Evaluating the Uptake of Biomimicry Towards More Sustainable Cities

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SUMMARY

There are various concepts that address the vast proportion of materials, waste and energy use attributed to the built environment, which exacerbate the effects of climate change. One such concept is known as 'Biomimicry', the emulation of the natural world and application to human problems. Biomimetic Architecture is the application of natural models/systems to the built environment. This involves mimicking the functioning of an ecosystem or a specific trait of an organism. This thesis investigates why biomimicry is not popular or widespread despite its solution to unsustainable design and development.

Here I show that although biomimicry is viewed as a viable alternative to conventional architecture, the widespread application and uptake of biomimicry is thwarted by a number of barriers and knowledge gaps, namely a lack of educational offerings for professionals and knowledge of biomimicry by design firms. Means of overcoming these barriers and knowledge gaps is discussed.

The most significant outcome of this study was the development of a novel framework for assessing biomimetic architecture, as previously no such framework existed. Four case studies were selected for evaluation against the presence/absence of key biomimetic elements within the framework. The application of this framework yielded several key findings. Most importantly, it was found that biomimetic buildings represent much more resource efficient and sustainable alternatives to traditional buildings. Although much literature supports this finding, none has done so in such a systematic way. My results demonstrate that biomimetic architecture can lead to a more sustainable and resource efficient built world.

I anticipate that my findings concerning the number of biomimetic courses and degrees available to professionals and the number of design firms incorporating biomimicry into their design process, will provide a starting point for the evaluation of biomimetic professional offerings. Similarly, it is expected that the development of the framework will allow for the assessment of future supposed biomimetic architectural sites and encourage discussion on evaluating the sustainability of the built world and cities.

DECLARATION

I certify that this thesis does not incorporate without acknowledgment any material previously submitted for a degree or diploma in any university; and that to the best of my knowledge and belief it does not contain any material previously published or written by another person except where due reference is made in the text.

Signed: Jackson Tuohy

Date: 20/10/2017

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INTRODUCTION

Finding solutions to reduce the vast environmental impacts of cities is of great significance. Climate change, coupled with the proliferation of cities and the built world, has created major environmental challenges in the 21st century. 'Biomimicry' is a powerful solution to reduce the environmental impacts of cities, however, it is not widely understood or applied.

In 2016, approximately 55% of the world's population resided in urban settlements and by 2030 an estimated 27% of people globally, will inhabit cities with at least 1 million citizens (UN 2016). Buildings are accountable for 40% of annual global energy use and cities are responsible for 80% of Carbon dioxide emissions and 75% of global energy consumption (Buck 2015; Ramesh, Prakash & Shukla 2010). Air, soil and water pollution, biodiversity loss, excessive land use and resource depletion are progressively threatening Earth's ecosystems (Geissdoerfer *et al* 2017). By 2050, Carbon dioxide emissions from buildings are expected to grow faster than any other sector (Chayaamor-Heil and Hannachi-Belkadi 2017). There is an urgent need for less environmentally damaging cities (Newman 2006; Newman and Jennings 2012).

Humans have lived in cities for 8000 years and during this time cities have become the most complex human creation (Roggema 2012). They emerged as human settlements that developed and expanded as a result of lifestyle changes that evolved as humans survived and thrived (Goucher and Walton 2013). Cities are hubs of consumption, production and waste disposal, driving land change and numerous worldwide environmental problems (Agudelo-Vera *et al* 2012). Demanding vast amounts of energy, water and materials, cities convert land into consumption and production landscapes, generating wastes and emissions to air, land and water. Understanding the relationship between the natural world and the built environment is central to the management and planning of sustainable human settlements (Newton 2006).

Global increases in population and rural-urban migration are further increasing the ecological footprints of cities (Newman and Jennings 2012; Zari 2017) necessitating a move towards more 'ecologically oriented cultures' (Newman and Jennings 2012). The prevailing attitude towards energy and material consumption can no longer be accepted (Mont and Bleischwitz 2007; Quoquab and Sukari 2017). New design methods such as biomimicry exist for providing sustainable solutions.

The natural world has solved many of the problems we are currently contending with. Animals, microbes and plants have already found what is appropriate, what works and what lasts on Earth (Benyus 1997). If cities can be envisioned as ‘natural’, there could be advantages to managing and designing them accordingly (Buck 2015). Further, Benyus (1997, p. 3) envisioning a biomimetic world writes,

> …we would manufacture the way animals and plants do, using sun and simple compounds to produce totally biodegradable fibers, ceramics, plastics, and chemicals. Our farms, modeled on prairies, would be self-fertilizing and pest-resistant…

The degree of human alteration of the global environment has become substantial enough to necessitate the formal recognition of a new ‘Anthropocene’ era, terminating the current Holocene geological era (Crutzen and Stoermer 2000, cited in Smith and Zeder 2013). Benyus wants the human race to move from this ‘Anthropocene’ into a new ecological age whereby biomimicry is at the core of any human development.

STATEMENT OF TOPIC

Aims

The aim of this thesis is to evaluate the uptake of Biomimicry towards more sustainable cities.

Objectives

1. To explore the benefits of biomimicry in architecture and building design;
2. To develop a framework by which to evaluate the benefits of biomimetic architecture;
3. To apply the framework to a select number of existing biomimetic sites at a range of scales in order to fully understand the benefits and limitations of biomimetic architecture compared with traditional architecture;
4. To identify knowledge gaps in current biomimetic practice/theory;
5. To investigate the availability of professional development courses for biomimetic design;
6. To identify barriers to the uptake of biomimetic design; and
7. To suggest a number of ways to encourage the uptake of biomimetic architecture.

LITERATURE REVIEW

Introduction

Finding ways to reduce the environmental impacts of the built environment is of great importance. Sustainable architecture is the field that deals with this topic. Sustainable architecture is a topic highly prevalent in the literature, with many models and approaches. 'Biomimicry' or 'Biomimetic Architecture' is one such model. Gaps in the literature, barriers to the widespread adoption of biomimicry and possible solutions to these barriers are also discussed.

The global contribution from the building sector, both commercial and residential, towards energy consumption is steadily growing (Perez-Lombard, Ortiz & Pout 2008). This vast consumption of energy and water accounts for significant environmental impacts, namely greenhouse gas emissions.

Between 1970 and 2010 building sector greenhouse gas emissions more than doubled and the industry currently consumes approximately 45-50% of global energy use, accounting for almost 35% of Carbon dioxide emissions, related to total direct and indirect energy use (Berardi 2017; OECD 2002). Buildings also account for 60% of materials for buildings and roads (Willmott Dixon 2010).

Energy demand in buildings is predicted to increase by 50% between 2010 and 2050 (IEA 2013). This demand is driven by a number of factors including rapid growth in residential and services floor area, the number of households and greater ownership rates for electrical devices (IEA 2013). Buildings have also been estimated to be responsible for 50% of global water as producing energy requires large amounts of water for cooling and treating and pumping drinking water and waste water also uses significant energy (Willmott Dixon 2010).

Thus, finding solutions to reduce the environmental impacts of the building and construction sectors is vital.

Sustainable Design, Sustainable Architecture and Sustainable Buildings

Within the building sector a number of ideas are emerging to reduce the aforementioned impacts of cities. This includes sustainable design in general, sustainable architecture and sustainable buildings. Sustainable design is the overarching theory of the study. Sustainable architecture is a field within sustainable design; it is also the field in which biomimetic buildings occupy. Sustainable buildings are discussed, as they represent the most analogous mainstream architectural concept to biomimicry and allowed for the advent of biomimetic architecture.

The 1987 'Brundtland Report' commissioned by The United Nations published the terms 'Sustainable', 'Sustainability' and 'Sustainable Development'. As a result of the Report, the concept of Sustainable Development was established as a central concept of international politics, giving rise to Sustainable Design. Importantly, in 1993, a global commitment was made which included a number of assertions stating the architectural and building design professions would place environmental sustainability at the core of their professions (UIA 1993, cited in Bennetts, Radford & Williamson 2003). In turn, this movement towards sustainability allowed for biomimicry to be viewed as a design concept.

Sustainable Design

> Biological systems are truly sustainable. They are efficient, drawing all that they need from within the immediate environment (Hes 2006, p. 2).

Sustainable design means ensuring that the decisions made by design professionals will not negatively affect future generations; design should be sustainable and responsible (Farid, Zagloul & Dewidar 2016). Also referred to as 'Green Design' and 'Ecological Design', Sustainable Design reduces the impact of buildings on the natural environment (Iwaro and Mwasha 2013; McLennan 2004). McLennan (2004, p. 4) defines sustainable design as '…a design philosophy that seeks to maximize the quality of the built environment, while minimizing or eliminating negative impact to the natural environment.' As a philosophy, sustainable design seeks the best solution that can balance design aspects such as comfort, aesthetics and cost with environmental concerns (Farid, Zagloul & Dewidar 2016). Based on his definition of sustainable design, McLennan (2004, cited in Farid, Zagloul & Dewidar 2016) developed six governing principles of sustainable design, outlined in Table One.

To introduce design that cooperates with nature, architects embraced 'The Biomimicry Principle', listed in Table 1, which encourages treating nature as a mentor and model and to understand how ecosystems function (Farid, Zagloul & Dewidar 2016). This notion of respecting nature and viewing the natural world as a guide and system gave rise to sustainable architecture and sustainable buildings.

Table 1. The Governing Principles of Sustainable Design (McLennan 2004)

Principle	**Description**
The Biomimicry Principle	Design that understands how the ecosystem functions and how humans can develop design that cooperates with nature.
The Human Vitality Principle	Respecting people's unique needs by giving control of their environments and personal comfort back.
The Ecosystem Principle	Seeks a responsible long-term planned design that respects the concept of regionalism. It also respects all aspects of place (geographical aspects, land value and culture of place).
The 'Seven Generations' Principle	Concerns the safety of the buildings and achieving closed loops with no waste products.
The Conservation Principle	Focuses on both energy and natural resources as complementary elements ensuring energy is used wisely and responsibly. Technologies should maintain the minimum use of natural resources as much as possible.
The Holistic Thinking Principle	This principle is classified into sub-principles such as: • A commitment to collaboration and interdisciplinary communication; • A commitment to lifelong learning and continual improvement; and • A commitment to rewarding innovation.

Sustainable Buildings

Sustainable Architecture is a reformed architectural theory in response to the numerous human effects on the environment. Farid, Zagloul and Dewidar (2016, p. 2) write 'architecture significantly defines the built environment and '…buildings define cities, culture, and the built environment context.' At the beginning of the 21st century the term, 'sustainable architecture' was the focus of many architectural discussions (Rahaei, Derakhshan & Shirgir 2016). This discussion lead to the development of key concepts such as the idea of 'Sustainable Buildings'.

The development of sustainable buildings has become a principal goal for local and national policies in reducing energy consumption and greenhouse-gas emissions (Jensen *et al* 2012). Sustainable buildings are defined as 'those that have minimum adverse impacts on the built and natural environment, in terms of the buildings themselves, their immediate surroundings and the broader regional and global settings' (OECD 2002). The Organisation for Economic Cooperation and Development (OECD), an international body whose mission is 'to promote policies that will improve the economic and social well-being of people around the world' (OECD 2017), identifies five objectives for sustainable buildings:

1. Resource efficiency (e.g. presence of passive design);
2. Energy efficiency (including reduction of greenhouse gas emissions);
3. Pollution prevention (including abatement of indoor air quality and noise);
4. Harmonisation with environment (including environmental assessments); and
5. Integrated and systemic approaches (including environmental management systems) (OECD 2002, cited in Godfaurd, Clements-Croome & Jeronimidis 2005, p. 5).

Referring to Objective One listed above and in the context of sustainable buildings, 'Resource efficiency' is understood as '…the broad concept aiming to reduce resource use and limit the environmental impacts from buildings throughout their lifecycle' (Herczeg *et al* 2014, p. 14). The OECD lists the presence of passive design as an example of resource efficiency. Kibert (2016, p. 277) defines passive design as 'the design of the building's heating, cooling, lighting and ventilation systems, relying on sunlight, wind, vegetation and other naturally occurring resources on the building site.' Further, passive design involves using all potential measures to reduce energy consumption before external energy sources, other than wind and the sun, are considered (Kibert 2016).

The emergence of the sustainable building concept, allowed for biomimicry to enter the architectural field.

Biomimicry

Multiple authors believe biomimicry is an important new contribution an important source of inspiration to sustainable building design (e.g. Buck 2015; Cohen and Reich 2016; Rao 2014). The main argument behind the usefulness of biomimicry is that living organisms have been evolving and undergoing research and development for 3.8 billion years, where the price of failure is extinction (Frishberg 2015).

Biomimicry Concept

Biomimicry derives from Ancient Greek, ‘bios’, meaning life, and ‘mimesis’, to imitate (Biggins, Kusterbeck and Hiltz 2011). An emerging paradigm, biomimicry can be defined as ‘a new science that studies nature’s models and then imitates or takes inspiration from these designs and processes to solve human problems’ (Benyus 1997, p. iii). The objective of Biomimicry is to achieve sustainability, challenging designers to create products with a beneficial impact or ‘create conditions conducive to life’ (Benyus 2013), referring to a trait of organisms to function in a way that assists or promotes their habitat (De Pauw, Kandachar & Karana 2015). Benyus (1997, p. 291) argues that the following questions should be asked of any new technologies that attempt to emulate nature:

- Does it run on sunlight?
- Does it use only the energy it needs?
- Does it fit form to function?
- Does it recycle everything?
- Does it reward cooperation?
- Does it bank on diversity?
- Does it use local expertise?
- Does it curb excess from within?
- Does it tap the power of limits?
- Is it beautiful?

These guiding questions are widely accepted in the literature as an effective means by which to evaluate how well a new technology emulates nature (Buck 2017; Kibert, Sendzimir & Guy 2000; McGregor 2013).

Terminology

There are a number of terms used synonymously with biomimicry including ‘biomimetics’, ‘bionics’ and ‘bio-inspired design’. These terms, defined in Table 2, inform the literature on biomimicry as they help to frame biomimicry's place in the design field.

