchange mechanism maintains homeostasis?	What is the solution?	What principle is central to the solution?	What properties of a living organism the central thermal adaptation principles belong to?	What method of heat transfer allows for thermoregulation?	Which parameter in the heat transfer equation is changed?	TE/PE
A	PA	Increasing heat gain	Nest building					
A	PA	Increasing heat gain	Orientation					
A	PA	Increasing heat gain	Shuttling	Surface area	Morphological properties	Convective heat transfer	Surface area	TE
A	PA	Increasing heat gain	Heliothermy/ basking					
A	PA	Increasing heat gain	Thigmothermy					

Table 10-8 shows how the ThBA Version 02 was reorganised. With this and knowing that cooling, heating, or a combination of these are the thermal challenges of the four case studies (Table 10-2), it was decided to reorganise the whole of ThBA Version 01 to become Version 02 (Table 10-8).

When 'heating' was the thermal challenge, the relevant actions were 'generating heat', 'preventing heat loss', 'stealing heat', 'decreasing heat loss', and 'increasing heat gain'. Table 10-8 shows the actions are scattered. It was therefore decided to group the same actions to facilitate comparison of the solutions documented for each (Table 10-9). This led to creation of the ThBA Version 03 for heating challenges.

Having the relevant actions grouped, some had similar heat transfer variables as shown in the 'variable in the equation' column. For each solution, irrespective of the central thermoregulatory principle the main heat transfer variable was responsible for thermoregulation. In addition, since both buildings and living organisms have similar heat transfer equations governing homeostasis, sorting the relevant actions based on the main parameter in their heat transfer equation seemed to assist recognition of possible design strategies. Table 10-10 shows the final reorganisation of the relevant actions (the ThBA Version 04 for heating challenges) when the thermal challenge was 'heating'.

The same process was taken for 'cooling' (Table 10-11) where the relevant actions were 'decreasing heat gain', 'avoiding heat gain', and 'increasing heat loss'. Table 10-11 shows the ThBA Version 04 for cooling challenges.

Table 10-8 ThBA Version 02, scattered actions related to 'heating' as the thermal challenge

Passive/ active	Animals /plants	Action	Solution	Links for the main thermoregulation principles		Method	Variable	Temporary/ Permanent
				Column 4	Column 2			
PA/AC	A/p	What change in the heat exchange mechanism maintains homeostasis?	What is the solution?	What principle is central to the solution?	What properties of a living organism do the central thermal adaptation principles belong to?	What method of heat transfer allows for thermoregulation?	What was the main parameter in the heat transfer equation?	TE/PE
AC	A	Heat generation	Nesting	Population	Energy use (chemical properties)	-	Metabolism (multiplies)	**T**
PA	A	Stealing heat	Kleptothermy	Distance	Spatial properties	Conductive heat gain	Temperature gradient	T
PA	A	Increasing heat gain	Nest building (Termites mound only)	Orientation	Spatial properties	Solar heat gain	Surface area	P
PA	A	Increasing heat gain	Orientation	Orientation	Spatial properties	Solar heat gain	Surface area	T
PA	A	Increasing heat gain	Shuttling	Location	Spatial properties	Convective heat gain	Temperature gradient	T
PA	A	Increasing heat gain	Movement along thermal gradient	Distance	Spatial properties	Convective heat gain	Temperature gradient	T
PA	A	Increasing heat gain	Heliothermy/basking	Surface area	Morphological properties	Solar heat gain	Surface area	T
PA	A	Increasing heat gain	Thigmothermy	Distance	Spatial properties	Conductive heat gain	Temperature gradient	T
PA	A	Decreasing heat loss	Hunch	Surface area	Morphological properties	Convective heat loss	Surface area	T
PA	A	Decreasing heat loss	Nest material	Thermal conductivity	Material properties	Conductive heat loss	Heat transfer coefficient	P
PA	A	Avoiding heat loss	Burrowing	Location	Spatial properties	Convective heat loss	Temperature gradient	T
PA	A	Avoiding heat loss	Migration	Location	Spatial properties	Convective heat loss	Temperature gradient	T
PA	A	Avoiding heat loss	Daily torpor	Metabolism	Energy use (chemical properties)	Convective heat loss	Heart rate	T
PA	A	Avoiding heat loss	Estivation	Metabolism	Energy use (chemical properties)	Evaporative heat loss	Heart rate	T
PA	A	Avoiding heat loss	Hibernation	Metabolism	Energy use (chemical properties)	Convective heat loss	Heart rate	T
AC	A	Decreasing heat loss	Insulation	Thickness	Material properties	Conductive heat loss	Heat transfer coefficient	P
AC	A	Decreasing heat loss	Preening	Water flow	Substance properties	Evaporative heat loss	Water surface area	T
AC	A	Decreasing heat loss	Piloerection	Thickness	Morphological properties	Conductive heat loss	Heat transfer coefficient	T
AC	A	Decreasing heat loss	Ptiloerection	Thickness	Morphological properties	Conductive heat loss	Heat transfer coefficient	T
AC	A	Decreasing heat loss	Hidromeiosis	Surface area	Morphological properties	Evaporative heat loss	Surface area	T
AC	A	Decreasing heat loss	Body shrinkage	Surface area	Morphological properties	Evaporative heat loss	Surface area	T
AC	A	Decreasing heat loss	Countercurrent heat exchange	Distance	Spatial properties	Convective heat loss	Temperature gradient	P
AC	A	Decreasing heat loss	Vasoconstriction	Diameter, fluid flow rate	Morphological properties	Convective heat loss	Heat transfer coefficient (heat flux)	T
AC	A	Avoiding heat loss	Supercooling	Freezing point	Substance properties	-	Stop heat transfer	T
AC	A	Avoiding heat loss	Extracellular freezing	Water flow	Substance properties	-	Stop heat transfer	T
PA	P	Increasing heat gain	Thin cuticle	Thickness	Morphological properties	Solar heat gain	Heat transfer coefficient	P
PA	P	Increasing heat gain	Orientation	Orientation	Spatial properties	Solar heat gain	Surface area	T
AC	P	Increasing heat gain	Light channelling (Columnar palisade cells)	Depth	Morphological properties	Solar heat gain (instantaneous)	Solar heat gain coefficient (transmission)	P
AC	P	Increasing heat gain	Lens-shaped epidermal cells	Shape	Morphological properties	Solar heat gain (instantaneous)	Solar heat gain coefficient (absorption)	P
PA	P	Increasing heat gain	Chlorophyll (pigmentation)	Colour	Material properties	Solar heat gain	Solar heat gain coefficient (absorption)	P
AC	P	Avoiding heat loss	Supercooling	Freezing point	Substance properties	-	Stop heat transfer	T
AC	P	Avoiding heat loss	Extracellular freezing	Water flow	Substance properties	-	Stop heat transfer	T
PA	P	Avoiding heat loss	Dormancy	Metabolism	Energy use (chemical properties)	-	Stop metabolism	T
PA	P	Decreasing heat loss	Leaf surface area	Surface area	Morphological properties	Evaporative heat loss	Surface area	T
AC	P	Decreasing heat loss	Waxy cuticle	Water flow	Substance properties	Evaporative heat loss	Surface area	?
AC	P	Decreasing heat loss	Epidermal hair or trichomes	Air flow	Material properties	Evaporative heat loss	Wind speed	P
PA	P	Decreasing heat loss	Losing leaves	Surface area	Morphological properties	Evaporative heat loss	Surface area	T
AC	P	Decreasing heat loss	Stomata closure	Surface area	Morphological properties	Evaporative heat loss	Surface area	T
AC	P	Decreasing heat loss	Decreased stomata density	Density	Morphological properties	Evaporative heat loss	Surface area	T
AC	P	Decreasing heat loss	Insulation	Thickness	Material properties	Conductive heat loss	Heat transfer coefficient	P
PA	P	Decreasing heat loss	Leaf rolling	Surface area	Morphological properties	Evaporative heat loss	Surface area	T
AC	P	Decreasing heat loss	Sunken stomata	Air flow	Material properties	Evaporative heat loss	Wind speed	P

Table 10-9 ThBA Version 03, grouping similar actions related to 'heating' as the thermal challenge

Passive/ active	Animals /plants	Action	Solution	links for the main thermoregulation principles		Method	Variable	Temporary/Permanent
				Column 4	Column 2			
PA/AC	A/p	What change in the heat exchange mechanism maintains homeostasis?	What is the solution?	What principle is central to the solution?	What properties of a living organism do the central thermal adaptation principles belong to?	What method of heat transfer allows for thermoregulation?	What was the main parameter in the heat transfer equation?	TE/PE
AC	A	Heat generation	Nesting	Population	Energy use (chemical properties)	-	Metabolism (multiplies)	**T**
PA	A	Stealing heat	Kleptothermy	Distance	Spatial properties	Conductive heat gain	Temperature gradient	T
PA	A	Increasing heat gain	Nest building (termites mound only)	Orientation	Spatial properties	Solar heat gain	Surface area	P
PA	A	Increasing heat gain	Orientation	Orientation	Spatial properties	Solar heat gain	Surface area	T
PA	A	Increasing heat gain	Shuttling	Location	Spatial properties	Convective heat gain	Temperature gradient	T
PA	A	Increasing heat gain	Movement along thermal gradient	Distance	Spatial properties	Convective heat gain	Temperature gradient	T
PA	A	Increasing heat gain	Heliothermy/basking	Surface area	Morphological properties	Solar heat gain	Surface area	T
PA	A	Increasing heat gain	Thigmothermy	Distance	Spatial properties	Conductive heat gain	Temperature gradient	T
PA	P	Increasing heat gain	Thin cuticle	Thickness	Morphological properties	Solar heat gain	Heat transfer coefficient	P
PA	P	Increasing heat gain	Orientation	Orientation	Spatial properties	Solar heat gain	Surface area	T
AC	P	Increasing heat gain	Light channelling (columnar palisade cells)	Depth	Morphological properties	Solar heat gain (instantaneous)	Solar heat gain coefficient (transmission)	P
AC	P	Increasing heat gain	Lens-shaped epidermal cells	Shape	Morphological properties	Solar heat gain (instantaneous)	Solar heat gain coefficient (absorption)	P
PA	P	Increasing heat gain	Chlorophyll (pigmentation)	Colour	Material properties	Solar heat gain	Solar heat gain coefficient (absorption)	P
PA	A	Decreasing heat loss	Hunch	Surface area	Morphological properties	Convective heat loss	Surface area	T
PA	A	Decreasing heat loss	Nest material	Thermal conductivity	Material properties	Conductive heat loss	Heat transfer coefficient	P
AC	A	Decreasing heat loss	Insulation	Thickness	Material properties	Conductive heat loss	Heat transfer coefficient	P
AC	A	Decreasing heat loss	Preening	Water flow	Substance properties	Evaporative heat loss	Surface area	T
AC	A	Decreasing heat loss	Piloerection	Thickness	Morphological properties	Conductive heat loss	Heat transfer coefficient	T
AC	A	Decreasing heat loss	Ptiloerection	Thickness	Morphological properties	Conductive heat loss	Heat transfer coefficient	T
AC	A	Decreasing heat loss	Hidromeiosis	Surface area	Morphological properties	Evaporative heat loss	Surface area	T
AC	A	Decreasing heat loss	Body shrinkage	Surface area	Morphological properties	Evaporative heat loss	Surface area	T
AC	A	Decreasing heat loss	Countercurrent heat exchange	Distance	Spatial properties	Convective heat loss	Temperature gradient	P
AC	A	Decreasing heat loss	Vasoconstriction	Diameter, fluid flow rate	Morphological properties	Convective heat loss	Heat transfer coefficient (heat flux)	T
PA	P	Decreasing heat loss	Leaf surface area	Surface area	Morphological properties	Evaporative heat loss	Surface area	T
AC	P	Decreasing heat loss	Waxy cuticle	Water flow	Substance properties	Evaporative heat loss	Surface area	P
AC	P	Decreasing heat loss	Epidermal hair or trichomes	Air flow	Material properties	Evaporative heat loss	Wind speed	P
PA	P	Decreasing heat loss	Losing leaves	Surface area	Morphological properties	Evaporative heat loss	Surface area	T
AC	P	Decreasing heat loss	Stomata closure	Surface area	Morphological properties	Evaporative heat loss	Surface area	T
AC	P	Decreasing heat loss	Decreased stomata density	Density	Morphological properties	Evaporative heat loss	Surface area	T
AC	P	Decreasing heat loss	Insulation	Thickness	Morphological properties	Conductive heat loss	Heat transfer coefficient	P
PA	P	Decreasing heat loss	Leaf rolling	Surface area	Morphological properties	Evaporative heat loss	Surface area	T
AC	P	Decreasing heat loss	Sunken stomata	Air flow	Material properties	Evaporative heat loss	Wind speed	P
PA	A	Avoiding heat loss	Burrowing	Location	Spatial properties	Convective heat loss	Temperature gradient	T
PA	A	Avoiding heat loss	Migration	Location	Spatial properties	Convective heat loss	Temperature gradient	T
PA	A	Avoiding heat loss	Daily torpor	Metabolism	Energy use (chemical properties)	Convective heat loss	Heart rate	T
PA	A	Avoiding heat loss	Estivation	Metabolism	Energy use (chemical properties)	Evaporative heat loss	Heart rate	T
PA	A	Avoiding heat loss	Hibernation	Metabolism	Energy use (chemical properties)	Convective heat loss	Heart rate	T
AC	A	Avoiding heat loss	Supercooling	Freezing point	Substance properties	-	Stop heat transfer	T
AC	A	Avoiding heat loss	Extracellular freezing	Water flow	Substance properties	-	Stop heat transfer	T
AC	P	Avoiding heat loss	Supercooling	Freezing point	Substance properties	-	Stop heat transfer	T
AC	P	Avoiding heat loss	Extracellular freezing	Water flow	Substance properties	-	Stop heat transfer	T
PA	P	Avoiding heat loss	Dormancy	Metabolism	Energy use (chemical properties)	-	Stop metabolism	T