Table 2. Biomimicry Related Terminology

Term	**Definition/Description**
Biomimetics	The International Organisation for Standardisation, Technical Committee (266) Biomimetics Committee (2015, cited in Fayemi *et al* 2017, p. 2) define Biomimetics as the: Interdisciplinary cooperation of biology and technology or other fields of innovation with the goal of solving practical problems through the function analysis of biological systems, their abstraction into models and the transfer into and application of these models to the solution. (Biomimicry and biomimetics are used interchangeably both in the literature and in this paper.)
Biologically inspired Design	Typically used in the engineering field (Appio *et al* 2017), 'Bio-inspired Design' is synonymous with biomimetics to mean emulating natural models, systems, and processes to solve human problems' (Shu *et al* 2011, p. 673). This definition is very closely related to that of biomimicry.
Bionics	Also an engineering term, 'bionics' is used to describe the copying and taking ideas from nature (Lodato 2010; Cohen and Reich 2016). An example is an exoskeleton, powered device that can be worn to enhance the endurance, mobility and strength of paraplegics (Norman and Paul 2017).
Bio-utilisation	Commonly associated with biomimicry, Bio-utilisation refers to 'the direct use of nature for beneficial purposes, such as incorporating planting in and around buildings to produce evaporative cooling' (Pawlyn 2011, p. 2).
Ecocities	Defined as an 'urban environmental system in which input (of resources) and output (of waste) are minimized' (Register 1987, p. 31).
Smart Cities	The main goal of a smart city is '…to provide a supposed "intelligence" to the city in order to obtain a more efficient management of infrastructure and services' (Solano *et al* 2017, p. 67).
Intelligent Buildings	Zari (2016, p. 57) defines an intelligent building as '…one that is able to respond to and adapt to its immediate climatic, ecological and social context.'

History of Biomimicry

A living encyclopedia of ingenuity, nature has inspired human design for three millennia (Vincent *et al* 2006). For example, Leonardo Da Vinci (1952, cited in Buck 2015) wrote 'the genius of man…will never discover a more beautiful, a more economical, or a more direct [approach] than nature's, since…nothing is wanting and nothing is superfluous.' Well-known examples of human technology mimicking nature include da Vinci´s 'flying machine' drawings; mimicking birds in flight and the invention of Velcro by amateur inventor, George de Mestral while observing cockleburs attached to dog fur; and photovoltaic cells that transform solar radiation into electricity, mimicking the functioning of plant cells (Eilouti 2010; Garcia- Holguera *et al* 2013).

Biophysicist and father of biomedical engineering Otto Schmitt created the term Biomimetics in 1969 (Harkness 2001; Louguina 2013; Schmitt 1969 cited in Hwang *et al* 2015). Schmitt was attempting to design a device that mimicked the biological system within squid nerves (Johnson 2011). The term biomimicry first appeared in an academic journal article in 1982 (Lange 1982), however, the word wasn't publicly used until 1974 in Webster's Dictionary where it was defined as,

> The study of the formation, structure, or function of biologically produced substances and materials (as enzymes or silk) and biological mechanisms and processes (as protein synthesis or photosynthesis) especially for the purpose of synthesizing similar products by artificial mechanisms which mimic natural ones (Bhushan 2009, p. 1443).

Author and scientist Janine Benyus truly popularised and provided the foundation for Biomimicry in her seminal 1997 book, 'Biomimicry: Innovation Inspired by Nature.' The most up-to-date, internationally standardised definition defines biomimetics as,

> An interdisciplinary cooperation of biology and technology or other fields of innovation with the goal of solving practical problems through the function analysis of biological systems, their abstraction into models, and the transfer into and application of these models to the solution (ISO 18458 2015)

Finally, most recently, ecologist Arnim von Gleich invented the phrase ' biomimetic promise', referring to the application of biology to technical products and how biomimetic solutions can contribute to the development of sustainable technology (Von Gleich 2007, cited in Speck *et al* 2017).

In 1998, following the success of her book, Benyus, together with scientists Dayna Baumeister and

Bryony Schwan established ‘Biomimicry 3.8’ (previously the Biomimicry Guild), the world’s first ‘bio-inspired consultancy’ (The Biomimicry Institute 2017b). Located in Missoula, Montana, USA, Biomimicry 3.8 is a not-for-profit consultancy that fosters the study of the natural world and the collaboration of architects, scientists and engineers to find sustainable solutions (The Biomimicry Institute 2017b). The Institute offers workshops, courses, and other resources and there is now a ‘Master’s of Science in Biomimicry’ degree available from Arizona State University in partnership with Biomimicry 3.8 (Biomimicry 3.8 2016; Blake 2011).

In 2006, Benyus co-founded The Biomimicry Institute with Dayna Baumeister, a non-profit firm that consults companies globally, including Portugal (Vitalis Water bottle design) and Denmark (Kalundborg Industrial Park) on how to incorporate biomimetic design into their practices (Biomimicry 3.8 2016b). Currently, Biomimicry 3.8 has worked with over 250 clients, including General Electric, Procter and Gamble, Shell and HOK Architects (Biomimicry 3.8 2016). The Institute also provides practitioners with a biomimicry database, ‘AskNature’, as a design starting point (The Biomimicry Institute 2017b).

Numerous start-up firms specialising in biomimetic technologies have emerged globally, including ‘NBDNano’ in Boston, Massachusetts. Formed in 2012, the firm received funding to research ‘…a nanomaterial coating inspired by the Namib Desert beetle that harvests water directly out of the air’ (Johnson and Goldstein 2015, p. 6) (Figure 1). In 2016, French start-up ‘Elbé Pétro’ developed a technology, ERIS (Evaporation Reduction Intelligent System) (Figure 1), inspired by duckweed, small aquatic plants that free-float on still water ponds (Elbé Pétro 2017). ERIS reduces toxic organic compound emissions, a primary issue for chemical, gas and oil industries via self-positioning, collaborative floaters (Elbé Pétro 2017). Lastly, ‘Tyer Wind’, a Tunisian based start-up, developed wind turbine technology (Figure 1) that mimics the mechanical action of hummingbird wings, a figure-eight pattern, which generates energy on both the upstroke and downstroke and is much more efficient than conventional bladed wind turbines (Tyer Wind 2017).

Value of Biomimicry

Recently, Fortune Magazine (Harnish 2017) named biomimicry a top trend of 2017 for ‘forward-looking companies’ highlighting its potential value. Yurtkurana, Kirli and Taneli (2013) found that global patents involving biomimetic design have increased by a factor of 93 since 1985. Biomimetic journal publications have also rapidly grown from several hundred papers per year in 2002 to more than 1000 publications per year by 2005 (Lepora, Verschure & Prescott 2013). Since 1990, this growth in journal publications has far exceeded that across science in general (Lepora, Verschure & Prescott 2013). Currently, 3,000 biomimetic journal papers are published per year demonstrating a significant growth in interest (Lepora, Verschure & Prescott 2013).

Figure 1. Clockwise from left: The Namib Beetle (NBD Nano 2016, n.p.), **'ERIS' (**Elbé Pétro 2016, n.p.**)** and **The Hummingbird Wind Turbine** (Tyer Wind 2017, n.p.)

Buck (2015) completed a global study on biomimicry and urban infrastructure interviewing multiple stakeholders from India, China, the UK and the USA. He determined the value of biomimicry in relation to transdisciplinarity, finding it helped to align design teams around a central goal (Buck 2015). Further, Buck (2015, p. 22) found a developing interest for the adoption of a biomimicry by businesses writing '…some developers realise biomimicry is a useful tool in community engagement and helps to secure planning permission by getting buy-in from the local community and planners. Buck (2015, p. 23) also established urban biomimicry's positive effect on property value writing that biomimicry is viewed as '…one route to creating a unique product that results in market differentiation…'

Key Biomimicry Concepts

The following sections discuss six key concepts related to biomimicry, Biophilia, Circular Economies, Ecomimetics, Ecosystem Services, Regenerative Design and Self-sufficiency. Each concept is central to understanding the benefits of biomimicry in architecture and building design as they best demonstrate the effectiveness of biomimetic architecture over traditional architecture.

Biophilia

Although Biophilia differs from biomimicry conceptually, it is viewed as central to any discussion of biomimicry as the two concepts are very similar in their views of the natural world and our relationship with it (Beatley 2011; 2017; Kellert 2016; Kellert, Heerwagen & Mador 2011). Popularised by biologist E. O. Wilson (Pawlyn 2011), biophilic design stems from the Biophilia hypothesis, which suggests '…humans have an innate connection with the natural world and that exposure to the natural world is therefore important for human wellbeing' (Gillis and Gatersleben 2015, p. 948). Biophilia is a deliberate effort to translate this connection into the design of the built world (Kellert, Heerwagen & Mador 2008). Importantly, biophilic design leads to architecture that improves psychological and physical health (Zari 2010).

One way to assess a biomimetic building is whether it effectively shows its inherent qualities as a '…visually resolved architectural form, rather than as a box full of eco-tech objects' (Morris-Nunn 2007, p. 92). One of the key principles of biophilic design is exposure and access to nature or open space by city dwellers such as green roof spaces, vertical gardens or indoor vegetation (Beatley 2011; 2017; Huelat 2008; Ottelé 2015). Further Kellert (2008, cited in Ramzy 2015, p. 251) defines the following qualities as a basis for Biophilia in the built world;

> **Prospect**: brightness, wide horizons, or ability to see into the distance;
> **Refuge**: sense of enclosure and shelter with canopy effect or branch-like forms overhead;
> **Livability and movement**: with real moving water or reflecting surfaces;
> **Biodiversity**: vegetation elements or symbolic representation of them (trees, plants, or flowers);
> **Sensory variability (or ephemeral qualities of space)**: changes and variability in environmental color, temperature, air movement, light and texture;
> **Fractals**: self-similarity, natural patterns or cycles, hierarchal characteristics;
> **Sense of playfulness**: elements that aim at delight, surprise, or dazzle; and
> **Enticement**: complexity and richness of details to be seen, or gradual openness of views.

The presence of these qualities can be used to evaluate the 'success' of a building in incorporating Biophilia into its design.

Circular Economies

Nature does not waste anything; one organism's waste is another's food, with the sun providing energy (Weetman 2016). This concept is known as a 'Circular Economy'. The concept of the Circular Economy (CE) recently appeared in response to the need for disassociating resource consumption and environmental impacts from economic growth (Mendoza *et al* 2017). Aiming to maximise resource efficiency, the CE is a substitute to the existing '…linear take-make-use-dispose economic model' (Mendoza *et al* 2017, p. 526). The CE looks for better management of resources throughout the lifecycle of systems and is characterised mainly by closed loops, recycling, reuse and remanufacturing (Saidani *et al* 2017). Figure 2 outlines a Circular Economy. The CE concept is guided by the following three principles:

> 1. Preserving and enhancing natural capital by controlling finite stocks and balancing renewable resource flows (e.g. encouraging flows of nutrients within the system);
>
> 2. Optimising resource yields by circulating products, components and materials at the highest utility and value at all times within technical and biological cycles (e.g. maximising use of end-of-use bio-based materials); and
>
> 3. Fostering system effectiveness by revealing and designing out negative externalities (e.g. managing externalities, such as release of toxic substances) (EMF 2015).

In Figure 2, the centre spine of the diagram shows raw materials moving to manufacturing then disposal/landfill (linear materials economy), powered by fossil fuels. Spiralling out from the diagram on either side are concepts that bypass this model. For example, instead of waste going to landfill it is used to generate biogas or extracted for biochemical feedstock. Waste is reused and redistributed and energy recovered in closed looped cycles. To achieve a Circular Economy on any large scale, humans would need to mimic an ecosystem, a field known as ecomimetics.

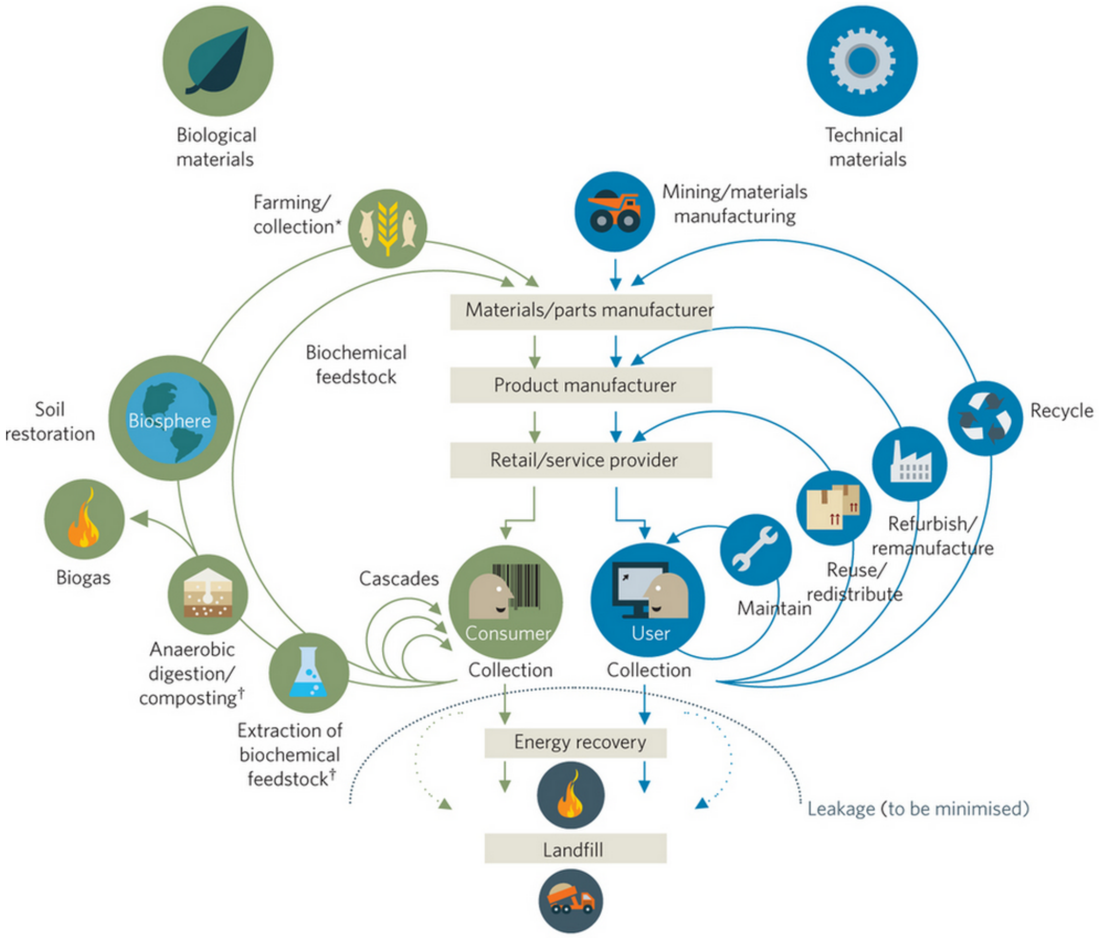

Figure 2. Circular Economy Diagram (EMF 2015, n.p.)