Table 10-10 ThBA Version 04, the final reorganisation of relevant actions related to 'heating' as the thermal challenge

Passive/active	Animals/plants	Action	Solution	Links for the main thermoregulation principles		Method	Variable	Temporary/Permanent
				Column 4	Column 2			
PA/AC	A/p	What change in the heat exchange mechanism maintains homeostasis?	What is the solution?	What principle is central to the solution?	What properties of a living organism do the central thermal adaptation principles belong to?	What method of heat transfer allows for thermoregulation?	What was the main parameter in the heat transfer equation?	TE/PE
AC	A	Heat generation	Nesting	Population	Energy use (chemical properties)	-	Metabolism (multiplies)	T
PA	A	Stealing heat	Kleptothermy	Distance	Spatial properties	Conductive heat gain	Temperature gradient	T
PA	A	Increasing heat gain	Shuttling	Location	Spatial properties	Convective heat gain	Temperature gradient	T
PA	A	Increasing heat gain	Movement along thermal gradient	Distance	Spatial properties	Convective heat gain	Temperature gradient	T
PA	A	Increasing heat gain	Thigmothermy	Distance	Spatial properties	Conductive heat gain	Temperature gradient	T
AC	P	Increasing heat gain	Light channelling (columnar palisade cells)	Depth	Morphological properties	Solar heat gain (instantaneous)	Solar heat gain coefficient (transmission)	P
AC	P	Increasing heat gain	Lens-shaped epidermal cells	Shape	Morphological properties	Solar heat gain (instantaneous)	Solar heat gain coefficient (absorption)	P
PA	P	Increasing heat gain	Chlorophyll (pigmentation)	Colour	Material properties	Solar heat gain	Solar heat gain coefficient (absorption)	P
PA	A	Increasing heat gain	Orientation	Orientation	Spatial properties	Solar heat gain	Surface area	T
PA	A	Increasing heat gain	Nest building (termites mound only)	Orientation	Spatial properties	Solar heat gain	Surface area	P
PA	A	Increasing heat gain	Heliothermy/basking	Surface area	Morphological properties	Solar heat gain	Surface area	T
PA	P	Increasing heat gain	Orientation	Orientation	Spatial properties	Solar heat gain	Surface area	T
PA	P	Increasing heat gain	Thin cuticle	Thickness	Morphological properties	Solar heat gain	Heat transfer coefficient	P
PA	A	Decreasing heat loss	Hunching	Surface area	Morphological properties	Convective heat loss	Surface area	T
AC	A	Decreasing heat loss	Preening	Water flow	Substance properties	Evaporative heat loss	Surface area	T
AC	A	Decreasing heat loss	Hidromeiosis	Surface area	Morphological properties	Evaporative heat loss	Surface area	T
AC	A	Decreasing heat loss	Body shrinkage	Surface area	Morphological properties	Evaporative heat loss	Surface area	T
PA	P	Decreasing heat loss	Leaf surface area	Surface area	Morphological properties	Evaporative heat loss	Surface area	T
AC	P	Decreasing heat loss	Waxy cuticle	Water flow	Substance properties	Evaporative heat loss	Surface area	?
PA	P	Decreasing heat loss	Losing leaves	Surface area	Morphological properties	Evaporative heat loss	Surface area	T
AC	P	Decreasing heat loss	Stomata closure	Surface area	Morphological properties	Evaporative heat loss	Surface area	T
AC	P	Decreasing heat loss	Decreased stomata density	Density	Morphological properties	Evaporative heat loss	Surface area	T
PA	P	Decreasing heat loss	Leaf rolling	Surface area	Morphological properties	Evaporative heat loss	Surface area	T
PA	A	Decreasing heat loss	Nest material	Thermal conductivity	Material properties	Conductive heat loss	Heat transfer coefficient	P
AC	A	Decreasing heat loss	Insulation	Thickness	Morphological properties	Conductive heat loss	Heat transfer coefficient	P
AC	A	Decreasing heat loss	Piloerection	Thickness	Morphological properties	Conductive heat loss	Heat transfer coefficient	T
AC	A	Decreasing heat loss	Ptiloerection	Thickness	Morphological properties	Conductive heat loss	Heat transfer coefficient	T
AC	A	Decreasing heat loss	Vasoconstriction	Diameter, fluid flow rate	Morphological properties	Convective heat loss	Heat transfer coefficient	T
AC	P	Decreasing heat loss	Insulation	Thickness	Morphological properties	Conductive heat loss	Heat transfer coefficient	P
AC	A	Decreasing heat loss	Countercurrent heat exchange	Distance	Spatial properties	Convective heat loss	Temperature gradient	P
AC	P	Decreasing heat loss	Epidermal hair or trichomes	Air flow	Material properties	Evaporative heat loss	Wind speed	P
AC	P	Decreasing heat loss	Sunken stomata	Air flow	Material properties	Evaporative heat loss	Wind speed	P
PA	A	Avoiding heat loss	Burrowing	Location	Spatial properties	Convective heat loss	Temperature gradient	T
PA	A	Avoiding heat loss	Migration	Location	Spatial properties	Convective heat loss	Temperature gradient	T
AC	A	Avoiding heat loss	Supercooling	Freezing point	Substance properties	-	Heat transfer (stop)	T
AC	P	Avoiding heat loss	Supercooling	Freezing point	Substance properties	-	Heat transfer (stop)	T
AC	A	Avoiding heat loss	Extracellular freezing	Water flow	Substance properties	-	Heat transfer (stop)	T
AC	P	Avoiding heat loss	Extracellular freezing	Water flow	Substance properties	-	Heat transfer (stop)	T
PA	P	Avoiding heat loss	Dormancy	Metabolism	Energy use (chemical properties)	-	Metabolism (stop)	T
PA	A	Avoiding heat loss	Daily torpor	Metabolism	Energy use (chemical properties)	Convective heat loss	Heart rate (drops)	T
PA	A	Avoiding heat loss	Estivation	Metabolism	Energy use (chemical properties)	Evaporative heat loss	Heart rate (drops)	T
PA	A	Avoiding heat loss	Hibernation	Metabolism	Energy use (chemical properties)	Convective heat loss	Heart rate (drops)	T

Table 10-11 ThBA Version 04, relevant actions related to 'cooling' as the thermal challenge

ssive/ active	Animal s/plant s	Action	Solution	Links for the main thermoregulation principles		Method	Variable	Temporar y/Perman ent
				Column 4	Column 2			
Pa/ac	A/p	What change in the heat exchange mechanism maintains homeostasis?	What is the solution?	What principle is central to the solution?	What properties of a living organism do the central thermal adaptation principles belong to?	What method of heat transfer allows for thermoregulation?	What was the main parameter in the heat transfer equation?	TE/PE
PA	A	Decreasing heat gain	Orientation	Orientation	Spatial properties	Solar heat gain	Surface area	T
PA	P	Decreasing heat gain	Orientation	Orientation	Spatial properties	Solar heat gain	Surface area	T
PA	P	Decreasing heat gain	Spiny outer surface	Surface area	Morphological properties	Solar heat gain	Surface area	P
PA	P	Decreasing heat gain	Compact forms (spherical or cylindrical)	Surface area	Morphological properties	Solar heat gain	Surface area	P
PA	P	Decreasing heat gain	Laying low and packing together	Surface area	Morphological properties	Solar heat gain	Surface area	P
PA	P	Decreasing heat gain	Thylakoids' structure (at chloroplast)	Surface area	Morphological properties	Solar heat gain	Surface area	P
PA	A	Decreasing heat gain	Sidewinding	Surface area	Morphological properties	Conductive heat gain	Surface area	T
PA	A	Decreasing heat gain	Stilting	Surface area	Morphological properties	Conductive heat gain	Surface area	T
PA	A	Decreasing heat gain	Shuttling	Location	Spatial properties	Convective heat gain	Temperature gradient	T
PA	A	Decreasing heat gain	Climbing	Distance	Spatial properties	Conductive heat gain	Temperature gradient	T
PA	A	Decreasing heat gain	Colouration (pigmentation)	Colour	Material properties	Solar heat gain	Solar heat gain coefficient (absorption)	T
AC	P	Decreasing heat gain	Colouration (pigmentation)	Colour	Material properties	Solar heat gain	Solar heat gain coefficient (absorption)	T
PA	P	Decreasing heat gain	Reflective colour of waxy cuticle	Colour	Material properties	Solar heat gain	Solar heat gain coefficient (absorption)	P
PA	P	Decreasing heat gain	Lightly coloured hair	Colour	Material properties	Solar heat gain	Solar heat gain coefficient (absorption)	P
AC	A	Decreasing heat gain	Insulation	Thickness	Morphological properties	Conductive heat gain	Heat transfer coefficient	P
PA	P	Decreasing heat gain	Tick cuticle	Thickness	Morphological properties	Solar heat gain	Heat transfer coefficient	P
AC	P	Decreasing heat gain	Insulation	Thickness	Morphological properties	Conductive heat gain	Heat transfer coefficient	P
PA	A	Avoiding heat gain	Shading	Surface area	Morphological properties	Solar heat gain	Surface area	T
PA	A	Avoiding heat gain	Burrowing	Location	Spatial properties	Convective heat loss	Temperature gradient	T
PA	A	Avoiding heat gain	Migration	Location	Spatial properties	Convective heat loss	Temperature gradient	T
PA	A	Increasing heat loss	Climbing	Location	Spatial properties	Evaporative heat loss	Wind speed	T
PA	A	Increasing heat loss	Nest building (mounds)	mound structure, cavity shape	Morphological properties	Convective heat loss	Temperature gradient	P
AC	A	Increasing heat loss	Selective brain cooling	Diameter, fluid flow rate	Morphological properties	Convective heat loss	Heat transfer coefficient (heat flux)	T
PA	A	Increasing heat loss	Saliva spreading	Surface area	Morphological properties	Evaporative heat loss	Surface area	T
PA	A	Increasing heat loss	Wallowing	Surface area	Morphological properties	Evaporative heat loss	Surface area	T
AC	A	Increasing heat loss	Sweating	Surface area	Morphological properties	Evaporative heat loss	Surface area	T
AC	A	Increasing heat loss	Thermal hyperpnea	Volume	Morphological properties	Evaporative heat loss	Surface area	T
AC	A	Increasing heat loss	Thermal tachypnea	Volume	Morphological properties	Evaporative heat loss	Surface area	T
AC	A	Increasing heat loss	Gular fluttering	Surface area	Morphological properties	Evaporative heat loss	Surface area	T
AC	P	Increasing heat loss	Increased stomatal density	Surface area	Morphological properties	Convective heat loss	Surface area	T
AC	P	Increasing heat loss	Increased trichome density	Surface area	Morphological properties	Solar heat gain	Surface area	P
AC	P	Increasing heat loss	Opening stomata	Surface area	Morphological properties	Evaporative heat loss	Surface area	T
AC	P	Increasing heat loss	Elongated lignified cells to stop rolling up	Length	Morphological properties	Evaporative heat loss	Surface area	T