Ecomimetics

Ecosystem biomimetics or 'ecomimetics' represents an essential paradigm shift in sustainable architecture (Garcia-Holguera *et al* 2013; Ning 2015; Pan and Ning 2014; Woo 2011). Ecosystems are opportunistic and resilient, utilising existing relationships for symbiotic advantage to create conditions conducive to ongoing life (Zari 2016). Ecomimetics is a sustainable design approach where ecosystems are mimicked with the goal of reducing human dependence on finite resources (Henden 2012). In the building environment, ecosystem characteristics that could be mimicked include the effective use of solar energy and rainwater collection (Garcia-Holguera *et al* 2013). These characteristics can be defined as ecosystem services.

Ecosystem Services

Ecosystem services are '…the direct and indirect contributions of ecosystems to human well-being' (Kumar 2010, p. xxxiv). They can be divided into four distinct categories;

- Provisioning services (such as the provision of food, water, and energy);
- Regulation services (such as the regulation of climate, purification, and pollination);
- Supporting services (such as soil formation, provision of habitat, and fixation of solar energy); and
- Cultural services, which includes education, artistic inspiration and recreation (Costanza *et al* 1997 cited in Zari 2017, p. 2).

Zari (2010) believes all future buildings should provide ecosystem services to the occupants. Such opportunities already exist, for example, renewable energy generation (Provisioning) and green roof spaces (Regulation and Cultural). The provision of ecosystem services by the built world is classed as 'Regenerative Design'.

Regenerative Design

Zari (2007, cited in Henden 2012, p. 13) in reference to ecomimetics writes '…buildings which look at ecosystems or draw inspiration from the natural world can become regenerative.' Regenerative design means 'the built environment would need to contribute more than it consumes while simultaneously remediating past and current environmental damage' (Zari 2012, p. 54). Numerous authors stressed the importance of Regenerative design when designing biomimetic buildings (Eisenberg and Reed 2003; Reed 2007; Zari 2007b; 2012; 2015; 2017; Zari and Storey 2003). Regenerative buildings produce more ecosystem services than they consume, act as producers of energy, water and habitat and as filters or sinks of pollution rather than contributors to the degradation of ecosystems and climate (Zari and Cruz 2016).

Self-Sufficiency

Any discussion of regenerative design means defining the term 'Self-Sufficiency' (Gunnell, Du Plessis & Gibberd 2009; Nallathiga *et al* 2015; Royall 2010). It is a general term referring to a building's ability to function without external sources of energy via the incorporation of 'Sustainable Technologies.' Such technologies can be defined as those that,

> Serve to contribute, support or advance sustainable development by reducing risk, enhancing cost effectiveness, improving process efficiency, and creating processes, products or services that are environmentally beneficial or benign, while benefiting humans.

(NSTC 1994, cited in Vanegas, DuBose & Pearce 1996).

Sustainable technologies include photovoltaic panels, which generate electricity directly from sunlight and Cogeneration, the generation of electricity and heat in one process (Gunnell, Du Plessis & Gibberd 2009).

Biomimicry Inspired Technology

Biomimicry is an 'innovation engine' (Cohen and Reich 2016, p.7) cutting across not only Hi-tech industries but also traditional industries inspiring many fields of technology (Cohen and Reich 2016). Based on 218 references, Lurie-Luke (2014) conducted an analysis of biomimicry inspired technology, finding material development to be the chief area of biomimetic research. This includes smart materials and materials with targeted applications such as bioadhesives based on bivalve molluscs and anti-cancer drugs derived from allicin, a naturally occurring plant defence compound (Lurie-Luke 2014).

The second most prevalent area of biomimicry research is movement applications modelled on animal locomotion models, such as 'NanoCyte', a drug delivery technology modeled on sea anemone microinjectors (Lurie-Luke 2014, cited in Cohen and Reich 2016). The United States and China are the countries most active in the field, followed by European countries including the United Kingdom, France and Germany (Gebeshuber *et al* 2009).

The 100 most profitable biomimetic products have generated approximately AUD$2billion over the period 2005 - 2008 (Bhushan 2009). The Fermanian Business & Economic Institute (2010, cited in Kennedy 2016) write, 'biomimicry… is projected to account for $1.6 trillion global output, as well as $0.5 trillion savings associated with reduced resource depletion and pollution, by 2030.' Further, by 2025 biomimicry could allow for 1.6 million jobs in the U.S.A. (Fermanian Business & Economic Institute 2010) and biomimicry topped the Society of Manufacturing Engineers' 2012 annual list of 'innovations that could change the way you manufacture' (Society of Manufacturing Engineers 2012, cited in Goel, McAdams & Stone 2015, p. viii). Biomimicry has particularly impacted the architectural field, producing improvements in for example, climate control, ventilation, and structural integrity (Kennedy 2016).

Other Fields Benefited by Biomimicry

Architecture is one of many fields that have benefitted from biomimicry. Biomimetics encompasses an expanding range of research areas including aviation and nanotechnology (Conrad, Lofthouse, & Escobar-Tello 2016). One specific example is the application of insect communication strategies in the distribution of goods (Gebeshuber *et al* 2009). However, seven main areas in biomimetic research can now be identified: architecture and design, biomechatronics[1] and robotics, communication and sensorics, such as a dolphin based sonar receiver (Speck and Speck 2008), fluid dynamics, lightweight constructions and materials, optimisation and surfaces and interfaces. As biomimicry becomes more widespread and accepted the number of fields it benefits will steadily increase.

Biomimetic Design

Approaches to the biomimetic design process fall into two categories,

> Defining a human design problem and looking to the ways other organisms or ecosystems solve this (design looking to biology), or identifying a particular characteristic in an organism or ecosystem and translating that into a human need (biology influencing design) (Biomimicry Guild 2007).

Within these two categories, three levels of mimicry exist, the organism, behaviour and ecosystem,

- The Organism level refers to mimicking whole or part of the organism;
- The Behaviour level refers to mimicking behaviour and may include translating an aspect of how an organism behaves, or relates to a larger context; and
- The Ecosystem level is the mimicking of whole ecosystems and the common principles that allow them to successfully function (Zari 2017, p. 33).

Within each level, five potential dimensions to the mimicry exist; the biomimetic design may be a function of what it is able to do (function), what it is made out of (material), what it looks like (form), how it works (process) or how it is made (construction) (Zari 2007a).

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[1] The 'interdisciplinary study of biology, mechanics, electronics and control. It focuses on the research and design of assistive, therapeutic and diagnostic devices to compensate (partially) for the loss of human physiological functions or to enhance these functions' (University of Twente 2016).

Several authors have developed principles defining biomimicry (El-Zeiny 2012; Gamage and Hyde 2012; Zari 2010) however, Benyus' 1997 guiding principles are the first and most cited in the literature. Benyus (1997, p. viii) defines biomimicry via three main principles:

> 1. 'Nature as Model': Biomimicry is a science that studies nature's models and emulates or takes inspiration from their designs and processes to solve human problems;
> 2. 'Nature as Measure': Biomimicry uses an ecological standard to judge the "rightness" of our innovations. After 3.8 billion years of evolution, nature has learned, what works, what is appropriate, and what lasts; and
> 3. 'Nature as Mentor': Biomimicry is a holistic 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.

These guiding principles act as a design starting point and help to inform designers of the significance of biomimicry.

Biomimetic Architecture

There is a growing body of biomimetic architecture literature (e.g. Buck 2017; Hunter 2017; Rao 2014). Garcia-Holguera *et al* (2016) found that biomimicry has only become more recognised and accepted in the architectural design profession during the last twenty years. Biomimetic architecture is defined as '…examining living organisms or whole ecosystems as models for designing buildings or urban environments' (Zari and Cruz 2016, p. 83). Biomimetic architecture can reduce weight and complexity, improve resource efficiency and reduce maintenance and materials use (Buck 2016).

There are numerous biomimetic architecture literature reviews (e.g. Gruber 2008; John *et al* 2005; Zari 2007a), however, the majority focus on highly specialised applications. Examples include superhydrophobic building coatings emulating the self-cleaning mechanism of lotus leafs and biomimetic building envelopes (Nanaa and Taleb 2015; Al-Obaidi *et al* 2017). There is a clear lack of research addressing how biomimicry can be generally applied to sustainable architecture.

History of Biomimetic Architecture

During the last decade biomimetic architecture been the subject of rigorous research (Garcia-Holguera *et al* 2012). Historically, the greatest influence of biomimicry has been in architecture (Hwang *et al* 2015), however, Gruber (2011, p. 128) writes 'a defined starting point in time for biomimetics in architecture cannot be stated.' The ornamentation of Ancient Greek columns and temples, dating back to 500 B.C, were modeled on local plant life to represent nature (Mazzoleni 2013; Radwan and Osama 2016). More recently, James Paxton in 1851 designed the structural system of the crystal palace and the lily house in Stratsbourg based on giant water lilies (Radwan and Osama 2016).

The building sector has traditionally attempted to manipulate and control environmental variables via design by controlling and limiting environmental resources. Nevertheless, a paradigm shift occurred in the last 20-30 years acknowledging the natural world as a dynamic system worthy of study (Albertson 2010).

Around the turn of the 20th century, progress in building technology enabled the use of biology as a 'library of shapes' (Borsari 2017, p. 53) that could be transformed into a new variety of architectural forms, especially represented by the work of architect Antoni Gaudi (Figure 3). In the mid 20th century, Frei Otto produced efficient lightweight tensile structures emulating spider webs (Vincent *et al* 2006). Current progress in computer-aided design systems has seen an increase in the design and construction of buildings displaying biological forms (El Ahmar 2011). Most recently, Gruber (2008) conducted a comprehensive comparative study of the overlaps of architecture and biology, finding that the integration of biomimicry into the design process produces innovative results.

The Living Building

The term 'Living Building' is commonly cited in biomimetic architecture literature (Berkebile and McLennan 2004; Hegazy, Seddik & Ibrahim 2017; Turner and Soar 2008). This concept precisely describes a biomimetic building. The 'Living Building Challenge' originated in the USA and is a global building certification programme focusing on regenerative design with projects in the US, Europe and Australasia (ILFI 2017). The living building philosophy aims to achieve development at all scales, where buildings define the most advanced measure of possible sustainability in the building sector, bridging the gap between artificial and natural environments (ILFI 2014, cited in Hegazy, Seddik & Ibrahim 2017).

Figure 3. Antoni Gaudi's 'Casa Mila' (Barcelona Museum 2017, n.p.)

The living building encapsulates the ideal biomimetic building, as it will:

- Harvest all its own water and energy needs on site;
- Be adapted specifically to site, and climate and built primarily will local materials;
- Operate pollution free and generate no wastes that aren't useful for some other process in the building or immediate environment;
- Promote the health and well being of all inhabitants–consistent with being an ecosystem;
- Be comprised of integrated systems that maximize efficiency and comfort; and
- Be beautiful and inspire us to dream (Berkebile and McLennan 2004, p. 7).

The Living Building Challenge asks designers to 'fix the damage' rather than just 'do less harm'. To become a fully certified living structure, a building must demonstrate after a year of occupation that it:

- Produces or collects more energy and water than it consumes;
- Is net zero positive in terms of waste;
- Uses no toxic materials; and
- Fulfills requirements in terms of habitat exchange, equity and beauty among others (Zari and Cruz

2016, p. 83).

Hegazy, Seddik and Ibrahim (2017, p. 1) summarise the benefits of living buildings in Table 3,

Table 3. The Living Building' Benefits

Environmental benefits	**Economic benefits**	**Social benefits**
• Improve and protect biodiversity and ecosystems; • Enhance air and water quality; • Reduce waste streams; and • Preserve and restore natural resources	• Decrease operating costs; • Enhance occupant productivity; and • Improve life-cycle economic performance.	• Improve occupant comfort and health; • Enhance aesthetic qualities; • Minimise strain on local infrastructure; and • Improve overall quality of life.

These environmental, economic and social benefits of the living building listed in Table 3 are relevant to any discussion of biomimetic buildings as they essentially represent the benefits an ideal biomimetic building would provide. For example, a biomimetic building reduces waste streams by incorporating closed loop cycles, decreases operating costs by utilising renewable energy and improves occupant comfort and health by maximising the use of natural light and proximity to nature.

Barriers, Knowledge Gaps and Recommendations

The growing body of biomimetic architecture literature has identified several barriers that currently impede the widespread integration of biomimicry and architecture. The following sections discuss these barriers, current knowledge gaps in the literature, and recommendations for overcoming these barriers.

Barriers

In a seminal study on biomimicry and urban infrastructure, Buck (2015) conducted interviews with eight significant actors in urban biomimicry, including three built environment designers and three specialist urban biomimicry consultants from India, China, The UK and The USA (Buck 2015). Buck determined a number of pitfalls to the widespread adoption of biomimicry as an urban sustainability solution, namely inadequately defined and vague problems, making solutions difficult (Buck 2015). Further, generalisations of complex biological functions that miss the significance of underlying principles was also found to be a drawback to the biomimetic design approach (Buck 2015).

The potential for biomimicry to fall prey to 'greenwashing' and be viewed as an '…environmentally conscientious act with a greater, underlying purpose of increasing profits' (Kahle and Gurel-Atay 2013, p. 44) is a view shared by many scholars (Buck 2015; Johnson and Goldstein 2015; World Green Building Council 2013).

Loosemore (2017) identified a number of factors that determine the speed of technological innovation diffusion in industry. These are important when attempting to understand why the building industry lags many other industries in sustainable technology uptake. Looosemore (2017) lists some of these factors

- Designers who are loyal to traditional, tried and tested designs and technologies;
- Uncertainty about the capital and life-cycle maintenance costs of new technologies;
- Lack of experience in using these new technologies;
- Lack of knowledge and perceived high risk of failure;
- The complexity and 'trialability' of the innovation; and
- The amount of supervision and coordination needed to support it.

Other barriers to the widespread adoption of biomimicry include a lack of access for architects to biomimetic design strategies and the traditional building culture sacrificing value for cheap capital cost and undervaluing innovation (Chayaamor-Heil and Hannachi-Belkadi 2017; Torgal *et al* 2015). Badarnah and Kadri (2015) view scaling difficulties as another barrier as some functions work on specific scales (e.g. Nano to micro). Biomimicry's interdisciplinary nature and the fact that traditionally, biology hasn't been viewed as a significant source of knowledge for architects and the absence of a clearly defined approach to biomimetic design that architects can initially employ were also recurrent barriers in the literature (Vincent *et al* 2006; Zari 2007a).

Knowledge Gaps

The lack of completed biomimetic sites to act as case studies and the cost of research and development (R&D) represents one of the main knowledge gaps preventing the widespread adoption of biomimetic architecture (Buck 2015; Zari 2007a). Costly and longer R&D means the absence of a strong venture capital market around biomimicry. As more biomimetic sites are developed, builders and designers will able to experience and understand the benefits of biomimicry. Further, Webb (2012) highlights how building practitioners often lack the expertise, resources or time to fully develop a biological knowledge base. Lastly, little research has been conducted on evaluating biomimicry teaching and training methods (Wanieck *et al* 2017).

At present there is no literature that applies an assessment framework to biomimetic architecture, however, John, Clements-Croome and Jeronimidis (2005) completed a review of biomimetic literature relevant to building materials and design and Zari (2007) published an examination and comparative literature review of existing biomimetic technologies. Zari's review of existing biomimetic literature has made it clear that noticeably different biomimetic design approaches have developed and can have different results with reference to increases in sustainability. Further, De Pauw, Kandachar and Karana (2015) developed an assessment method for evaluating sustainability in nature-inspired design.

Frameworks that architects can use to develop biomimetic design concepts exist such as that created by Badarnah and Kadri (2015) titled 'BioGen', which identifies successful natural systems and then abstracts their strategies and mechanisms (Badarnah and Kadri 2015). Zari (2012) also developed a model for implementing ecosystem biomimetic design into architectural practice. Although these exist, as stated, there is currently no system for evaluating the success or effectiveness of biomimetic design in buildings.

Recommendations

Overall, for all of these barriers to be overcome, the education of design professionals, as early as possible, is essential (Dahl 2013; El Zeiny 2012; Gruber 2011; Helms, Vattam & Goel 2009; Lenau 2009; Wanieck *et al* 2017; Yurtkuran, Kırlı & Taneli 2013). The introduction into a greater number of academic programmes and further development of specific biomimicry courses is a key recommendation for the widespread adoption of biomimicry by the architectural field. Early education, i.e. secondary or tertiary, will enable professionals to be made aware of the benefits of biomimicry and that there are alternatives to the traditional building sector practices. As Wanieck *et al* (2017) highlight, this training and teaching must also be evaluated to ensure its effectiveness in promoting the benefits of biomimicry.

Buck (2015) argues that the phrase 'sustainability' needs thorough management to foster clarity by ensuring definite connections between biological models and design function and to avoid potential 'greenwashing'. In order for biomimicry to succeed at a city-sized scale it will be imperative to resolve the different approaches and rhetoric used by biologists, designers and engineers via improved comprehension of biomimicry's benefits within each field (Buck 2015).

Regarding the costly R&D associated with biomimicry, Pawlyn (2011) contends that Governments could prompt firms to invest in biomimicry by creating '…new types of incentives, such as tax based on overall resource use.' Further, the lengthy R&D time required to develop a biological solution to a design problem could potentially be reduced or overcome by builders and designers undertaking compulsory training and education in order to understand the benefits of biomimicry.

Clearly, for biomimetic architecture to become widespread, ease of access for architects to biomimetic design concepts must greatly improve. The development of design tools and methods to support collaboration between biologists and architects is also of crucial importance. This is where the potential for organisations such as Biomimicry 3.8 (https://biomimicry.net/) to provide the tools and access are key.

Finally, research on the integration of biomimicry into urban design and planning and how it compares with traditional approaches is essential, as well as broader societal benefits of biomimicry if it is to be accepted and used on any large scale (Buck 2015).

Conclusion

The building sector accounts for significant global environmental problems, namely greenhouse gas emissions in the form of Carbon dioxide. As a result, there is a need for new sustainable design concepts to reduce these effects. The vast majority of scholars view biomimetic architecture as a powerful design tool for sustainability that represents a new design paradigm in current building design theory. The natural world offers the most fundamental sustainability model, providing a vast database of designs that can inspire creative ideas. This new philosophy of architecture can lead to a quantum leap in resource use and efficiency but in order for the widespread adoption of biomimetic architecture to occur, the aforementioned barriers and knowledge gaps must be overcome.

METHODS

A number of strategies were used to achieve the aim and objectives of this study. The study is primarily based on a desktop analysis of a range of different materials. The research aim was addressed by performing a qualitative analysis via content analysis on Biomimetic Architecture. Four case studies were then chosen and evaluated using an assessment framework. A desktop analysis of biomimetic educational offerings and design firms incorporating biomimicry was also completed.

Assessment Framework for Evaluation of Case Studies

A key objective of this study was to evaluate a number of biomimetic sites. An evaluation framework was developed, based exclusively on key biomimicry concepts present in the literature. Application of the evaluation framework to the selected case studies provided a systematic means of analysing the success or perceived failure of different case studies in incorporating biomimetic design. The framework is based upon two key principles of biomimicry:

- **Resource Efficiency** (Presence of Circular Economies and Level of Self-sufficiency) discussed the extent to which biomimetic technologies used at each site have reduced dependency on traditional resources, i.e. switching from fossil fuels to renewable energies, e.g. solar power and the incorporation of passive design. Within this element, the 'Presence of Circular Economies' and 'Level of Self-sufficiency' is discussed. Namely, whether the site incorporated Circular Economies (CE) and to what extent the site incorporated sustainable technologies; and
- **Presence of Biophilic Design** (Balance between nature and technology and degree of Psychological Health and Well Being) discussed the integration of technology with natural surroundings and the Psychological Health and Well Being of occupants by analysing the presence of Biophilic Qualities as defined by Kellert (2008).

By discussing the presence/absence of these elements, the success of each case study in adopting the principles of biomimicry was established. The elements and associated criteria of the Assessment Framework are outlined in Table 4,

Table 4. Assessment Framework

Element	Criteria
Resource Efficiency (Presence of Circular Economies and Level of Self-sufficiency)	**Circular Economies** • Incorporates closed loop cycles of energy, water and waste; • Reduces the release of toxic substances; and • Encourages the flow of nutrients. **Level of Self-sufficiency** • Generates its own power (via renewable energies, e.g. photovoltaic cells and wind turbines); • Manages waste (e.g. grey water systems for composting toilets, reducing sewage and use on garden beds); and • Recycle its water (e.g. rain water collection).
Presence of Biophilic Design (Balance between Nature and Technology and Degree of Psychological Health and Well Being)	Does the site balance well the integration of technology with presence of natural surroundings e.g. proximity to green spaces and vertical gardens? Does the site enhance the Psychological Health and Well Being of its residents? This will be assessed by discussing the presence of **Biophilic Qualities** such as: • **Prospect**: brightness, wide horizons, or ability to see into a distance; • **Refuge**: sense of enclosure and shelter with canopy effect or branch-like forms overhead; • **Liveability and movement**: with real moving water or reflecting surfaces; • **Biodiversity**: vegetation elements or symbolic representation of them; • **Sensory variability:** changes and variability in temperature, air movement, light and texture; • **Sense of playfulness**: elements that aim at delight, surprise, or dazzle; and • **Enticement**: complexity and richness of details to be seen, or gradual openness of views. (Kellert 2008, cited in Ramzy 2015, p. 251)

Case Studies

The framework above was applied to four case studies. In selecting the case studies, specific parameters were sought. Firstly, they needed to represent successful or ambitious projects at the forefront of biomimetic architecture. The case studies also needed to offer new directions for future research and to have succeeded in becoming true biomimetic sites. A variety of sites was important to demonstrate different ways of integrating biomimicry into the design process.

Secondly, as this study is based on a desktop review, literature on each case study needed to be substantial, enabling analysis based on a wide variety of sources. Thirdly, the ways in which Biomimetic Design Practices had been incorporated into the case studies must be evident. Lastly, this study sought to explore biomimetic architecture at a range of scales from ecosystem sized to single buildings. Geographically diversity was also considered in order to properly gain an understanding of the success of biomimetic architecture. Following the criteria above, the following case studies were selected for evaluation by the framework:

- Council House Two (CH2), Melbourne, Australia;
- The Eastgate Centre, Harare, Zimbabwe;
- Kalundborg Eco-Industrial Park, Kalundborg, Denmark; and
- Lavasa Hill Town, Maharashtra, India.

Justification for selecting the Case Studies is summarised in Table 5. As Table 5 shows, each case study was chosen for specific reasons.

Table 5. Justification for Case Studies

Case Study	Justification
Council House Two	Demonstrates a successful example in a major Australian city and the application of similar biomimetic design implemented in another case study being assessed, The Eastgate Centre.
The Eastgate Centre	Although CH2 and Eastgate share the same design system, there are differences in their success pertaining to the other elements evaluated and their overall design and function.
Kalundborg Eco-Industrial Park	Demonstrates the application of biomimetic design in a completely different manner, but also at a large scale. It directly tackles the mitigation of climate change in a very clear manner, which is at the core of this thesis.
Lavasa Hill Town	Lavasa was chosen for its size, scale and ambition. By far the largest in area, (25,000 acres/ 100km^2 of the four sites, Lavasa is biomimicry at the largest scale to date, globally (HOK 2017). Although still under construction, a large portion has been completed.

The case studies were then evaluated using the assessment framework to determine how successfully they integrated biomimicry into their design and functioning. The presence/absence of each element of the framework was discussed in detail in relation to each case study. The case studies were then also compared and contrasted with each other.

Desktop Surveys

Design Firms offering a Biomimetic Approach and Biomimetic Courses and Degrees

In order to investigate the availability of professional development courses and degrees for biomimetic design, barriers to the uptake and knowledge gaps in current biomimetic practice/theory, I completed a Desktop Survey on biomimetic educational offerings and design firms offering the biomimetic approach.

I completed the desktop survey on Biomimetic Educational Offerings by searching Google using keywords and phrases such as ‘biomimicry courses’, ‘biomimicry degree’, ‘biomimicry education’ and ‘biomimetic architecture courses’. When assessing biomimicry related courses and degrees I analysed the course/degree descriptions and ‘key outcomes’ sections or equivalent, in order to determine how biomimicry was integrated.

I also completed a desktop survey on Design Firms offering a Biomimetic Approach by searching Google using keywords and phrases such as ‘green design firms’ and ‘biomimicry and design firms’. When assessing the design firms I analysed their ‘about us’ sections, previous and current projects and their overall design philosophies in order to determine if and how they incorporated biomimicry into their design methodology.

Limitations

My study had a number of limitations. Firstly, as Lavasa was still in the development phase, some data relating to the ‘resource efficiency’ element of the assessment framework was unavailable. However, there was sufficient data relating to the remaining elements of the framework to allow for a detailed analysis of the site.

The ‘Biophilic Design’ (Balance between Nature and Technology and Psychological Health and Well Being) element proved the most difficult to evaluate as literature pertaining to biophilic design and the chosen case studies was scarce in some cases. As it was not possible to physically visit each site, this element was assessed by applying Kellert's (2008) characterisation of Biophilia in the built environment. Literature relating to 'Biophilic Design' at Kalundborg and Eastgate was not found.

This assessment framework was by no means exhaustive i.e. it did not assess every possible element of biomimetic architecture/design. Rather, it was developed to assess the presence of key biomimicry concepts identified by the literature review. Had I been able to physically visit the sites, a greater array of criteria could have been applied, including interviews with occupants and the distribution of surveys regarding psychological health and wellbeing.

RESULTS

This study set out to evaluate the uptake of Biomimicry towards more sustainable cities. The following two sections address the aim and objectives of the study. Section One contains the evaluation of the case studies using the assessment framework and Section Two lists the results of the desktop surveys.

SECTION ONE

Evaluation of Case Studies Using the Assessment Framework

The following sections discuss the application of the Assessment Framework to the four case studies, Council House Two (CH2), Australia, The Eastgate Centre, Zimbabwe, Kalundborg Eco-Industrial Park, Denmark and Lavasa Hill Town, India.

Council House Two (CH2), Melbourne, Australia

Introduction and Background

Australia’s first biomimetic building, ‘The Council House No. 2’ (CH2) is a 10 story, 12,536m^2 building in Melbourne, Australia (Morison, Hes & Bates 2005; Morris-Nunn 2007). CH2 includes nine floors of office space, basement areas, largely underground parking and 500m^2 of ground floor retail (C40 2007; Paevere and Brown 2008). Construction by ‘Hansen Yuncken’ began in early 2004, finishing in 2005, with the building officially opening in August 2006 (City of Melbourne 2006; Green Building Council of Australia 2015).

CH2 (Figure 5) was designed by the City of Melbourne, namely Chief Designer Rob Adams, in partnership with architect Mick Pearce and his architecture and design firm, ‘Design Inc’ (Morris-Nunn 2007). The overall design goal was to attain a six-star energy rating, showcase advanced sustainable design (Morris-Nunn 2007) and to design ‘…a revolutionary office building that would drive the [building] industry forward’ (Webb 2005). CH2 was also designed to replace the outdated Council House 1 (CH1) (City of Melbourne 2006), which although centrally located, was nearing the end of its lifespan (City of Melbourne 2017). Other CH2 design goals included, increasing confidence in the selection of green products and awareness and understanding of green building benefits (Aranda-Mena, Sperling & Wakefield 2008).

The $51mil building (See Table 6 for full cost breakdown) is located in Melbourne's CBD at 240 Little Collins Street, overlooking Swanston Street (Figure 4), rehousing 540 City of Melbourne Council staff in open-plan accommodation (Morris-Nunn 2007; Zandieh and Nikkhah 2015). Melbourne City Council's design brief to Design Inc. for CH2 stipulated the following parameters:

- The building is to be a lighthouse for future City developments;
- It is to provide a comfortable, adaptable and stimulating working environment for its users, the staff of Melbourne City Council;
- It is to be seen and understood to respond to its natural as well as its social environment and to make use of resources bearing in mind the efficient use of embodied energy both in the choice of materials and in the process of their use;
- It should maximise the use of renewable energy within the bounds of present technology by harvesting sunlight, wind and rainwater together with the complexities of the Melbourne climate, and by following these principles the building should reduce Carbon dioxide emissions to almost zero;
- It should also provide at least the same area of green cover as its footprint, bearing in mind that this area can be measured vertically as well as horizontally; and
- Finally, as a work of art, the building should inspire a new relationship between the City and nature (Morison, Hes & Bates 2005, p. 14).