10.4 R0017 in Dunedin (using the ThBA Version 04, test 01)

As Table 10-2 shows, the thermal challenge for R0017 was heating, therefore, the new version of the ThBA related to 'cooling' (Table 10-10) was used to look for relevant solutions. As explained previously, the column named 'links' shows the generalised thermal adaptation principle behind thermoregulation. Heat transfer methods and the main parameters in their equations are also shown in the columns labelled 'method' and 'variable' respectively.

The following sections introduce the solutions that were considered to be either irrelevant to R0017 or impossible to be translated into architecture given the current state of technology. The inappropriate solutions were identified by looking at the 'variable' column, and where the main parameters in their heat transfer equation were similar, they were grouped in one category within a box with an orange boundary (Table 10-10). They are highlighted in orange.

10.4.1 Inappropriate solutions

As shown in the 'variable' column in Table 10-10, for the five main actions (heat generation, stealing heat, increasing heat gain, decreasing heat loss, and avoiding heat loss) a number of solutions were inappropriate. However, the inappropriate solutions were categorised based on the main heat transfer parameter they had in common. This was done for solutions with similar main parameters, meaning the same architectural variable needed to be controlled to allow thermoregulation in the building design. Accordingly, the solutions were recognised as irrelevant if changing the main parameter of the heat transfer was not feasible for the case study. Solutions with dissimilar main parameters in their heat transfer mechanisms were grouped individually.

10.4.1.1 Action one: increasing heat gain + generating heat + stealing heat

10.4.1.1.1 Population

Increasing the population in a nest can be used to raise the temperature inside it. Thinking of users as the nest population, one design approach would be fitting more people into the same building for the purpose of metabolic heat generation raising the internal temperature. This is not a feasible approach as even if increasing the number of users was useful for winter, an extra cooling load would be added to the building energy use in summer. To make this strategy work, a building needs to have temporary occupants whose work schedules follow a seasonal pattern.

10.4.1.1.2 Temperature gradient

While for organisms spatial movement (distance and location) leads to thermoregulation, the parallel design strategy would be either moving a building to a new site or changing the distance between thermal zones and the main source of heat gain in a building. One way to follow the former principle would be to move R1007 to a warmer climate, but this would not be feasible.

The design strategy for the latter was also identified as irrelevant because as R0017 is a skin-load dominated building, an equivalent mechanism in architecture might be drawing zones closer to the envelope to gain heat which was not feasible.

10.4.1.1.3 Solar heat gain coefficient (absorption and transmission)

Organisms increase solar heat gain through absorption or transmission by changing either the morphological properties (shape and depth of light penetrating organs), or the colour of their tissues. For R0017, except for changing the colour of the building envelope, none of these strategies could be used to increase solar heat gain. However, in the past glass houses have been painted white in the summer to avoid over heating by reflecting more of the incoming solar radiation, so this strategy has been used in buildings before, but only to avoid overheating.

Introducing atria (morphological changes in the building anatomy) and using nanostructure light responsive materials (morphological change at the nanoscale of materials) for the building envelope could enhance light harvesting and subsequent solar heat gain. The former design strategy might be feasible for an existing building that was undergoing radical refurbishment, but this was not the nature of the problem set for R1007 as the atrium would lead to a loss of useable floor area.

10.4.1.1.4 Surface area

Termites increase solar heat gain through their special properties and by orienting their nest walls and their opening towards the sun. Likewise, the essential principle behind heliothermy, in which leaves or animals orient towards the sun, is to expose a larger surface area of an organ or tissue to direct solar radiation. A parallel strategy in architectural design could be a reorientation of the building envelope to follow the sun path for maximum heat absorption.

The heat balance characteristics of R0017 show conductive and radiative heat gain through the glazing. Subsequently, for R0017, a temporary increase in the surface areas or reorientation of the windows could result in more heat gain in winter, and consequently, less need for heating energy. Another possible strategy could be controlling the conductive and radiative heat gain through some form of shutter installed on the window to increase or decrease the exposed area during the year. This again is a strategy used at the domestic scale in many traditions, both to keep heat in at night and out during a hot sunny day. At the scale of an office building this strategy would probably need automation so energy would be needed to control the shutters. For this to be considered an energy-saving solution, an energy balance equation would be needed to investigate whether the gains exceeded the extra energy needed for the mechanical control.

Another familiar building strategy to avoid excess solar radiation that does not require mechanical control is the use of permanent sunshades to reduce the surface area of windows exposed to the direct solar radiation. However, these can only ever be optimised for one moment as they are fixed.

10.4.1.2 Action two: Decreasing heat loss

10.4.1.2.1 Surface area

Decreasing surface area to reduce evaporative heat loss is the central thermoregulatory principle for preening, hidromeiosis, hunching, body shrinkage, leaf size, leaf loss, leaf rolling, waxy cuticle, and decreased stomata density. This is however an irrelevant strategy for R0017.

As explained in section 0, in complementary strategies, responding to one stressor leads to or is associated with regulating another stressor. For decreasing heat loss, except for hunching, all strategies mentioned above seemed to be functioning through regulating water flow. These were identified as irrelevant solutions for R0017 since the heat is not lost due to the evaporation of water but rather because of the temperature difference.

As discussed in section 8.4.1.1.3.1, animals hunch to reduce the surface area of their body in order to decrease conductive heat loss through their skin. As shown in Table 10-3, conductive heat loss through the opaque surfaces was high in R0017. Consequently, an equivalent design solution would be reducing the surface area of the building envelope during winter, which is not possible.

10.4.1.2.2 Temperature gradient

As explained in section 10.4.1.1.2, there seemed to be two design strategies which would allow thermoregulation in a building through either conductive or convective heat transfer if the principle was changing the distance between the building and heat source to control the temperature gradient. This was not feasible for R0017.

10.4.1.2.3 Wind speed

One of the variables affecting evaporative heat transfer is wind speed. An exact translation of the two biological solutions in this category (epidermal hair, and sunken stomata) into architectural design would be beneficial where water is a medium in the thermoregulatory mechanism and needs to be controlled in a building. For R0017, conductive heat loss through the opaque surfaces was high but was not associated with water flow. Therefore, the solutions in this category were recognised as unhelpful. Furthermore, the thermoregulation process happens due to the change in environmental conditions rather than in the organism.

10.4.1.3 Action three: avoiding heat loss

10.4.1.3.1 Temperature gradient

Controlling the temperature gradient by changing the location of the zones and the impossibility of applying this to the redesign stage of R0017 was discussed in sections 10.4.1.1.2 and 10.4.1.2.2.

10.4.1.3.2 Stop heat transfer/metabolism

This section introduces a different process of thermal adaptation in which the organism stops heat transfer. This happens in conditions where only decreasing or increasing heat loss is not enough for the organism to survive. For example, lowering the freezing point of the water in the cell would allow the fluid to remain at a lower temperature. This means, the temperature at which the fluid in the cell starts freezing remains below the ambient temperature during cold seasons. Likewise, extracellular freezing inhibits water loss through solidification of the cell wall. Crystallisation of the walls prevents water flowing out of the cell. This would stop dehydration of the cells and hence ensure survival of the organism.

Where metabolism needs to be stopped, eliminating heat generation as one of the parameters of the heat transfer equation would inhibit heat transfer and hence enable the organism to survive. In other words, a pause in heat transfer allows the organism to survive. This the major difference between living organisms and buildings, as the former can stop their activities for a temporary period of time, thus saving energy to be consumed later when the period of extreme environmental conditions is passed. However, office buildings cannot be shut down temporarily on a regular basis, though this does happen in extreme weather conditions when people are sent home early (Edge, 2011). However, the solutions in this category were not applicable to an office building.

10.4.1.3.3 Drop heart rate/photosynthesis rate

Reducing heat transfer in plants (extracellular freezing) or reducing heat generation in animals (torpor) are avoidance mechanisms used by organisms to acclimate to their environment. The analogy of reducing the heart rate in animals for R0017 would be reducing energy use, which would be either reflected in turning off the HVAC systems or stopping using the work spaces. Neither seemed a reasonable solution to avoiding heat loss in R0017.

10.4.2 Appropriate solutions

10.4.2.1 Heat transfer coefficient for decreasing heat loss

Among all solutions from the ThBA where the heat transfer coefficient was the central parameter in the heat transfer equation, some were relevant to R0017. Looking at column 4 of the ‘links’ section in Table 10-10, increasing the thickness (morphological properties) or thermal conductivity (material properties) of an insulating layer in biological tissues changes the heat transfer coefficient, which limits conductive or convective heat loss from the surface.

Changing the thickness of leaves in plants and the insulating tissues of animals reduces their U-value. While biological organisms control the thickness of the insulating layer, altering the thermal conductivity of the wall is a solution used in building design. Therefore, a semi-similar approach for R0017 would be decreasing the thermal conductivity of the insulating layer of the envelope. For R0017, a temporary change in the thickness or thermal conductivity of the insulation material in winter would decrease heat loss. This however needs movable insulating layers. A more realistic solution would be to add more insulation to the opaque surfaces of R0017 to reduce heat loss. At this stage it seemed pointless to redesign and re-simulate R0017 since insulation is a common technique for thermal regulation that has been used by architects for centuries in many places around the world. The ThBA failed to come up with an innovative solution to the thermal challenge of heating.

10.5 R0017 in Auckland (using the ThBA version 04, test 02)

As explained in the research methodology, it was necessary to test the ThBA for the simplest case study in two climates.

Table 10-2 shows in Auckland R0017 had the two thermal challenges of cooling and heating. As the heat transfer characteristics of R0017 in Auckland were similar to those in Dunedin (Table 10-3) there was no need to look for solutions to the heating challenge as this had already been covered in the investigation of R0017 in Dunedin. The ThBA chart related to cooling challenges was thus searched to find relevant solutions.

10.5.1 Action one: decreasing heat gain

10.5.1.1 Incident solar radiation (absorption and transmission)

Using light colours for the external surfaces has proved to improve the thermal performance of buildings (Bansal et al., 1992; Synnefa et al., 2007). This is claimed to contribute to the mitigation of the urban heat island effects. Even white painted roof structures have shown to reduce peak cooling loads (Sadineni et al., 2011). In light of these, the application of cool coloured coatings in the manufacturing building materials has been suggested for achieving energy savings (Synnefa et al., 2007). Figure 10-5 shows an example of using white coloured roofs in Greece. Although, this was a relevant and feasible strategy for R0017, it was necessary to use it on a seasonal basis which correspondingly demanded dynamic colour changing characteristics of the glazing. While the permanent use of light-coloured coatings is a known sustainable design strategy especially for hot climates, smart glass windows and intelligent colour-changing facades can be regarded as innovative design solutions that are expected to be incorporated into future buildings.

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Figure 10-5 Left) Smart windows (Perelaer, 2017); Right) White roofed Greek houses (Lewis, 2017)

10.5.1.2 Heat transfer coefficient

This is discussed in section 10.4.2.1.

10.5.2 Action two: avoiding heat gain, and action three: increasing heat loss

No relevant solution was identified in this category.

10.6 Architects know biomimicry by instinct

Reviewing the solutions for redesigning R0017 in Auckland and Dunedin, it seems the simple translation of the majority of these solutions have been used in architectural practice and thus the ThBA has not offered any solutions to architects. As explained earlier (see 10.3.1, Table 10-5), the two columns of 'method' and 'variable' in Table 10-10 and Table 10-11, seemed to play similar roles in biology and architecture and therefore, were used as a basis for categorising the in-use thermal adaptation strategies in building design. This categorisation might suggest another structure for the ThBA including the examples of organisms and 'means', through which the architectural and thermal performance specifications of an office building would guide designers to find relevant solutions in it. Below are the new categories.

10.6.1 Controlling conductive and convective heat gain through temperature gradient

Different building design approaches seem relevant to the idea of 'decreasing distance from a heat source' as a thermoregulatory principle.

Depending on the main source of heat gain in a building, the distance between the thermal zone and the heat source needs to be decreased to allow conductive or convective heat gain. For internally-load dominated office buildings, internal heat gains are the heat sources, while for a skin-load dominated one, the environmental conditions are the heat source. For the former, an equivalent mechanism in architecture could be placing colder internal spaces next to those that generate too much heat, while for the latter, zones that need heat might be drawn closer to the envelope to gain heat from outside.

For buildings with significant heat gain through the envelope, changing the arrangement of the thermal zones in a manner such that they share at least one surface with the envelope would increase heat gain. This would require trying to place more zones so they receive solar energy through some type of glass façade oriented towards the sun.

Buildings with high internal heat gain can have other zones places around the sources of this, whether the heat is generated by the metabolic activities of users or gained through equipment and HVAC operations.

10.6.2 Controlling convective and conductive heat loss through temperature gradient

The landscape surrounding a building creates microclimatic conditions for the interior and the external skin which could result in reduced energy consumption. Using vegetation for shade is a passive design strategy for protecting outdoor spaces and zones close the envelope in summer, and for reducing wind speed and heat loss in winter.

Zero-energy earth sheltered buildings seem to be inspired by the burrowing strategy (Vale & Vale, 2013). Figure 10-6 shows a zero-energy south-facing house with the northern side buried in the ground.

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Figure 10-6 Autonoumous house (Hockerton Housing project)(Annable, 2006)

10.6.3 Controlling solar heat gain through transmission and absorption

Light-induced temperature regulation was discussed in the focus group (see 9.4.2.6.1.1) as there can be an interaction between thermoregulatory stressors such that responding to one stressor can induce the regulation of another environmental stimulus. Similarly, in a building increasing light absorption and transmission would increase heat gain.

Parallel building design solutions where the change in the depth of light penetration through use of shape and structure and colour to increase light absorption and transmission, are almost conventional.

While, the morphological properties of palisade cells in plants (columnar and spherical shapes) adjust the light transmission so light can penetrate deep into leaves, windows and atria also transmit light into the building. Plants employ the light-focusing shape of epidermal cells to increase heat gain. Changing the colour of the façade has been commonly employed to increase light and heat absorption in buildings.

At the macroscale for a building there could be substantial light harvesting through windows by changing the shape and geometry of these. While the biological mechanism is permanent, any temporary architectural translation in a building of such a permanent thermoregulatory mechanism in nature needs to be either manually or mechanically controlled. This biological solution could be translated into architectural design through the temporary geometric transformation of windows over the course of a year. This might be better exploited at the early design phase of a new building, although an energy balance check would need to be made.

At the microscale, light-responsive biomaterials incorporate an optical nanostructure to adjust light transmission. Hydrogels have been used as smart materials to control illumination through active and passive strategies. A new hydrogel biomaterial has recently been developed to be used in the building envelope. Windows made with hydrogels become opaque in response to high temperature and hence inhibit light transmission by scattering light beams on the surface (Khoo & Shin, 2018)(see 3.4.2.1 for more detail).

10.6.4 Controlling solar heat gain through surface area

This is discussed in section 10.4.1.1.4.

10.6.5 Controlling evaporation through surface area

Passive and active evaporative cooling strategies are controlled by water surfaces or flows. There are several passive and active strategies used in conventional architecture such as green roofs/walls, cooled soil, and evaporative coolers. These are discussed in section 8.5.1.1.4.2 and 8.5.2.1.3.1.

10.6.6 Controlling evaporation through air flow

The courtyard effect and solar chimneys have been used as passive evaporative cooling strategies. The cooled air from the surface of the water flows towards the warmer spaces and creates air flow. The best examples for application of these techniques can be seen in Iranian traditional houses in hot and dry, and hot and humid climates (see 8.5.1.1.4.2).

10.6.7 Controlling conductive and convective heat gain through surface area

A similar approach in architecture to stilting and sidewinding, which are two strategies animals use to decrease conductive heat gain, could be stilt construction which has been used in earthquake prone areas and as a response to climatic constraints. Examples of these are the stilt constructions and pile dwellings of southern Asia (Figure 10-7) that allow for natural ventilation in hot and humid climates (Ara & Rashid, 2018).

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Figure 10-7 Pillar construction (Ara & Rashid, 2018)

Designing buildings in a compact form reduces the surface area of the building envelope and hence helps to minimise heat loss.

10.6.8 Controlling convective and conductive heat loss and heat gain through heat transfer coefficient

Using thermal insulation materials is one of the most popular sustainable design strategies, and units like R values ($m^2 \cdot K/W$) have been used to describe the thermal performance of insulation materials (Asdrubali et al., 2015). The historical background of insulation materials is linked with the history of temporary dwelling constructions made by prehistoric people (Bozsaky, 2010). Because buildings had to be moved and hence be light, the one strategy they could use to reduce heat loss was use of fluffy materials, such as wool and other animal fibres, in the envelopes. A typical example would be the felt coverings of the Mongolian yurt (Figure 10-8).

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Figure 10-8 A Mongolian Yurt

10.7 Analogy between architecture and biology

Almost all the ‘variables’ suggested by the ThBA have already been used in architectural design as a means of regulating indoor temperature. While for most solutions the parameters of the heat transfer equations contributing to thermal regulation in architectural design are similar to their biological equivalents, for some, the central thermoregulation principle(s) of architectural and biological solutions are different. This seems to be caused by the limited number of parameters that have the potential to be changed in building design. Considering heat gain to be imposed by either gain through the building envelope or internal gains, and the heat transfer to be happening through the skin of buildings, the thermoregulatory design opportunities would be limited to the envelope, space organisation, and HVAC systems. The analogies of these would be the skin of animals or tissues of plants, the clustering behaviour of animals, and respiratory and circulatory mechanisms (Table 10-12).

Table 10-12 Analogy between architecture and biology

Where is the central thermoregulatory principle centred?	Heat	Biology	Architecture
Inside	Generation	Thermogenesis	HVAC, and internal gains
Outside	Generation	Clustering	Space organisation
Inside	Transfer	Respiratory mechanism	HVAC (Air conditioning)
Inside	Transfer	Circulatory mechanism	HVAC (Cooling and heating pipes)
Outside	Transfer	Body	Envelope (glazing and opaque surfaces)
Outside and inside	Transfer	Cell, tissue, Skin	Interior and exterior materials
Outside	Transfer	Between organism and environment	Between building and the environment

10.7.1 Obstacles inform future design opportunities

Reviewing the parallels for biological thermal adaptation strategies in architecture revealed that a large number of biological solutions are currently employed in building design. However, it worth mentioning that, for most of the architectural equivalents, the biological solutions represent at best a simple translation of the intricate natural application of their heat transfer principle. This means despite the simple translation of the majority of these solutions being used in architectural design, the sophistication and internal hierarchical connections of almost all physiological strategies remained unexplored. The main barrier to their exploration is that the technology falls short when compared to the hierarchically organised, dynamic, and multiscale operational characteristics of living things (cells, tissue, organs). Naming these 'obstacles' could also outline the areas of future exploration. The followings summarises the design opportunities that biological organisms could provide for future buildings.

a) **Circulatory mechanisms:** In vasoconstriction, thermal regulation happens through heat transfer between blood vessels and skin, these being the internal and peripheral tissues. Thinking of blood vessels as pipes with a fluid flow transferring the thermal energy to where it is demanded in a building, the smaller the diameter of the pipes, the less fluid will flow, and thus, the less heat will be taken away through conduction and convection, due to the temperature difference between the pipes and the adjacent surfaces. Such pipes could be used in any thermal transfer system such as a roof mounted solar collector, a geothermal ground heat exchange system, or as a dynamic thermal barrier in walls. An equivalent design solution might be creating a mesh of capillary pipes that can change their diameter embedded between the materials used for either external or internal surfaces. Having flexibility in narrowing the fluid channels is expected to decrease heat loss through less fluid flowing in the pipes. Another possible design solution could be bio-inspired capillary HVAC plant loops. However, none of these approaches is relevant to R1007 as, bearing in mind the transitory characteristics of vasodilation, new materials that can imitate this would have to be developed.

b) Temporary solutions necessitate dynamic movement: While nearly all biological thermal adaptation solutions are reversible, the application of their equivalent solutions in buildings needs to be alterable to allow them to be exact analogies of their biological parallels. For example, altering the material properties of the building envelope and its thermal zones, and dynamic changes in building geometry and size, orientation and size of shading devices, and space organisation, could imitate the design principles of temporary solutions in nature.

The next generation of buildings might be capable of being buried in the ground during extreme periods of the year and emerging back on the surface when the extreme conditions are over. They might be able to move on their construction site shuttling between sun and shade. The movement of the whole building to a cooler environment is expected to be more effective that shading devices, as the latter only partially keep the envelope cool.

Animals migrate to avoid harsh climates for a certain period of time. Thinking of a parallel to migration in architecture seemed unfeasible. Although it might be possible to create a microclimate around a building to influence the temperature outside and inside, and hence reduce energy use in winter, this is not analogous to migration, as a proper translation for migration in architecture would be moving a building from one site to another.

Likewise, burrowing is based on moving from one place to another. A somewhat similar approach has been used in architecture with buildings being entirely dug into the ground.

c) Permanent solutions: Looking at the ThBA charts, there were several permanent solutions for different actions. Reviewing the permanent biological solutions, raised the question of whether their principles could be translated to architecture and employed temporarily in a building.