It's clear from the analysis of CH2 to follow, that all six design parameters were met.

Awards

CH2 has received many awards including the 2007 RAIA National Award for Sustainable Architecture and the 'National Best Green Building Award' [City of Melbourne in collaboration with DesignInc] (Design Inc. n.d.). CH2 also received the President's Award, National Awards for Planning Excellence from The Planning Institute of Australia in 2007 (City of Melbourne 2017).

Council House 2 (CH2) : Context

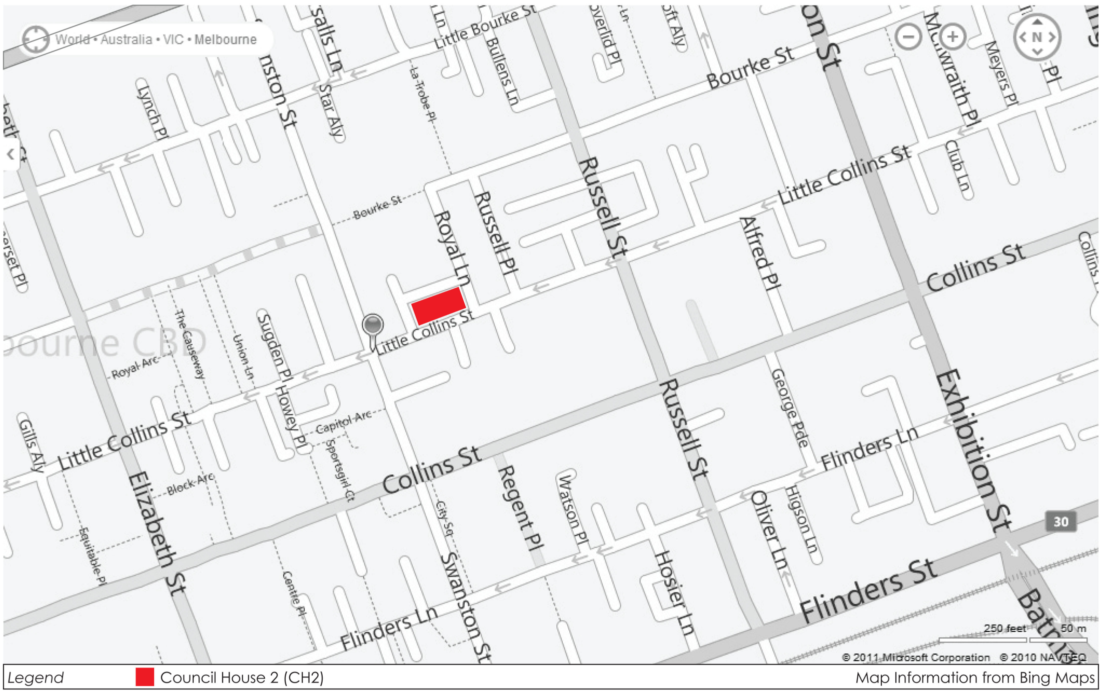

Figure 4. Location of CH2 (Bing Maps 2011, n.p.)

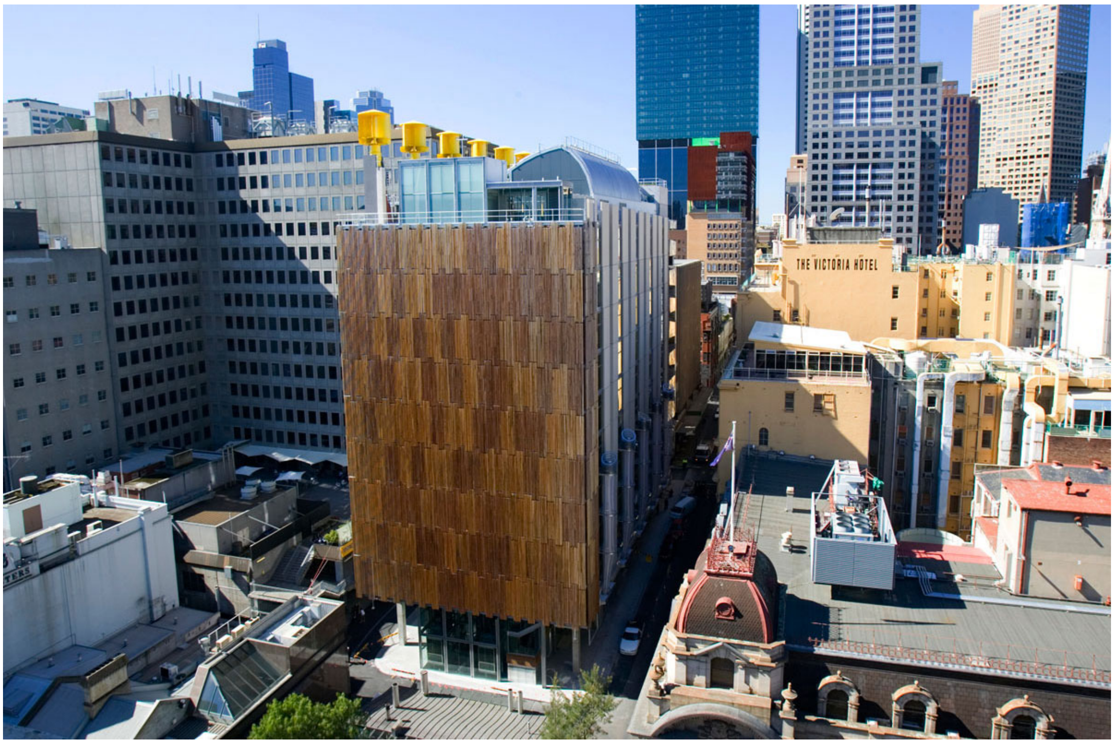

Figure 5. CH2 (City of Melbourne 2017, n.p.)

Table 6. CH2 Building Costs (Adapted from C40 2007, p. 3)

Amount	**Element**
$29.9 million/58.5% of cost.	Base building ($2,334/ m²)
$11.3 million/22.1% of cost.	Sustainability Features ($884/m²)
$7.1 million/ 13.9% of cost.	'Requirements specific to Council use, such as special design and communications ($553/m²)' (C40 2007).
$2.8 million/5.5% of cost.	Education and Demonstration ($218/m²)
Total: $51.1 million	

As Table 6 shows, over $11.3 million was spent on sustainability features, representing 22.1% of the overall investment.

Assessment Framework

The following sections discuss the application of the assessment framework to CH2.

Biomimetic Principles

Sustainable technologies are present in every aspect and level of CH2 and although most of the principles employed are not new, for example, the use of heat storage for cooling, they have never been used in such a comprehensive and interconnected way in Australia (Abaeian, Madani & Bahramian 2016).

The design of the building challenged traditional approaches to sustainability and building design as was designed to imitate growth structures of a tree (Aljuaid 2016). CH2 was the first purpose-built Australian office building awarded a maximum Six Green Star rating by the Green Building Council of Australia, the premier body assessing the sustainability of Australian buildings (City of Melbourne 2017). Table 7 lists the total points possible, and points awarded for CH2,

Table 7. CH2 Green Star Assessment (Hes 2007a, p. 1)

Category	**Maximum Points Available**	**Points Awarded**
Management (e.g. ongoing monitoring and metering)	12	10
Indoor Environment Quality	26	20
Energy	24	16
Transport	11	9
Water	12	12
Materials	14	9
Land Use & Ecology	8	2
Emissions	13	9
Innovation (*not included in total*)	(*5*)	(*5*)
Total Points	**120**	**87**

As Table 7 shows, CH2 performed best in the water and innovation categories. Its performance in the these categories can be attributed to its water mining system, which recycles sewer water from the city and uses it for cooling, plant irrigation and toilet flushing (City of Melbourne 2017).

The construction of CH2 cost approximately 22% more than a conventional building of its size, however, the 10% higher energy efficiency reimbursed the extra cost after only five to seven years (Abaeian, Madani & Bahramian 2016). This suggests that biomimetic design is a viable approach for managing changes in environmental conditions while providing a comfortable atmosphere and should be given preference in technology-oriented designs.

CH2's emissions are 64% lower than a building with a five Green Star rating and when compared to CH1, CH2,

- Reduces electricity consumption by 85%;
- Reduces gas consumption by 87%;
- Produces only 13% of the emissions;
- Reduces water mains supply by 72% (Newton 2008); and
- Increases employee productivity by 10.9% (due to a healthier building, e.g. non-toxic finishes and clean fresh air) (Abaeian, Madani & Bahramian 2016, p. 274).

Architect Mick Pearce, adopted a method used in the Eastgate Centre in Zimbabwe (See next section). CH2's system is partially based on temperature regulation and passive ventilation techniques observed in termite mounds using water, purified and mined from sewers underneath CH2, comparable to how termites use aquifer water for evaporative cooling (Zari 2017).

Table 8 summarises the application of the assessment framework to CH2,

Table 8. CH2 Assessment Framework

Element	**Examples**
Resource Efficiency	**Presence of Circular Economies** • Water Mining Plant **Level of Self-sufficiency** • High thermal mass concrete ceilings. • Automatic night-purge windows. • Wind turbines. • Passive cooling system. • Rainwater collection and water recycling. • Air conditioning system. • Solar Panels. • A gas-fired micro-turbine/ Cogeneration Plant. • Photovoltaic cells.
Presence of Biophilic Design	**Biophilic Qualities present:** Biodiversity, prospect and Sensory Variability (Kellert 2008). **Balance between Nature and Technology** • Natural lighting and integrated electric lighting and day lighting systems (Paevere and Brown 2008). **Psychological Health and Well Being** • Interior and exterior plants. • Operates on 100% fresh air. • External balconies, green roof[2] spaces access to views and use of recycled materials (C40 2007; Green Building Council of Australia 2015).

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[2] 'Intentionally vegetated roofs…comprised of plantings with a soil and/or crushed aggregate medium overlain on various synthetic layers eliminating the passage of moisture and roots' (Yao 2013, p. 124).

As Table 8 shows, CH2 incorporated ten different sustainable technologies into its design. Occupant wellbeing was also valued highly by designers as evidenced by the many different biophilic qualities.

Resource Efficiency

The following sections discuss CH2's success in incorporating circular economies and self-sufficient systems into its design.

Presence of Circular Economies

The only true circular economy within CH2 is the water mining plant. The plant delivers 100,000 litres of recycled water daily, reduction CH2's consumption of mains water by 70% representing a significant savings in water (C40 2007). Water is mined and purified via three stages from sewers below the building and is used in a similar manner to the way termites access aquifer water for evaporative cooling (Zari 2010). CH2 cools the water passively underground and sends it through each floor's concrete ceilings (Goss 2009). Water is also used for irrigation and toilet flushing and is cleaner than tap water (ABC 2014; City of Melbourne 2017). Some water also continues to the basement where it is used in chilled beams that cool the building's interior, representing another closed loop system (Zari 2015a). Although CH2 possesses an innovative ,closed loop water mining plant, in relation to the assessment framework, it does not encourage the flow of nutrients or reduce the release of toxic substances.

One way in which CH2 does reduce the release of toxic substances is via minimal use of low toxic interior paint (City of Melbourne 2017). Further, particular attention was paid to the choice of CH2's building materials (Low 2005). For example, no construction materials used have any off gassing[3] and are mostly natural or recycled, eliminating air impurities. Lastly, recycled products used in CH2's construction included carpet, concrete, cement, steel and timber (C40 2007; City of Melbourne 2017). The use of these materials and products all helped to reduce the release of toxic substances.

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[3] 'The emission of especially noxious gases' (Merriam-Webster 2017a, n.p.).

Level of Self-Sufficiency

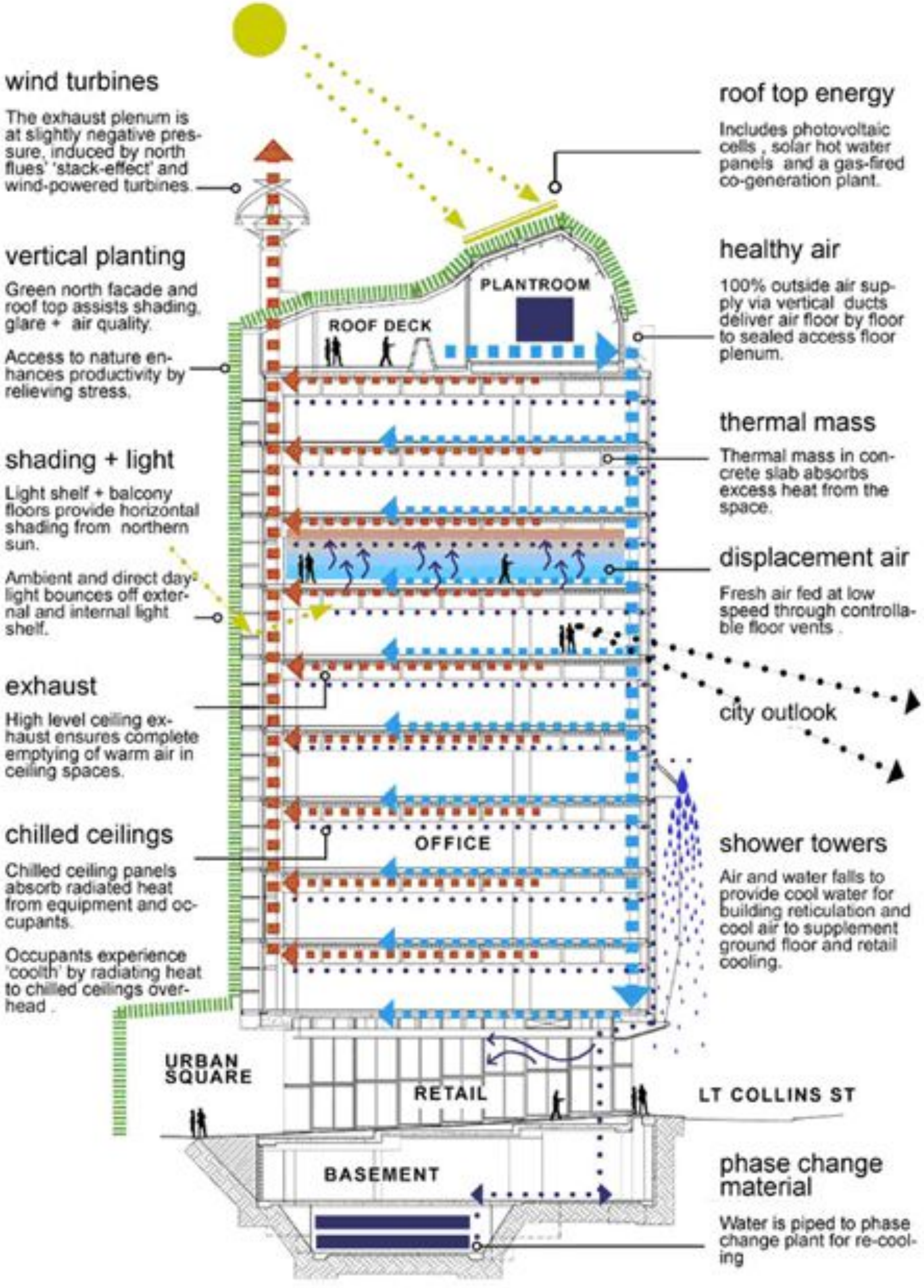
The reduction of greenhouse gas emissions, namely Carbon dioxide, was the main impetus for CH2's energy efficiency measures, as part of The City of Melbourne Council's 'Cities for Climate Protection' commitments (Hes 2007c). Consequently, CH2 excels in the area of self-sufficiency, featuring sustainable technologies throughout its structure. The following two sections, 'Energy Generation' and 'Cooling' outline CH2's assortment of sustainable technologies. Figure 6 provides an outline of CH2's plethora of sustainable technologies.