The permanent solutions used by animals were insulation, counter current heat exchange, and the orientation and material of termite mounds. Compared to animals, for plants there were several permanent solutions that could also be used temporarily by some species. The changes were temporary where the climatic conditions became extreme in some seasons. For others, the harsh climate was enduring and hence, the adaptive solutions were constantly used by plants.

Despite these solutions being a permanent strategy, they might have a temporary application in buildings where a relevant action is required over the course of the year. For example, 'counter current heat exchange' seemed to be an effective strategy for the arrangement of thermal zones and 'permanent insulation' for the building envelope. However, when it comes to a temporary application, it seems the translation of the former solutions was unlikely to be to be reflected in the space arrangements of an office building. The reason for this is the limitation in the dynamic reconfiguration of the thermal zones.

Dynamic insulation does not change its nature, but is permeable insulation that allows air to flow from outside to inside, normally through an insulated timber frame wall (Taylor & Imbabi, 1998). The idea is the fresh air will be pre-warmed by passing through the temperature gradient across the wall. The air flow depends on the wind pressure, so is hard to control. However, once the permeable insulation is installed it cannot be changed, so this is really a permanent solution.

d) **Finding inspiration in one of the three thermoregulatory levels can be translated into different building characteristics:** The thermal regulation principles behind some active solutions in plants involve the cellular and molecular level and occur through biochemical reactions. These mechanisms, however, could be useful for buildings design as morphological changes in cellular levels could be translated to the design of the envelope through the nanostructure of materials.

e) **Buildings are not living organisms:** It seems buildings cannot be called 'living organisms'. Even the phrase 'living architecture' (Eng et al., 2001; Garnier et al., 2013; Flynn, 2016) does not seem to do justice to what 'living' literally means. Except for behavioural thermal adaptation, the two physiological thermoregulatory solutions in plants and animals, and some morphological thermoregulatory solutions that only occur in plants, happen in a hierarchy, meaning that a specific change in the chemical reactions has an impact on the cellular level that would then cause change in a tissue to enable thermoregulation.

Envisaging buildings in such manner that they could enable thermoregulation through hierarchical connections seems unfeasible considering the current state of architectural technology. For this to happen HVAC operation, cooling, heating and air-conditioning vents, space layouts, materials used for interior and exterior surfaces, and the size and shape of glazing and opaque surfaces need to be synchronised to allow a dynamic and multilevel thermoregulation similar to biological thermoregulation.

Insulating tissues are used by organisms to control temperature and air flow. These are counted as exceptions when it comes to physiological solutions, as translation into insulating materials has been well developed, ranging from conventional insulation materials to smart biomaterials.

Compared to the physiological and morphological adaptations, it seems that the behavioural thermal adaptation mechanisms used by organisms have been translated to architectural design, since almost all animal behaviours except the three types of torpor, are independent of the internal thermoregulatory principles. For these, interaction with the environment is the most important principle in thermoregulation. Animals might move in space, orient towards the sun, and change shape, colour and posture. All these ideas have a place in building design but the building has to be made to move through human intervention.

Identification of the points above seems to be evidence for the illegitimacy of envisaging buildings as living organisms.

Buildings do not stop operating: Referring back to the definitions in Chapter 8 for daily torpor, estivation, hibernation, and dormancy, an equivalent strategy to be used for a building would be to shut the building down in winter and to ask the occupants to come back to the office in summer. However, as noted earlier some buildings like school do shut down periodically and parts of buildings like conservatories must also remain unused during cold weather.

Kinetic movements might not be efficient: As mentioned earlier the static structure of buildings seems to be a barrier to them being recognised as living organisms. In light of this, kinetic architecture has been developed to imitate the moving capability of organisms through partial movements of a building's structure (Bayhan & Karaca, 2019). The adjustable and dynamic character of kinetic design follows the rhythms of nature (El Razaz, 2010) yet needs to be evaluated from an energy efficiency point of view, as energy balance calculations are required to know whether the bio-inspired design approach is more efficient in energy terms.

10.8 Summary

This chapter detailed the key steps taken for testing the ThBA framework. The thermal challenges and the heat balance characteristics of the simplest case study (R0017) in the climate of Dunedin were used to identify the relevant actions which were then used as inputs into the ThBA to look for the relevant solutions. Testing the ThBA for the first time revealed the inappropriateness of the organisation of the first draft. This became apparent when a small part of the ThBA was searched to look for bio-inspiration. This, accordingly necessitated its reconfiguration so as to be useful for architects in such manner that designers could systematically connect the required actions to relevant thermal adaptation solution in nature.

Given this, it was decided to reorganise the ThBA for cooling and heating challenges before starting the redesign of R0017 in Dunedin. Having reorganised the ThBA for these, the ThBA took a new shape. Compared to the first draft of the ThBA that was developed in Chapter 8, and that had three parts related to passive and active strategies for animals, and plants, the new version of the ThBA had only two branches. The first was for cooling and the second for heating challenges.

These new ThBA charts were then searched to find appropriate solutions for R0017. This was done firstly by removing inappropriate solutions from the list, and secondly by investigating the possible translation of appropriate solutions. However, exploring the possible translation of the key thermoregulatory biological principles of the appropriate solutions into architecture, did not suggest translatable building redesign strategies for R0017 in Dunedin, so no redesign and simulation was carried out.

To establish whether the ThBA could also work for finding solutions to cooling challenges, R0017 in Auckland was selected as it had both heating and cooling as the thermal challenges. However, the second search process also failed to suggest any solutions that could be applied to redesigning R1007 given the limitations of current technologies.

Testing the ThBA for R0017 in two climates in New Zealand, highlighted the fact that the simple translations of the majority of biological thermal adaptation principles are being used by architects, although for some, the architectural equivalents did not function in exactly in the same way as biological thermoregulation strategies. The differences were seen either in the central thermoregulatory principles or the broader properties within which the key principles fitted. Apart from that, for both architectural and biological thermoregulatory strategies the heat transfer parameter and methods were the same.

The ThBA, however, suggested a few strategies that might address opportunities for designing a new generation of buildings in the future. The existing bio-inspired thermal regulation strategies that have been employed in the design of energy efficient buildings for decades, and the current gaps and limitations in the applications of some innovative and complex methods were summarised.

The next chapter will discuss the answer to the research question, the contribution to the knowledge, the limitations of this research, and future steps to build on this study.

11 Conclusion

11.1 Introduction

This chapter discusses the answer to the research question set out in section 5.1.1.2.1. The conclusion is derived from the results achieved in stages 3 and 4 of the research method (see 6.7, and Figure 6-4) that deal with data collection and analysis. It also elaborates on the contribution of this research to knowledge while explaining the research limitations as well as future research opportunities that could build on the current results, including the final version of the thermo-bio-architectural framework (ThBA).

11.2 Developing a framework for bio-inspired energy efficient building design

The main drivers behind this research were the fashionable concept of biomimetic architecture or bio-inspired building design and the ongoing debates centring on its dual philosophical promises of promoting sustainability and aiding innovation (see 2.3). Given the world's buildings are huge consumers of energy, and bearing in mind the apparent potential of biomimicry to offer solutions for solving issues in human ways of living, this study sought to investigate if a systematic process could be set up to assist architects in connecting the thermal challenges in a building to solutions new to architecture used by living organisms to endure or respond to unfavourable environmental conditions.

Since the term 'biomimicry in architecture' was first coined by Benyus in 1997, a number of internationally recognised roadmaps have been developed to bridge the gap between biology and architecture in the context of designing energy-efficient buildings. The only recent one by Badarnah (2012) (Chapter 5) stated that it was neither comprehensive, nor evaluated by experts in biology, and even more significantly there was no exploration of the architectural side of the framework to explain the process architects could take to identify the sources of high energy uses in either an existing building or a building at the concept design phase. As a result, this research aimed to investigate the possibility of developing a thermo-bio-architectural framework. This framework would be set up in such a manner that users could find innovative thermoregulatory bio-inspired principles as they worked through a top-down design process in which the thermal challenges were identified beforehand. This became the ThBA.

11.3 Answering the Research Question

This research had only one main question. However, several sub-questions were embedded in the main question. Even though the investigation of these was conducted individually, the connectivity of the results provided a valid response to the main research question. Therefore, the main question-embedded queries were not highlighted separately as sub-questions in section 6.2.3, but rather listed in sequence as objectives (see 6.2.2).

The main research question was:

> **"How could a generalised thermo-bio-architectural framework be developed as an aid to making energy efficient buildings through a systematic process of connecting thermal problems to relevant thermoregulatory solutions in nature?"**

1 **It is not possible to answer the main research question without first discussing issues that arose during the research. These will be presented here as a series of sub-questions.**

11.3.1 Sub-question 1

In the context of a building's simulated thermal performance, how can the heat transfer principles of its thermal behaviour be articulated so as to create a useful link to the generalised thermoregulatory principles, and how can the energy simulation process narrow the results to the main thermal challenges in a building?

The interdisciplinary nature of the research question necessitated an understanding of energy efficient building design and the processes needed to evaluate the energy performance of a building. Regarding the focus of this research on the problem-based biomimetic design approach, an energy simulation strategy was developed for recognition of the emerging patterns of energy use. This in turn led to identification of the thermal issues in a particular building, and allowed for the articulation of the heat transfer principles in buildings so they could be linked to their biological equivalents. This worked showed it was possible to develop a process for doing this.

Case study buildings were used for testing the validation of the framework within the context of real buildings. Using the developed energy simulations, the results of the energy performance of each case study were visualised through a treemap structure. Also, the research reported on the major energy end-use breakdowns and heat balance characteristics of five archetypal office buildings to show the main thermal challenges for each building. Normalisation of the energy results revealed that two office buildings had comparatively higher energy uses from which one was identified with a cooling challenge while for the other, both heating and cooling energy uses were high. The results also highlighted that cooling energy was significantly high for the five case study office buildings in New Zealand while heating energy was a challenge for some case studies.

Overall, energy analysis of the two thermally challenging office buildings in Auckland and Dunedin, identification of the location and duration of their thermal challenges and heat balance characteristics, together shaped an outline of how the energy results could be linked to the biology side of the ThBA framework (Chapter 7).

11.3.2 Sub-question 2

How can a generalised categorisation of biological thermal adaptation strategies be created?

Given the existing thermal adaptation strategies of plants and animals were scattered and not available as a complete list, a comprehensive literature review was conducted as the basis of creating a full list of generalised thermoregulatory mechanisms. The development of the ThBA (Chapter 8) was established using this review of the basic heat transfer methods in biophysics, and this later informed the classification of thermal adaptation strategies into passive and active categories.

Conducting an inclusive literature review on biological thermoregulatory principles was always going to be a problem as the author as an architect had limited knowledge of biology. As a result, the ThBA was confirmed by biology experts in another phase of the research (Chapter 9). At this stage of qualitative data collection, the list was pronounced to be comprehensive. The qualitative data collection revealed that thermal regulation mechanisms can be generalised and grouped into categories based on the environmental stimuli to which they respond (Chapter 9).

The classification of thermoregulation strategies into passive and active categories emerged as a result of the investigation. These were linked to the terms ectothermy and endothermy, as in biological textbooks these were generally the ways in which thermal adaptation mechanisms were categorised. It was also realised that acclimation strategies were dependent on the severity of the climatic conditions. This then shaped the categorisations of heat control strategies into preventing, decreasing, increasing, and generating heat. Another key concept observed was the commonality between some strategies that led to their aggregation into the categories.

In light of these points, it was possible to develop the biology side of the thermo-bio-architectural framework (ThBA), first to allow linkage between thermal challenges and the relevant heat control actions and sub-actions, then to the distinct categorisations of thermal adaptation mechanisms suggested for heat generation, heat gain and heat loss, and ultimately to relative means of heat transfer and examples of biological organisms.

11.3.3 Sub-question 3

How can biological thermal adaptation mechanisms be connected to their architectural parallels?

Having developed the biology side of the ThBA framework, the concern was how the thermal challenges of office buildings could be linked to relevant actions and sub-actions. Progressing through the ThBA classification, it was necessary to list a series of possible equivalent energy efficient solutions in architecture. This was done to suggest examples of appropriate strategies that architects might use to design energy efficient buildings when identifying the analogous thermoregulatory mechanisms in nature. Following this, the biological and architectural solutions were placed on the left-hand and right-hand sides of the ThBA framework.

As discussed in section 2.4.1.3, and given the importance of biological transfer, the gap between the two fields of knowledge was bridged with 'links'. These links were provided to assist architects in the biological translation phase that would come once the relevant mechanisms are identified.

Reviewing the physiological and behavioural thermal adaptation mechanisms, this research found there seems to be a hierarchical connection between thermoregulatory processes that happen at organismal level by using the whole body of an organism (in the context of behavioural ecology), and in or in-between organs, tissues, and cells (related to physiological ecology). It also appeared that at each of these levels the thermal adaptation principles could be linked to a more generalised category. To this end, a separate hierarchical structure was developed (see 8.7) to enable the generalisation of thermal regulation principles.

11.3.4 Sub-question 4

To what extent can the biology side of the framework be trusted and does the ThBA has include all biological thermal adaptation mechanisms in an acceptable classification scheme with an appropriate order?

To answer this question it was necessary to talk to experts in the field of biology. Interestingly, from all invited participants to the focus group session that was designed to address this issue, academics showed more interest in attending.

The focus group results supported the research hypothesis and confirmed it was possible to develop a systematic framework for designing bio-inspired energy efficient buildings. All participants confirmed the contents and structure of the ThBA were thorough and believed only a few strategies were missing. The group members twice emphasised the high quality of the research, once at the beginning and later near the end of the discussion. Also, no one suggested a better classification scheme.

11.3.5 Sub-question 5

To what extent is the ThBA useful for bio-inspired energy efficient building design in terms of suggesting relevant and innovative thermoregulatory solutions based on the thermal challenges identified for the office buildings?

Studying the relevant biological solutions found for the two most thermally challenging case studies through the ThBA, together with generalisation of the 'links', determination of the methods of heat transfer, and the main parameters in their governing equations, revealed that the simple translations of the majority solutions have been already used in building design (see 10.6). In the context of architectural design and considering the heat transfer processes as the essence of thermoregulation strategies, imitating biological forms that nature has evolved did not seem to be critical in improving building energy efficiency. This was supported by identification of parallel energy efficient design strategies that did not copy biological forms or control a parallel biological variable in response to environmental stimuli such as changes in temperature.

A question raised from the results of this research was: why architectural translation of biological systems are more frequently considered to be achieved through morphological configurations where the thermoregulatory tasks can be also achieved by emulating processes? This echoed the words of Jacobs (2014) who stated in biological systems, a function can be achieved from either form, process, or the relationship between two or more systems.

This research suggests that architects know instinctively how nature works when it comes to thermoregulation. This seems to be reasonable as people are part of nature and not separated from it.

11.4 Contribution to the knowledge

The contribution to knowledge of this research was proving that first it was possible to develop a systematic process or framework for designing bio-inspired energy efficient buildings to connect either the thermal challenges identified or pre-set thermal performance objectives to the relevant thermal adaptation mechanisms in nature. It was also discovered that architects are already familiar with most of these strategies when it comes to energy efficient building design. As a result, this raised a question over the usefulness of biomimicry in the context of bio-inspired energy efficient building design and the extent to which it can produce innovative sustainable design solutions. This has added to the philosophy of biomimicry.

Furthermore, this research investigated the inclusive application of biological thermoregulation mechanisms into energy efficient building design. As a result it has suggested possible future ways of translating bio-heat transfer mechanisms into strategies for HVAC distribution systems, optimisation of space organisation, and the development of new materials. This makes this research different from recent research into biomimicry and architecture that has been mainly focused on building facades (Badarnah, 2015; Y. Han et al., 2015; López et al., 2015a, 2015b; Reichert et al., 2015).

11.4.1 Unexpected findings

The following presents the unexpected findings that occurred during the data collection and analysis. These evolved during the interpretation of the results, and could form a basis for further investigation.

11.4.1.1 The ThBA includes complementary thermoregulatory mechanisms

The literature review highlighted the interconnectedness of circulatory and respiratory systems in living organisms. Various types of respiratory systems were reviewed and identified as equivalents to HVAC systems. Subsequently, an additional framework was developed to enable identification of the respiratory mechanism analogues to HVAC systems in buildings. The emerging point here was noticing the close relationship between heat transfer and gas exchange mechanisms in physiological thermoregulatory processes.

This seemed to address the concern raised in recent research (Badarnah, 2012) on the importance of developing a system for linking solutions that organisms use to respond to multiple environmental aspects so as to facilitate designing multifunctional environmentally adaptable buildings. Such multi-functionality would need to look for inspiration in nature so as to find ways of regulating light distribution, temperature, and water and air flow simultaneously.

Findings of previous studies do not seem to support the results of this research as they have placed emphasis on developing separate frameworks for different environmental aspects (light, humidity, air flow, temperature) (see 5.1). In contrast, what this research has put forward is the notion of the inseparable interconnectedness between most biological thermoregulatory responses to environmental stimuli. Close links were found between thermoregulatory, circulatory and respiratory mechanisms that highlight the relationship between temperature and air flow control. Plants had many interrelated mechanisms for regulating light levels and water flow which together result in temperature regulation. Therefore, if the aim is to find bio-inspiration for thermoregulation of buildings, using separate frameworks might not be useful as many physiological thermal adaptation mechanisms are interconnected. As a result, this research has introduced all co-dependent mechanisms that lead to homeostasis.

11.4.1.2 Are buildings more like plants?

In contrast to the majority of earlier research looking to animals for designing bio-inspired buildings (Turner & Soar, 2008; J. Wang & Li, 2010; Park & Dave, 2014; Nessim, 2015), the experts in biology (Chapter 9) discussed the similarity between buildings and plants. This change in focus could open a new window for further research.

11.4.1.3 Biological thermoregulatory processes may not be energy efficient

Another interesting outcome was the collective agreement of biologists on the fact not all strategies in nature are energy efficient. This interesting avenue is opposed to common beliefs about the concept of sustainability in nature.

11.5 Implications of the framework for architects

The system was successfully developed and tested and seemed to be useful for architects. It also suggested futuristic ideas for sustainable building design.

In general, the current use of biomimicry in architectural design does not seem to go beyond the approaches below:

1) The exact imitation of biological processes that mainly replicates biological forms in non-advanced terms or through simplification of morphological configurations at a more advanced level. These two approaches still seem to be attached to morphological properties rather than the functional and process characteristics of thermoregulatory principles.
2) A perhaps more successful approach has worked on the numerical heat transfer equations of energy simulation to incorporate the thermal properties of biological tissues into building façades (Webb et al., 2018). Such approaches taken to design bio-inspired energy efficient buildings seem to be in line with the results of this research. This is because they use biomimicry through non-morphology orientated design by the use of heat transfer principles. The ThBA allows for this approach.

11.6 Limitations

The limitations of current energy simulation software in modelling and calculating results in a cumulative process for all instant changes in the heat flow, space organisation, or thermal properties of materials, seems to be an obstacle for evaluating the dynamic behaviour of buildings. However, there is software like *TRaNsient SYstem Simulation (TRNSYS)* that can evaluate the thermal performance of biomimetic energy models through the use of mathematical models which employ fundamental principles of mass and fluid mechanics, thermodynamics and energy balances. The use of *EnergyPlus* in this research limited what could be modelled.

This research is limited to office buildings and New Zealand's climatic classification. In addition, the architectural side of this research was limited to temperature regulation and no other environmental aspects. Among the different ways biomimicry might benefit building design, this study only focused on thermal adaptation mechanisms.

Given the ThBA introduced some innovative solutions for designing energy efficient building, none were tested or translated into architectural principles in detail. The reason was first these were not relevant to the thermal challenges identified for the two case studies. Introducing a directive of all possible ways of translating biological solutions into architectural ones was outside the scope of this research.

Although not strictly a limitation of this research, the current state of building technology did not allow realisation of some solutions suggested by the ThBA as it is not currently possible to emulate the complexity of the thermoregulatory mechanisms suggested by the ThBA in design. However, the fact that many current energy efficient building design strategies reflect the basic translation of the thermoregulatory strategies embedded in the ThBA points to its successfulness and it is expected it will make a useful contribution to the design of future sustainable buildings.

11.7 Further research

Despite the fact that the majority of thermoregulatory strategies have simply been translated into architectural design, the ThBA framework suggested a number of innovative strategies whose exploration might lead to new ways of making sustainable buildings. Developing these innovative solutions, summarised below, is an avenue for further research.

- Capillary HVAC plant loops and capillary pipe embedded materials that can be used for external and internal surfaces for heating purposes.
- Developing a thermoregulatory system for buildings to allow the hierarchically connected thermal adaptation to occur at different scales such as those of the building envelope, material composition, and HVAC systems.

Given the current state of building technology, a full translation of the intricate connections between thermoregulatory mechanisms is not yet feasible. This implies the ThBA is currently of limited benefit in suggesting multilevel sophisticated bio-inspired ways of improving building energy efficiency. However, it does suggest that because people are essentially part of nature thinking of biomimicry as something separate from people may not be a productive approach. Thus, there may be further research to be undertaken in the philosophical positioning of biomimicry.

Another step in this research could be engaging building professionals to use the ThBA and to comment on the ways biological strategies can be transferred to energy efficient building design. This could be done through conducting a series of focus groups or surveys.

Despite the existence of the simplest translation of some of these biological thermoregulatory strategies in sustainable building design, their best combination still needs to be investigated to achieve the optimum energy use reduction when translated to architectural design. As further research, another framework could be created as an extension to the ThBA to introduce the various possible sets of thermoregulatory energy efficient solutions biological thermal adaptation principles suggest. However, the development of the ThBA remains a significant step in bridging the gap between biology and architecture in the search for more sustainable buildings.

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Appendix A

Human Ethics approval for focus group

TE WHARE WĀNANGA O TE ŪPOKO O TE IKA A MĀUI
VICTORIA
UNIVERSITY OF WELLINGTON

Phone 0-4-463 6028
Email judith.loveridge@vuw.ac.nz

MEMORANDUM

TO	Negin Imani
FROM	Dr Judith Loveridge, Convenor, Human Ethics Committee

DATE	5 November 2018
PAGES	1

SUBJECT	**Number:** 26789 **Title:** Bio-inspired Office buildings: A thermo-bio-architectural framework for improving the thermal performance of office buildings in New Zealand

Thank you for your application for ethical approval, which has now been considered by the Human Ethics Committee.

Your application has been approved from the above date and this approval is valid for three years. If your data collection is not completed by this date you should apply to the Human Ethics Committee for an extension to this approval.

Best wishes with the research.

Kind regards,

J. A. Loveridge

Judith Loveridge

Convenor, Victoria University of Wellington Human Ethics Committee

Appendix B

Focus group documents

TE WHARE WĀNANGA O TE ŪPOKO O TE IKA A MĀUI
VICTORIA
UNIVERSITY OF WELLINGTON

Bio-inspired Office buildings: A thermo-bio-architectural framework for improving the thermal performance of office buildings in New Zealand

INFORMATION SHEET FOR PARTICIPANTS

Who am I?