Energy Generation

Firstly, CH2 has 26m^2 of rooftop photovoltaic cells, generating approximately 3.5kW of electricity, powering a façade of slatted timber shutters (Figure 7). The shutters open and close according to the angle of the sun and time of day, pivoting vertically, ensuring the building is shaded whilst providing natural light (C40 2007; Morris-Nunn 2007; Tan 2007). Further, 60% of CH2's domestic hot water supply is provided by 23 (48m^2) rooftop solar panels (Jones 2008).

Six large roof mounted wind turbines (Figure 7) were intended to supply the majority of CH2's energy requirements. The turbines generate electricity throughout the day and expel air during the night (Aljuaid 2016; C40 2007). Despite good intentions, this sustainable technology failed to provide a self-sufficient power source for the building, as the turbines were too heavy to turn and don't contribute to CH2's energy generation, although they do assist with ventilation (Hes and Du Plessis 2014).

However, a gas-fired co-generation plant, also located on the roof, generates 40% of CH2's electricity, reducing dependence on the public energy grid (Newton 2008). The plant produces waste heat, used to support CH2's air-conditioning plant, providing 80% of the building's fresh air cooling and heating needs (Newton 2008). The plant has far lower Carbon dioxide emissions than coal-fired energy generation, reducing the release of 1,773 tons of Carbon dioxide annually (Cruz 2011; Hes 2007c).



wind turbines

The exhaust plenum is at slightly negative pressure, induced by north flues' 'stack-effect' and wind-powered turbines.

vertical planting

Green north facade and roof top assists shading, glare + air quality.

Access to nature enhances productivity by relieving stress.

shading + light

Light shelf + balcony floors provide horizontal shading from northern sun.

Ambient and direct daylight bounces off external and internal light shelf.

exhaust

High level ceiling exhaust ensures complete emptying of warm air in ceiling spaces.

chilled ceilings

Chilled ceiling panels absorb radiated heat from equipment and occupants.

Occupants experience 'coolth' by radiating heat to chilled ceilings overhead.

roof top energy

Includes photovoltaic cells, solar hot water panels and a gas-fired co-generation plant.

healthy air

100% outside air supply via vertical ducts deliver air floor by floor to sealed access floor plenum.

thermal mass

Thermal mass in concrete slab absorbs excess heat from the space.

displacement air

Fresh air fed at low speed through controllable floor vents.

shower towers

Air and water falls to provide cool water for building reticulation and cool air to supplement ground floor and retail cooling.

phase change material

Water is piped to phase change plant for re-cooling

Figure 6. Outline of CH2's Sustainable Technologies (Adapted from Newton 2008, p. 423)

Figure 7. CH2's roof mounted wind turbines (Hansen Yuncken 2017, n.p.)

Natural light and air circulation decrease summer energy demands by 14% and high thermal mass, undulating concrete ceilings improve cooling (C40 2007). The concrete ceilings are cooled by automatic night-purge windows that can be opened for four hours at night (C40 2007). The change in temperature between night and day saves 15% to 20% in energy (ABC 2014).

Cooling

CH2 uses an innovative air conditioning system, far more efficient than conventional air conditioning systems. Three enormous tanks, filled with 10,000 stainless steel balls cool the water for the air conditioning (Chua 2014). The balls contain a special substance comprised of a salt mix that freezes at 15 degrees Celsius, meaning the balls freeze easily, requiring a very small amount of energy (ABC 2014). On a hot day, water is flushed through the tanks and as the balls melt they cool the water used for the air conditioning system (ABC 2014).

The south façade of CH2 contains five shower towers (Figure 8), which form a passive evaporative cooling system. The 14m high towers are comprised of lightweight fabric, 1.4m in diameter (Hes 2007b; Tan 2007). Outside air is drawn in and channeled into the towers and as air falls within the tower, it is evaporatively cooled from the cascade of water (Hes 2007b). The cool air is directed to the ground floor retail spaces and the cool water is directed to 'phase change material' (Hes

2007b) where 'coolth'[4] is collected for the remainder of CH2, when needed (Hes 2007b). The towers function without the need of fans to drive the supply air, which is driven by the gravitational force on the water droplets and also on the cooler and denser air after the droplets are evaporated (Cheung 2012; Zari 2015b). This cooling technology represents an innovative, self-sufficient and sustainable technology.

The western façade of CH2 (Figure 9) was designed to have perpendicular boards, constructed using recycled timber, which open and close according to the direction of the sun (Aljuaid 2016). The north and west facades are designed with frames for vegetation to act as a ‘living sun screen’ (Morris-Nunn 2007, p. 211), reducing solar heat gain. CH2 also uses a "rock store" that is cooled at night by the outside temperatures, and the hot air coming in during the day is cooled by the rocks (Morris-Nunn 2007).

Figure 8. CH2’s Shower Towers (City of Melbourne 2017, n.p.)

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[4] ‘Pleasantly low temperature’ (Oxford University Press 2017, n.d.).

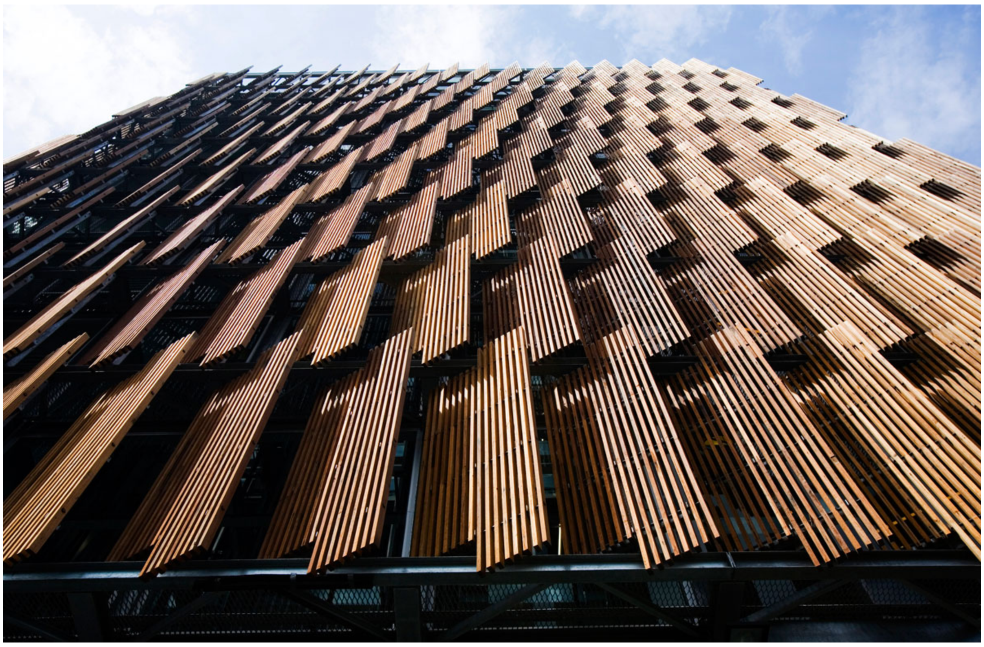

Figure 9. CH2's Façade of Timber Shutters (City of Melbourne 2017, n.p.)

It's clear from CH2's plethora of sustainable technologies, namely in the form of cooling and energy generation, that it excels in the area of self-sufficiency.

Presence of Biophilic Design

One of CH2's design parameters was 'to provide a comfortable working environment for its occupants' (Hes and Bates 2005). CH2 serves to enhance the psychological health and well being of its occupants via a number of measures including the presence of vegetation and use of natural light. Table 9 provides a summary of CH2's biophilic qualities.

Table 9. Summary of Biophilic Qualities present in CH2

Biophilic Quality	**Example(s)**
Sensory Variability (air movement)	• Supply of 100% fresh air
Biodiversity (vegetation elements)	• Interior and exterior plants • Green roof spaces
Prospect (brightness, wide horizons, or ability to see into a distance) (Kellert 2008)	• 80% of staff have access to views • Maximum use of natural lighting

A guiding diagram was developed to visually capture the '…natural analogies of the design concept' (Webb 2005) (Figure 10), centred on the notion of synergy, meaning, a building comprised of many interrelated systems. Natural and man-made landscapes, people, building fabric, energy flows and engineering systems, combined to form an inter-related whole (Webb 2005). This diagram ensured the design team integrated the concept of Biophilia into CH2's design (Webb 2005).

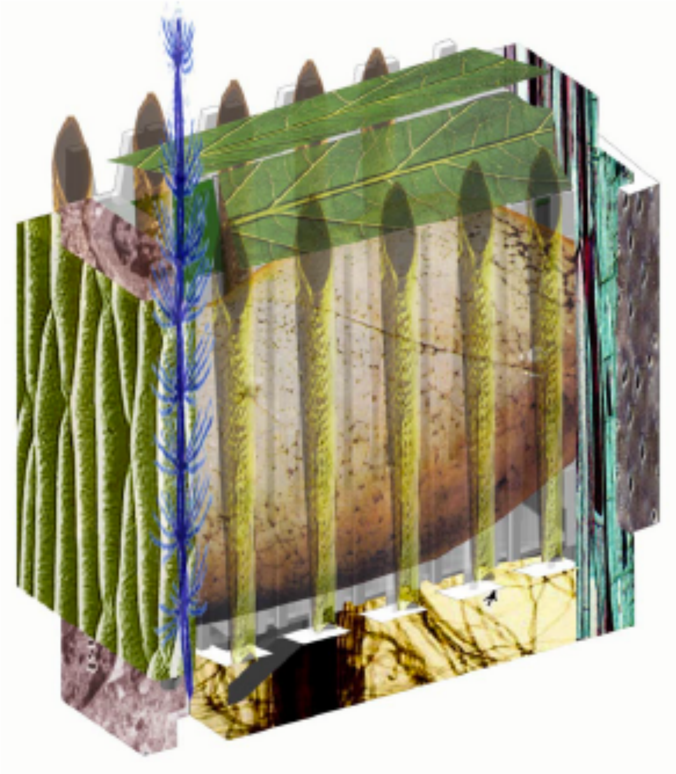

Figure 10. CH2's 'Emergent Design Concept' (Webb 2005, p. 5)

Plants are used extensively, both internally (Figure 11) and externally balancing well, the presence of technology with natural surroundings. Externally, they are located on the roof (Figure 12) and on the northern façade in the form of planter boxes (Figure 13). Overall, the exterior vegetation is equal in area to what would be on the site's original natural vegetated state, achieving one of CH2's design parameters (City of Melbourne 2017). Internally, there is one plant for every occupant of a building floor, cleaning the air (City of Melbourne 2017). This extensive use of internal and external vegetation clearly satisfies the 'Biodiversity' biophilic element (Kellert 2008).

CH2 balances the presence of technology with natural surroundings by maximising natural lighting and placing windows at the highest point in the roof vault with artificial lighting set at 150 lux[5], as opposed to 300 lux in conventional buildings (City of Melbourne 2017). This reduced lighting strength also reduces energy use. CH2's lighting strategy also utilises the building's height and orientation to reduce glare and maximise natural lighting. For example, windows are larger on lower floors, as they receive far less daylight than upper levels. Light shelves redirect sunlight onto ceilings, reducing dependence on artificial lighting (City of Melbourne 2006).

Paevere and Brown (2008) conducted a post-occupancy study of CH2 and found that staff productivity increased by 10.9% moving from their previous building, CH1, meaning an annual cost saving of AUD$2.4 million (Bond 2010). Paevere and Brown (2008) received responses from 260 employees of CH1 and CH2 and the authors study encompassed '…physical indoor environmental quality measures, an evaluation of occupant health, wellbeing and productivity based on occupant questionnaires, spot health symptoms questionnaires, staff turnover data and absenteeism' (Paevere and Brown 2008, cited in Bond 2010, p. 12).

Satisfying the 'Sensory Variability' (Kellert 2008) biophilic element, CH2 operates on 100% fresh air ventilation, drawn from the roof, which then rises up via registers in the floor and exhausted at ceiling height using natural convection (City of Melbourne 2017). Many occupants identified fresh air as one factor that increased their productivity (City of Melbourne 2017). Further, CH2 is considered to '…have low levels of occupant-reported rates for building-related health symptoms, when compared to levels in the general population' (Paevere and Brown 2008, p. 3).

Lastly, CH2's occupants have access to a summer terrace and external balconies (Paevere and Brown 2008). Occupants also have access to Green roof spaces (C40 2007; Paevere and Brown 2008) and 80% of staff have access to a view (Green Building Council of Australia 2015). These elements all fulfill the 'Biodiversity' and 'Prospect' biophilic qualities (Kellert 2008).

Clearly, CH2 excels in regard to this framework element with its abundance of biophilic qualities, which enhance the psychological health and well-being of occupants and provide a good balance between technology and nature.