Please read this information before deciding whether or not to take part in this research project. If you decide to participate, thank you. If you decide not to participate, thank you for considering this request.

My name is *Marzieh (Negin) Imani* and I am a Doctoral student in *architecture* at Victoria University of Wellington. This research project is work towards my dissertation.

This research has been approved by the Victoria University of Wellington Human Ethics Committee (reference no. 0000026789).

What is the aim of the project?

This project seeks to investigate the possibility of developing a framework for the purpose of facilitating a biologically inspired architectural design process. This framework includes generalised biological principles in terms of thermal adaptation mechanisms and is expected to help architects to systematically find appropriate innovative solutions in nature in regards to thermal challenges in office buildings. The main objective of the project is to gain feedback from experts in different fields of biology on the possible reliability and generalisability of this framework. Many architects internationally reference examples from nature as inspiration for their designs. There is currently no systematic means of finding or reviewing thermal adaptation strategies that organisms use to survive climate extremes.

How can you help?

You have been invited to participate because collecting feedback from biologists is critically important in this research. A framework has been developed which attempts to link thermal challenges in architecture to thermal systems and classifications in biology. Through this focus group this research seeks feedback from biologists to determine and evaluate the likely utility of the current draft framework. The feedback from this focus group will be tested on a set of case study New Zealand office buildings with the goal of informing further development of the current version of the framework.

If you agree to take part you will be part of a focus group that will be held at the school of biological science at Victoria University of Wellington during November 2018. You and other participants will be asked questions about the current framework. Before the questions, you will be provided with a short explanation of the framework. You are not expected to need to do any preparation for this and you will be given every opportunity to ask questions about the framework. This short presentation and the introductions and guide will take no more 10-15 minutes. Then the group will be asked five different questions all related to different parts of the framework. You will be asked to express your views and issues surrounding each individual question. Discussion on each question will take at most 15 minutes.

The total length of time planned for the focus group is one hour 1 hour and 30 minutes including introductions and refreshments. In agreeing to participate, you are giving permission that the focus group will be audio recorded and then transcribed for analysis. The information shared during the focus group is confidential. That means after the focus group, you may not communicate to anyone, including family members and close friends, any details of the information disclosed in the focus group.

You can withdraw from the focus group at any time before the focus group begins. You can also withdraw while the focus group is in progress. However, it will not be possible to withdraw the information you have provided up to that point as it will be part of a discussion with other participants.

What will happen to the information you give?

This research is confidential. This means that the researchers named below will be aware of your identity but the research data will be combined and your identity will not be revealed in any reports, presentations, or public documentation. Your organisation and particular expertise in the field will not be named. There is a small risk that as a participant in a small group like this, your identity might be obvious from your comments to others in your specialist community. The design of the research and analysis is intended to avoid this possibility, but there remains a small risk. It is not anticipated that any information disclosed during this focus group could be used in a way that could be harmful to you or your organisation.

Only my supervisors and, I will read the notes or transcript of the focus group. The focus group transcripts, summaries and any recordings will be kept securely and destroyed 1 year after the research ends on the 30th of April, 2019.

All data recorded from the focus group will be kept in a password protected file stored on an electronic hard-drive, securely locked at the Victoria University of Wellington Te Aro campus. No personal data or data that will enable you to be recognised. Please note that due to the confidentiality of the focus group, information discussed within the focus group should be kept confidential and all participants will be required to sign a consent form in regards to this.

What will the project produce?

The information from my research will be used in a PhD dissertation, academic publications and conferences.

If you accept this invitation, what are your rights as a research participant?

- choose not to answer any question;
- ask for the recorder to be turned off at any time during the focus group;
- withdraw from the focus group while it is taking part however it will not be possible to withdraw the information you have provided up to that point;
- ask any questions about the study at any time;
- read over and comment on a written summary of the focus group;
- be able to read any reports of this research by emailing the researcher to request a copy.

If you have any questions or problems, who can you contact?

If you have any questions, either now or in the future, please feel free to either me or primary supervisor:

Student:

Name: Marzieh (Negin) Imani

University email address: negin.imani@vuw.ac.nz

Supervisor:

Name: Michael Donn

Role: primary supervisor

School: Architecture School

Phone:

michael.donn@vuw.ac.nz

Human Ethics Committee information

If you have any concerns about the ethical conduct of the research you may contact the Victoria University HEC Convenor: Dr Judith Loveridge. Email hec@vuw.ac.nz or telephone +64-4-463 6028.

TE WHARE WĀNANGA O TE ŪPOKO O TE IKA A MĀUI
VICTORIA
UNIVERSITY OF WELLINGTON

FOCUS GROUP QUESTIONNAIRE

I. Section 1: Evaluation of the effectiveness of framework

1. Has this framework already included ***all*** biological thermal adaptation mechanisms manifested in an acceptable classification scheme with the appropriate order?
2. Has it used biological terminologies correctly?
3. Are there biological thermal adaptation principles or terms that this framework has failed to address?
4. If yes, how many of those you think I have missed to find?
5. If you think there are missing strategies could you add them to the list?
6. Is the hierarchy appropriate? Does the order of columns lead us to relevant biological information? If no, what is a better hierarchy?

II. Section 2: The spectrum of variation across which thermal adaptation principles vary

7. Do they think the strategies that organisms use to cope with thermal stresses differ from species to species?
8. If yes, are thermal adaptation strategies:
   A: environment-based? (For example all tropical birds? Or all polar animals)
   B: Taxonomy-based? (For example, all reptiles, all fish, all flatworms?)
   C: Size-based? (For example large size animals, small size insects, and large fish?)
9. Can you think of another way of classification of data?

III. Section 3: Multiple use of adaptation strategies

10. Do organisms normally use a combination of strategies to cope with thermal stresses? Or do they use only one at a time?
11. Can a response to temperature stress be induced by response to another environmental stress?

IV. Section 4: Tight feedback loop

12. Is tight feedback response to heat stress common in all organisms?

V. Section 5: A systematic framework for bio-inspired architectural design

13. Do you think, in general, it is possible to use a systematic approach for searching biological information related to thermal adaptation?

Appendix C

Evaluation of two qualitative data collection methods (Delphi survey and focus group)

2 Focus group

This method could be labelled as qualitative if:

1) The data are collected by conducting a semi-structured focus group;

2) Descriptive responses are consequently obtained in reply to open-ended questions;

3) There is the probability a number of issues in the discussion are identified during the panel discussion;

4) Information is recorded in a descriptive format and the data is also analysed in a descriptive manner; and

5) The findings are presented in a non-analytical style.

3 Delphi survey

This research could use a Delphi survey to be carried out in three rounds.

1) The data will initially be collected by conducting semi-structured interviews in the first round followed by two sets of questionnaires for each of the other two rounds of the Delphi survey;

2) Descriptive responses, however, similar to the previous approach, are acquired through answers to open-ended questions during the face-to-face interviews. The second round of the Delphi survey also includes open-ended questions while in the third round only closed-questions (Likert scale multiple choice questions) will be used;

3) Similar to the qualitative approach explained above, to an extent a number of issues in the discussions might be identified during the first stage of the data collection process (semi-structured interviews);

4) Information is recorded in a descriptive format for both the first (semi-structured interviews) and the second round (open-ended questions) of the Delphi process, but in a numerical format (Likert scale) for the third round;

5) Analysing the descriptive responses to the open-ended questions in the semi-structured interviews of the first round might develop a number of categories based on which the open-ended questions of the second round are shaped; and

6) Finally, the findings of the first round are presented in a descriptive format while the findings of the subsequent two rounds will be communicated numerically.

4 Examination of methodological choices

A major consideration for any sound investigation is that the research question determines the method to use (Then et al., 2014). Thus, having a better understanding of the steps required for both qualitative and mixed methods to produce trustworthy results, facilitates documenting the relative advantages and disadvantages of each methodology. This ultimately enables the determination of the suitable research method for this study.

4.1 Focus group: outline

A focus group is a group discussion of 4 to 14 participants with guidance from a moderator, where a discussion on a specific topic takes place among the participants (Dilorio et al., 1994; Morgan, 1996).

In terms of using primary or secondary sources for data gathering, there is no difference between the two possible options (focus group and Delphi survey). However, for the focus group, the consensus is obtained only after one session while for Delphi consensus will be obtained after three rounds.

4.1.1 Process

Conducting a focus group requires guidance from a moderator as focus groups are semi-structured interviews (Then et al., 2014). The guidance works as an outline of the whole process of the session and is unique depending on the nature of the topic and wishes of the researcher (Vaughn et al., 1996). Appendix-Figure 1, explains the first steps in setting up a focus group (Then et al., 2014).

Appendix-Figure 1 The first steps in setting up a focus group

Prior to beginning each session the moderator needs to request permission to tape the session to ensure that parts of the conversation are not missed (Morgan, 1996).

The guide for the moderator is normally in three sections: engagement questions, exploration questions (to get at the topic at hand) and exit questions. Exit questions allow the moderator to check if what she/he understood was correct and if there anything was missed (Then et al., 2014). Additionally, the questions developed should be broad in nature and it is the moderator's responsibility to maintain clear direction during the focus group.

Following the focus group session, the moderator undergoes debriefing regarding the content and process that occurred. This is followed by a write-up of salient findings and information from the session. The focus group session should always end with thanking the participants for their assistance in gathering valuable insights into the topic (Then et al., 2014).

4.1.2 Size and group composition

The size of the ideal focus group recommended in the literature varies from 4 to 14 (Dilorio et al., 1994), while Morgan (1996) and Bloor et al. (2001) suggest between 6 and 10. Krueger and Casey (1994) and Morgan (1996) suggest it is generally better to over-recruit up by approximately 20%, as last-minute changes, withdrawal and other issues may influence the focus group through insufficient numbers for conducting the session, resulting in its cancellation.

4.1.3 Timing

The time allocated for the focus group should never exceed two hours in total (Morgan & Kreuger, 1993; Plummer-D'Amato, 2008; Doody et al., 2013). The first and last 10 minutes of the session should be used for introduction and summarization/conclusions respectively (Then et al., 2014).

4.1.4 Analysis

Several data analysis techniques may be used (Glaser et al., 1968; Morgan, 1996). Specific analytical tools that can be used for data gathering and initial interpretation include demographic data, focus group map and questions, audiotapes, verbatim transcription, and moderator and observer field notes written prior to, during, and following the focus group (Miles & Huberman, 1994, pp. 312-314).

Analysis of the recorded audio and field notes should include, but not be limited to, the words, context, internal consistency (changing of individual ideas within the focus group session), frequency or extensiveness of the comments, intensity of the comments, specificity of the comments (for example, the experience of an event often carries more weight than no experience), and the three most important or "big" ideas (Krueger & Casey, 1994).

4.1.4.1 Advantages and disadvantages of the focus group

An important feature of conducting a focus group discussion is to create an opportunity for the participants to interact and talk more freely about the topic, which is why it is different from an individual interview (Beck et al., 1986). Participants may try to impress the interviewer during an individual interview session which may lead to bias in responses. However, a focus group reduces this as participants share and discuss ideas (Vaughn et al., 1996).

If the moderator has enough expertise, she/he can stimulate and support the discussion but cannot act as an expert on the topic (Degu & Yigzaw, 2006).

The focus group can be used as a stand-alone method as well as part of a mixed method study (e.g., focus groups and survey research).