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[5] 'A measure of the amount of light produced by something' (Cambridge University Press 2017).

Figure 11. CH2's Interior Vegetation (Paevere and Brown 2008, p. 6)

Figure 12. CH2's Rooftop Vegetation (City of Melbourne 2017, n.p.)

Figure 13. CH2's Northern Façade Vegetation (City of Melbourne 2017, n.p.)

Conclusion

A flagship building for sustainability and a catalyst for change, CH2 was designed to be 'a lighthouse for future City developments' and '…inspire a new relationship between the City and nature' (Morison, Hes & Bates 2005, p. 14). CH2 achieves these goals and is a visionary building at the forefront of biomimetic architecture. CH2 not only provides an optimum working environment for its occupants but also a standard in energy efficient design and a standard for future biomimetic buildings.

Eastgate Centre, Harare, Zimbabwe

Introduction and Background

Arguably the most well-known and successful example of biomimetic architecture globally, is the Eastgate Center (Figure 114), the world's first all-natural cooling building, located in Zimbabwe's capital, Harare (Figure 15) (Drake 2011; Turner and Soar 2008). Commissioned in March 1991 by 'Old Mutual Properties', one of Zimbabwe's biggest multinational companies, who own and operate Eastgate and designed by architect Mick Pearce, construction began in 1993, with the building officially opening in April 1996 (Pearce 2016a; Turner and Soar 2008). Costing US$35 million (exclusive of land), Eastgate is a 55,000m^2 mid-rise commercial office and shopping complex (Fink and Kaltenegger 2016; Johnston 2008; Royall 2010). Eastgate's design strategy was inspired by termites, native to the area, specifically, their ability to use natural ventilation to climatically control their nests (Hes and Du Plessis 2014; Hwang *et al* 2015).

Figure 14. The Eastgate Centre, Harare, Zimbabwe (Brazier 2008, n.p.)

Eastgate contains two buildings linked together side by side by a glass roof with lifts and steel bridges suspended from cables on steel lattice beams spanning the atrium below (Pearce 2016a). A suspended glass skywalk (Figure 15), running the length of the atrium at level two, connects with the lifts (Pearce 2016a).

Figure 15. Location of Harare, Zimbabwe (Google Maps 2017a, n.p.)

Figure 16. Eastgate's Interior showing Skywalk and Open Atrium (Pearce 2016a, n.p.)

Awards

Architect Mick Pearce attracted recognition for Eastgate's design, receiving a number of awards, including the 2003 'Prince Claus Award for Culture and Development' (Khan 2017, n.p.) and 'The International Council of Shopping Centres Certificate of Merit' (1997) by the International Council of Shopping Centres, New York, the first ever award for an African building (Old Mutual 2015; Pearce 2016). Pearce also received the 1997 'Fulton Award for excellence in the use of concrete' awarded by the Concrete Society of Southern Africa and the 'Steel Construction Award' (1997), Certificate of Merit from the Southern African Institute of Steel Construction (Pearce 2016). These awards demonstrate the significance of Eastgate's design and success as a biomimetic building.

Other Termite Inspired Buildings

The cost savings and environmental benefits of Eastgate have made it a seminal case study of biomimetic architecture, inspiring the design of CH2 and Portcullis House in London (Figure 17).

Figure 17. Portcullis House, London (Hisgett 2011, n.p.)

Opposite the Palace of Westminster, Portcullis House features several turrets for air circulation and passive cooling with its chimney system used to draw air through the building by exploiting natural convection flows (Goss 2009).

Assessment Framework

The following sections discuss the application of the assessment framework to The Eastgate Centre.

Biomimetic Principles

The design brief from Old Mutual Properties to Eastgate's architect Mick Pearce was for a 'relatively inexpensive building with acceptable levels of comfort in the offices, without air conditioning and without compromising the aesthetics and overall quality of rentable space' (Arup 2004, n.p.). From this, Pearce identified the challenge: to design a building that ventilates and cools passively in the extreme African climate (Pearce 2016). Pearce then interpreted the challenge biologically: what passively ventilates and cools in the extreme African climate?

The Termite Mound

Pearce discovered a model that would inform the design of Eastgate: the termite (*Macrotermes michaelseni*). Termite mounds (Figure 18) offered a self-regulating environment that responds to changing external and internal conditions (Loughborough University 2011). Pearce studied these termite mounds extensively via 'Project TERMES (Termite Emulation of Regulatory Mound Environments by Simulation)' (Barney 2013; Goss 2009), a 2004 study lead by Rupert Soar to digitally scan termite mounds in Namibia, Africa (Loughborough University 2011; Vierra 2016). Pearce then abstracted and emulated their design into his design of Eastgate, resulting in a sustainable building requiring no powered air conditioning system in the extreme African climate. Pearce also collaborated with scientist Scott Turner, an expert in collective intelligence among termites (Fayemi *et* al 2014; Hunter 2014) and 'Ove Arup' engineers (Kim, Choi & Lee 2015), who established a number of design rules, ensuring the success of Eastgate's air conditioning system:

- No direct sunlight could fall on external walls;
- The north façade (direction of the summer sun) window to wall ratio could not exceed 25%;

- There had to be a balance between artificial and external light to minimize heat gain and energy consumption;
- All windows had to be sealed because of noise pollution, unpredictable wind pressure and temperatures;
- Duct ventilation only;
- Windows had to function as light filters, control glare, noise and security; and
- Blinds and deep overhangs were used to keep direct sun off the windows and wall (Goss 2009, p. 28).

Figure 18. Termite (*Macrotermes michaelseni*) Mound (BBC 2015, n.p.)

One of the most notable examples of biomimetic architecture, the 6m-tall termite mound found in African grasslands is built from sand, soil, termite saliva and tree bark, yet they are stronger than concrete (Hwang *et* al 2015). Living in groups of over 2 million, termites are extremely heat sensitive, however, despite a daily temperature range of 3°C to 42°C, the mounds maintain an internal temperature of 30°C (Hwang *et al* 2015). They must maintain this exact temperature as termites survive off fungus farmed inside their mounds, which must be grown at exactly 30°C (Pronk, Blacha & Bots 2008). This system maintains temperature far more effectively than any cooling, heating and ventilation systems devised by humans (Turner and Soar 2008, cited in Hwang *et al* 2015). The termites achieve this by continuously opening and closing vents during the day (Royall 2010).

Eastgate's design is based on two understandings of termite mound functioning (Royall 2010). The first model, know as 'thermosiphon flow' (Figure 19), proposes that the heat generated by termites produces enough buoyancy to drive nest air up into the mound's porous surface, where it's refreshed due to respiratory gas and heat exchange with the atmosphere (Turner and Soar 2008). Denser, fresh air flows down into the nest and the cycle repeats.

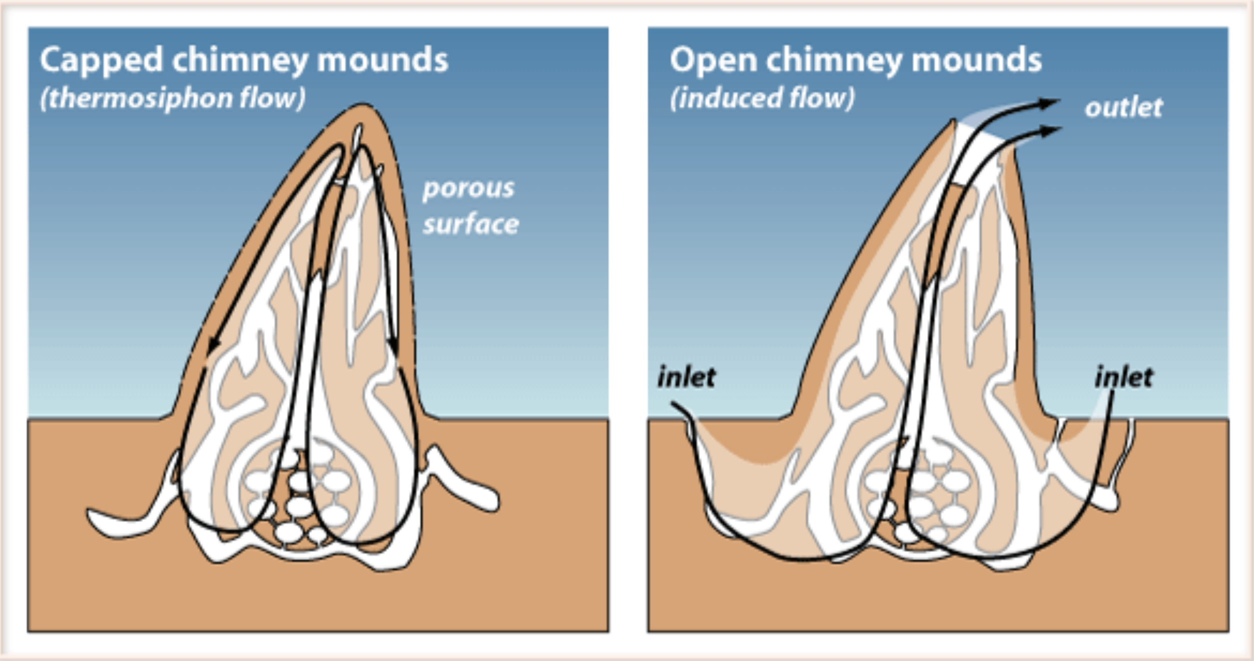

Figure 19. 'Thermosiphon' and 'Induced Flow' Models of Termite Mounds (ESF 2017, n.p.)

The second model, known as the 'stack effect' or 'induced flow' (Figure 19), involves the large chimney vent being exposed to higher wind speeds, causing a 'Venturi effect', drawing fresh air into the nest through ground openings (Al Shawa 2016).

Table 10 summarises the application of the assessment framework to The Eastgate Centre,

Table 10. Eastgate Assessment Framework

Framework Principle	**Examples**
Resource Efficiency	**Presence of Circular Economies** • Passive ventilation system. **Level of Self-sufficiency** • Passive ventilation system.
Presence of Biophilic Design	**Biophilic Qualities present:** Prospect, Refuge, Biodiversity and Liveability and movement (Kellert 2008) **Balance between Nature and Technology**

	- Indoor vegetation **Psychological Health and Well Being** - Indoor vegetation, fountains, large, open interior and branch like structures.

Resource Efficiency

The following section discusses Eastgate's success in incorporating circular economies and self-sufficient systems into its design. For Eastgate, these sections have been combined, as unlike CH2, Eastgate does not have a plethora of sustainable technologies. However, its cooling system inspired CH2's and has lead to significant energy and financial savings and forms the bulk of the assessment.

Presence of Circular Economies and Level of Self-sufficiency

Eastgate's entire passive ventilation system can be classed as a circular economy. This self-sufficient system requires only wind and fans to cool the entire building. Rather than operating a conventional fuel-based air-conditioning system to regulate temperature, Eastgate is designed to exploit more passive and energy-efficient methods of climate control (Pearce 2016b). Air inside Eastgate is exchanged twice per hour during the day and seven times during the night to and depending on the time of the year, exchanges are regulated to maintain an optimal temperature of 21°C to 25°C (Tessema, Taipale & Bethge 2009). Pearce designed a passive-cooling structure with variable thickness walls, light coloured paints and custom designed hooded windows to minimise heat absorption (Singh and Nayyar 2015). Eastgate's heavy masonry walls use an external shading system that minimises solar heat gain (Singh and Nayyar 2015). Cool air is distributed into floor voids that have a web of precast concrete elements with a large surface area to maximise heat transfer (Pawlyn 2011; Turner & Soar 2008 cited in Singh and Nayyar 2015).

Eastgate's cooling system functions only using fans meaning the monthly energy consumption is 90% less than comparable buildings in Harare and the relative power amounts to a savings of 17-52% compared with six similar mechanically ventilated buildings in Harare (Pohl and Nachtigall 2015). This equates to $700,000 in annual air conditioning costs (Blake 2011). The internal air temperature of the building has been reported at 24-25°C on a warm summer day of 28°C, 3-4°C cooler (Johnston 2008).

Lastly, Eastgate is mainly comprised of a combination of double thickness brick in the external walls and in situ concrete that moderate temperature extremes and mostly light coloured paint to minimise heat absorption (Gunnell, Du Plessis & Gibberd 2009).

Night Flushing

Eastgate was designed to take advantage of Harare's cool climate relative to its tropical location (Hunter 2014) utilising 'night flushing', whereby 'cool night air is driven through a multitude of air passages within the building's heavy concrete and masonry structure, cooling the concrete vaulted ceiling, which absorbs heat during the day' (Dahl 2013, p. 22). Despite Harare lying 1500m above sea level with temperatures barely reaching above freezing, heat is stored in the concrete, remaining there for the duration of the night and early morning (Pohl and Nachtigall 2015).

The daily accumulated heat is vented at night via these passages, by convection forces and fans in 48 chimneys (Figure 20) along the center of Eastgate (Dahl 2013). Further, Eastgate's jagged concrete facing combined with vegetation, is designed to release the most amount of heat during the night and absorb the least amount during the day (Dahl 2013) and the walls of the building are shaded by cantilevered sunscreens (Tessema, Taipale, & Bethge 2009).

Other than it's unpowered air conditioning system, there are no technologies within Eastgate that reduce the release of toxic substances or encourage the flow of nutrients.

Power, Waste and Water

Eastgate does not possess any sustainable technologies related to power generation, waste management or water recycling. Evidently, it clearly 'fails' in relation to the 'Level of Self-sufficiency' framework element.

Figure 20. Eastgate's Chimneys (The Source 2017, n.p.)

Presence of Biophilic Design

When applied to Eastgate, this element of the framework yielded surprising results. The building is widely cited in biomimetic architecture literature, however, in relation to biophilic design, literature is scant. It was found that Eastgate possesses a number of biophilic qualities. Table 11 provides a summary of biophilic design present within Eastgate.

Table 11. Summary of Biophilic qualities present within Eastgate

Biophilic Element	**Example**
Refuge (sense of enclosure and shelter with canopy effect or branch-like forms overhead);	• Steel lattice overhead
Biodiversity (vegetation elements)	• Interior plants
Prospect (brightness, wide horizons, or ability to see into a distance)	• Large Open interior
Liveability and movement (with real moving water or reflecting surfaces)	• Water features - Fountains

The biophilic qualities: 'Prospect', 'Refuge', 'Biodiversity' and 'Liveability and movement' (Kellert 2008) are present within Eastgate. For example, plants (Figure 22) and fountains (biodiversity) are located throughout the interior of Eastgate. Within Eastgate there is also the ‘ability to see into a distance’ (prospect) via the buildings large, open interior (Figure 22). Lastly, there are branch like structures overhead in the form of steel bridges, which are ‘…suspended on cables from steel lattice beams’ (Pearce 2016a, n.p.) spanning over the atrium (refuge) (Figure 21).