As demonstrated in Appendix-Table 1, some of the opportunities of the focus group method include direct, intensive contact with individuals; encouragement of participants to engage in a less-intense discussion; not forcing participants to read or write; allowing clarification and validation of ideas and responses through discussion; and as a result collecting rich, in-depth data in a relatively cost-effective way. Individual interviews allow for direct responses, while a focus group provides direct responses while fostering discussion.

A major disadvantage of a focus group is that although it is meant to facilitate rich, in-depth discussions, some participants might be lethargic and dull while others are dynamic and involved. Participants also may not share their opinions when they do not trust others in the group or will simply not want to share their information with some of the other participants. The work relationship between workplace colleagues may also affect how participants behave during certain types of focus group sessions, and this may be important for this research if the biologist experts are colleagues in the same institution. There may also be dominant or aggressive participants who can affect the discussion process. This will eventually discourage other individuals from participating. The session is also vulnerable to veering into irrelevant issues if the moderator fails to control the group.

Other limitations include the difficulty of assembly because of location or the various work schedules of participants, and difficulty in analysing and comparing the comments in comparison to individual interviews.

A comprehensive list of the advantages and disadvantages of a focus group is shown below in Appendix-Table 1.

Appendix-Table 1 Advantages and disadvantages of a focus group

Disadvantages of Focus Group	Advantages of Focus Group
• Some groups may be lethargic and dull • Reluctance to express their opinions if there is no good chemistry between group members • Dominant or aggressive individuals may influence the group dynamics • Lack of control may lead to a discussion of irrelevant issues • Poor organization can waste valuable time and energy • The difficulty of assembly due to location and time constraints • Data are more difficult to analyse than individual interviews	• Dynamic process • Opportunity to have direct intensive contact with individuals • Individuals feel listened to • Allows for individuals to give opinions or change opinions following discussion with other participants • Individual opinions valued • The ability of the moderator to encourage interaction with other participants • Relaxed group setting • Less intense environment • Talking is more convenient rather than reading or writing. • The discussion is more spontaneous and honest • Group dynamics and peer influences can be observed during the discussion • Beliefs can be validated and clarified during the discussion • Ability to collect rich, in-depth data • Relatively cost-effective

4.2 Delphi survey: outline

The Delphi method is used when the aim is to get the most reliable consensus from experts (Dalkey & Helmer, 1963). This research bridges between biology and architecture and the biological field would not be sufficiently explored without the input of biologists into the process. The Delphi method seems a useful approach for this study as there is almost no evidence of a systematic bio-inspired review process (Avella, 2016). Where there is little preceding research on the subject of interest and/or the collective judgment of experts is required, the Delphi technique can be extremely useful (Hejblum et al., 2008). Given the level of uncertainty about the accuracy of the draft ThBA framework in terms of search terms and order of broad categorisations, the Delphi method could be very helpful (X. J. Yang et al., 2012).

There are different types of Delphi methods according to the main purpose of the data collection. The one relevant for this research is "Policy" Delphi as this study seeks to devise a systematic method for biological data mining (Avella, 2016).

The repetitive nature of the Delphi method in terms of including multiple rounds effectively contributes to reduction in the variety of the responses to the limit where consensus is achieved. Irrespective of the design purpose, the Delphi method could also differ depending on the study objectives.

In each round experts are individually questioned either by interview using interview schedules or by questionnaires where a face-to-face meeting is not required. Some studies have used interviews for all three rounds (McIntyre-Hite, 2016), questionnaires for all rounds (Hsu & Sandford, 2007), or a combination of those (McBride, 2015).

While the conventional Delphi method seeks to achieve consensus through questionnaires (Hsu & Sandford, 2007), this study might employ a modified Delphi design in which the first round of questions does not generally target generating answers as an initial draft of the systematic framework will already have been developed based on reviewing the literature.

Information gathered using this method would be collected from both primary sources of interviews and questionnaires (R. Kumar, 2014) during the Delphi survey. However, secondary sources such as biological articles, journals, and books will be used to shape the open-ended questions for the first round. This is considered a pre-requisite step before starting the Delphi process.

4.2.1 Round 1

A series of open-ended questions will be asked of biologists in order to enable the categorisation of biological data and the search terms related to those categories. The first round mainly focuses on the configuration of the main structure of the ThBA. Questions for this round will be mostly open-ended. However, a number of closed questions will be used where the respondents will be asked to identify the first step of the ThBA.

In the first round interviewees will be asked to modify the information related to different sub-categories of the framework provided beforehand (derived from the literature review, section 6.9.1.2).

4.2.1.1 Interview vs questionnaires

The only difference between an interview schedule and questionnaire is that in the former the researcher records all the replies while in the latter respondents do it themselves (Kumar, 2014). The appropriate method for this study in the first round will be an interview schedule as open-ended questions might need to be clarified. This would not be feasible in a questionnaire approach.

4.2.1.1.1 Face-to-face interviews

Face-to-face interviews represent synchronous communication of time and space (Opdenakker, 2006) and as such are more appropriate for this research in comparison to interviews conducted using email, messengers or by telephone, as the whole discussion can be recorded with the interviewee's permission. This enables the researcher to check the quality of the interview by listening to the tape to see if all the questions have been asked or to identify a malfunction caused by either the tape or the interviewer (Opdenakker, 2006), as there is always the possibility of not remembering to push the record button or take notes.

Even though social cues, standardisation of the interview situation, and the anonymity of the respondents (Opdenakker, 2006) to the researcher are not important in this study, for the above-mentioned reasons face-to-face interviews are preferred to be used as a quantitative data collection method for the first round of a Delphi survey if a Delphi survey technique is selected rather than a focus group discussion.

Face-to-face interviews are classified into different categories (unstructured, semi-structured, and structured) based on their degree of flexibility.

4.2.1.2 Advantages and disadvantages of different types of interviews

Given the advantages and disadvantages of all three types of interview (Appendix-Table 2), this study would use the structured interview.

Appendix-Table 2 Advantages and disadvantages of different types of interviews

Type	Advantages	Disadvantages
Structured interviews	✓ Interview schedule can be used as a research tool for unstructured interviews comprising either closed, open-ended, or even a combination of questions in an order. Using the interview schedules provides the researcher with uniform comparable information. ✓ In contrast to an unstructured interview, the interviewer is not expected to have high interviewing skills, as most questions are determined beforehand. ✓ If respondents find the questions hard to understand, there is a chance questions can be paraphrased to help the interviewee understand them completely.	✓ There is no flexibility in wording or sequencing the questions. The interviewer must keep strictly to the pre-determined questions.
Semi-structured interviews	✓ Conducting a semi-structured interview, there is a degree of freedom in terms of deciding the format and the order by which one might choose to ask questions as they come to mind during the conversation. ✓ If respondents find the questions hard to understand, there is a chance questions can be paraphrased in order to help the interviewee understand them completely.	
Unstructured interviews (in-depth interviews)	✓ Conducting an unstructured interview, the interviewer has almost complete freedom in terms of the content, structure, phrasing, and order of the questions as they take shape based on the discussion. ✓ This is the most useful method of data collection if the researcher needs to dig deep into the content. ✓ Varied information can be collected easily if the researcher is unfamiliar with the topic under study. ✓ If respondents find the questions hard to understand, there is a chance questions can be paraphrased in order to help the interviewee understand them completely.	✓ The interviewer needs good interviewing skills otherwise no useful data will be collected in each session as the discussion might be unfocussed

Once responses to round 1 questions (Appendix-Figure 2) are summarised the second set of questions will be formulated and distributed to the same group of experts. These questions will be used to clarify areas of agreement and disagreement on the search terms generated in the previous round and put in the sub-categories.

How do you rank the following SEARCH TERMS ?

Search terms *Selected by the largest number of votes*	NOT AT ALL USEFUL	SLIGHTLY USEFUL	MODERATELY USEFUL	VERY USEFUL	EXTREMELY USEFUL
e.g. Search terms A for Plants: heat gain	☐	☐	☐	☐	☐
e.g. Search terms H for insects heat loss	☐	☐	☐	☐	☐
e.g. Search terms Q for marine animals only	☐	☐	☐	☐	☐
e.g. Search terms R for animals only	☐	☐	☐	☐	☐
e.g. Search terms S for human only	☐	☐	☐	☐	☐
Etc.					

Appendix-Figure 2 The first round questionnaire

4.2.2 Round 2

If evaluation of the first round responses reveals the experts believe there are many missing search terms in the subcategories of the current state of the ThBA, in the second round a set of questions will be developed for finding more search terms related to the thermal adaptation mechanisms generated in each sub-category. To identify these mechanisms (search terms in subcategories) requires mining a series of databases. Based on this questionnaire biologists will be asked to recommend database(s) for finding information (Appendix-Figure 3). The subject areas of these databases will be based on the analysis of the first round interviews and the names of these databases would be based on analysis of the responses in the second round.

NUM	SUBJECT	DATABASE	DATA TYPE
1	e.g. Multiple: animals, insects, marine animals	e.g. Database A,B,C	Please provide details: e.g. physiological adaptations only, classification of animals based on geographical locations, etc.
2	e.g. Multiple: Plants	e.g. Database D,E,F	Please provide details
3	e.g. Insects only	e.g. Database G,H	....
4	e.g. Marine animals only	e.g. Database I,K	
5	e.g. Animals only	e.g. Database NA	
6	e.g. Human only	e.g. Database P	
7	Etc.	e.g. Etc.	

This subjects are derived based on the analysis of the first round interviews

Appendix-Figure 3 The subjects are derived based on analysis of the first round interviews

4.2.3 Round 3

The third round questionnaire will be prepared once the second round answers are analysed (Appendix-Figure 4). In this round the expert biologists will be asked to rank a series of databases according to their level of relevance regarding the anticipated information to be found.

DATABASE *Selected by the largest number of votes*	NOT AT ALL USEFUL	SLIGHTLY USEFUL	MODERATELY USEFUL	VERY USEFUL	EXTREMELY USEFUL
e.g. Data base A for Plants: heat gain	☐	☐	☐	☐	☐
e.g. Data base H for insects heat loss	☐	☐	☐	☐	☐
e.g. Data base Q for marine animals only	☐	☐	☐	☐	☐
e.g. Data base R for animals only	☐	☐	☐	☐	☐
e.g. Data base S for human only	☐	☐	☐	☐	☐
Etc.					

Appendix-Figure 4 The third round questionnaire

4.3 Advantages and disadvantages of the Delphi technique

Table 3 sets out the advantages and disadvantages of the Delphi technique.

Appendix-Table 3 Advantages and disadvantages of the Delphi technique

Advantages of Delphi Technique	Disadvantages of Delphi Technique
Does not require face-to-face meetings	Information comes from a selected group of people and may not be representative
Gathering of individuals from different disciplines to share their knowledge (Pill, 1971)	The tendency to eliminate extreme positions and force a middle-of-the-road consensus
Individual dominance rather than social pressure and/or personality influence	More time-consuming than group process methods"
Gradual formulation of reliable judgments	Requires skill in written communication
Generate consensus in areas of uncertainty (Powell, 2003)	The possibility of research bias due to the high authority level of the experts (Avella, 2016)
Identify divergence of opinions	Poor summarizing of panel contributions or incomplete presentation of the group response for the next round (de Villiers et al., 2005)
Keep attention directly on the issue	Member anonymity increases chance for expression of minority opinions
Numbers of participants can vary in different rounds (Rivera Jr, 2013; Wynaden et al., 2014)	The consensus process does not necessarily lead to the "best" option
Allows sharing of information and reasoning among participants	Only non-controversial statements will be produced (Rennie, 1981)
Iteration enables revision of statements	
Highly cost-effective (Williams & Webb, 1994)	
Freedom of expression as a direct result of the anonymity (de Villiers et al., 2005)	

Appendix D

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