Figure 21. Eastgate’s Indoor Plants and Branch like Structures (Kiva 2017, n.p.)

Figure 22. Eastgate’s Interior showing fountain, plants and large open space (Doan 2012, n.p.)

Conclusion

Although Eastgate can be viewed as a simplistic representation of biomimetic architecture it can still be considered sustainable. The building's passive cooling system serves as a model for future biomimetic buildings and helped inform the design of CH2. The Eastgate Centre represents how just one aspect of a single species can inform the design and functioning of an entire building.

Kalundborg Eco-Industrial Park, Denmark

Introduction and Background

> As strange as it seems, industrial ecology will conduct business the way a sun-soaked hickory forest recycles its leaves (Benyus 1997, p. 239).

The town of Kalundborg in Denmark developed an 'industrial ecosystem' or 'Eco-Industrial Park (EIP)' in 1959, representing an example of biomimicry at the ecosystem level or 'ecomimetics' and a model of environmental sustainability. Kalundborg EIP involves four core industries and a local municipality who have collaborated where the waste of one partner is the resource of another, demonstrating 'industrial symbiosis' and 'circular economies'. The public and private entities involved exchange a number of waste components including natural gas, water and heat. Although other EIPs exist globally, Kalundborg EIP is viewed as the first recognised and archetypal example of industrial symbiosis and continually referred to in Industrial Symbiosis literature, thus, it was chosen for analysis (e.g. Branson 2011, 2016; Chertow 2007; Domenech and Davies 2011; Seto, Solecki & Griffith 2015).

Located approximately 110kms West of Copenhagen on the north-western coast of the Danish island of Zealand (Figure 23), Kalundborg Municipality is a small, seaside industrial town of approximately 16,000 people (Gulipac 2016; Robertson 2017). Kalundborg became an industrial center in the mid 1950's and remains largely an industrial and trading center in Denmark (Suarez 2012).

Kalundborg EIP (Figure 24) is a 6.7-km^2 site located 75kms West of Copenhagen (Fraccascia, Giannoccaro & Albino 2017; Van Renssen 2012). The initial $75 million infrastructure investment has produced a US$310 million return on investment since the program's inception, with the park saving approximately US$15 million annually (Harris 2007). Other benefits for the partners include, sharing of personnel, equipment and information (UNIDO 2015).

Industrial Symbiosis and Eco-Industrial Parks (EIP)

Kalundborg is the archetypal example of Industrial Symbiosis (IS) in Industrial Ecology (IE) literature and '…knowledge of Kalundborg has become foundational to IE' (Chertow and Ehrenfeld 2012, p. 15).

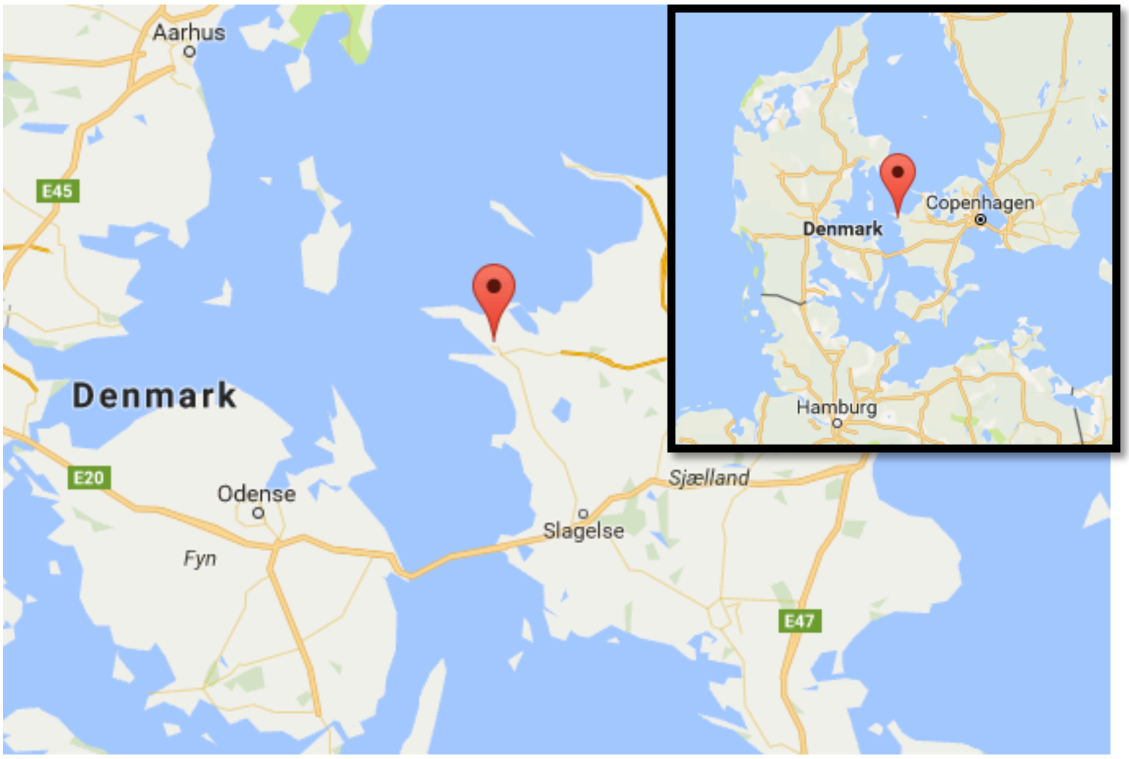

Figure 23. Location of Kalundborg EIP (Google Maps 2009, n.p.)

Figure 24. Aerial view of Kalundborg EIP (Van Renssen 2012, p. 388)

A subdiscipline of IE, IS was coined in Kalundborg and is defined as engaging 'traditionally separate industries in a collective approach to competitive advantage involving physical exchange of materials, energy, water, and by-products' (Chertow 2000, p. 313). The main benefits of IS are the synergistic possibilities and partnerships offered by geographic proximity (Lombardi and Laybourn 2012).

The science of IE arose in the 1980s studying the biological, chemical and physical interactions and interrelationships among and within ecological and industrial systems (Kibert 2016). In 2009 the OECD (2010) completed a global study on environmental innovation in Industry and sustainable manufacturing, studying practices in countries such as Japan and Denmark. In their study the OECD (2010) cited IE and Kalundborg as examples of solutions to be included in a new, sustainable, industrial revolution.

Since the 1960's, private and public businesses in Kalundborg have bought and sold waste products from industrial production in a circular economy (Salvador 2014). A residual product of one business becomes the raw material of another with key resources such as water, steam and gas shared between different enterprises, benefiting the environment and the economy. The most successful examples of Industrial Symbiosis in practice are Eco-Industrial Parks (EIPs), Cohen-Rosenthal (2003, cited in Gibbs and Deutz 2007, p. 1685) define an EIP as a;

> Community of businesses that co-operate with each other and with the local community to efficiently share resources (information, materials, water, energy, infrastructure and natural habitat) leading to economic gains, gains in environmental quality and equitable enhancement of human resources for the business and local community.

Currently, there are more than 40 EIPs globally, including Canada, China, Hong Kong and 18 in the USA, including North Carolina and Vermont (Myers and Spoolman 2013). In Australia, Kwinana EIP, the world's largest Industrial Symbiosis located 20km south of Perth, involves 27 partners including a Nickel Mine, Coal-fired power plant and Alumina refinery (Reap 2009).

Kalundborg Partners

There are currently five core partners involved in the Kalundborg EIP,

- Asnaes Power Station;
- Gyproc Nordic East;

- Novo Nordisk/ Novozymes A/S;
- Statoil A/S oil refinery (Kalundborg Symbiosis 2010); and
- Kalundborg Municipality

The partners are further outlined in Table 12 and their locations are shown in Figure 24.

Table 12. **Outline of Kalundborg Partners**

Name	**Description**
Novo Nordisk/ Novozymes	A Danish pharmaceutical and international biotechnological company, with annual sales of over $2 billion and the world's largest producer of insulin (Valentine 2016).
Gyproc Nordic East	The French-owned plasterboard factory produces 14 million m^2 of gypsum wallboard annually (Kibert 2016).
Kalundborg Municipality	Provides the water and heat supply to Kalundborg's 50,000 residents (Lödding *et al* 2017).
Asnaes Power Station (SK Power)	Owned by DONG Energy, the biggest power plant in Denmark, produces 10% (1500MW) of Denmark's electricity and is the world's first second generation bioethanol demonstration facility (Ehrenfeld and Gertler 1997; Suarez 2012)
Statoil	Owns Denmark's biggest oil refinery (Le Tellier *et al* 2017).

There are also another 33 marginal stakeholders involved in Kalundborg EIP including, material recycling companies, local farmers and a fishing factory that receive some material flows (Brown and Stigge 2017; Chertow and Park 2016), however, this analysis has only included the actors that have one or more exchange with another partner within the Park. Kalundborg shows how effective and successful an Eco-industrial park can be, despite not being planned. In support of this, numerous educational institutions have developed curricula focussing on Kalundborg and the model is exported to industrial areas globally including, China, Egypt and Singapore (Salvador 2014; Zawadzki 2015). Kalundborg EIP aims to involve up to sixty companies and thirty symbiosis products in the future (Taddeo *et al* 2017).

Figure 25. Map showing the locations of core Kalundborg Partners (Google Maps 2007, n.p.)

Outline of Kalundborg Processes

Figure 26 provides a breakdown of the processes occurring between the Kalundborg partners:

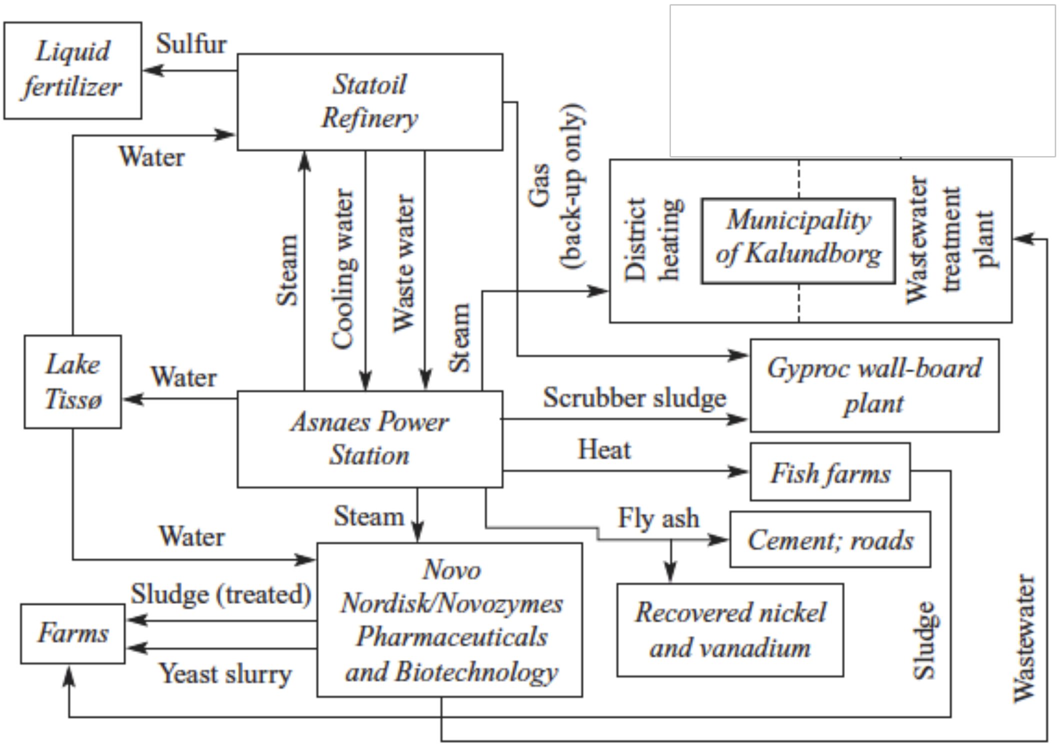

Figure 26. Diagram of Kalundborg Processes (Adapted from Ehrenfeld and Chertow 2002, p. 336)

The short physical distance between the partners enables them to exchange energy, waste and water relatively easily. As Figure 26 shows, there are 10 projects that recycle water, five that exchange energy and 12 that recycle waste and materials. Table 13 summarises the Mutual Benefits of the Kalundborg Partners. As Table 13 shows, DONG Energy, owner of Asnaes Power Station are involved in the majority (5) of collaborations.

History

Despite its success, there was no explicit design or preliminary planning of Kalundborg (Valentine 2016). The park organically evolved as a collection of bilateral agreements over a 25-year period between entities, without any Government or external funding, growing in scope and scale over time (Valentine 2016). The first step in the formation of Kalundborg was in 1961 when a new oil refinery, Statoil, expressed interest in using surface water from nearby Lake Tissø in order to reduce the consumption of local ground water (Valentine 2016). The City of Kalundborg offered to build the pipeline, while Statoil financed the construction (Suarez 2012).

Table 13. Mutual Benefits of Kalundborg Partners (Adapted from Valentine 2016, p. 71)

Year	Activity	Partner A	Partner B	Benefit to Party A	Benefit to Party B
1972	Natural gas transfer	Statoil	Gyproc	Sale of production by-product	Local acquisition of key resource
1973	Surface water acquisition	Kalundborg Municipality	DONG Energy (Asnaes Power Station)	New jobs, sharing of pipeline costs	Acquisition of water, sharing of pipeline costs
1976	Yeast slurry transfer	Novozymes	Local farms	Mitigate disposal costs	Cheaper source of fertiliser
1979	Fly ash transfer	DONG Energy	Cement industry	Mitigate disposal costs	Cheaper source of key factor input
1980	Heat transfer	DONG Energy	Fish farms	Payment for a waste stream	Operational enhancement
1982	Steam transfer	DONG Energy	Statoil	Payment for a waste stream	Cheaper stream
1982	Steam transfer	DONG Energy	Novo Nordisk	Payment for a waste stream	Cheaper stream

1993	Transfer of fly ash by-product	DONG Energy	Gyproc	Mitigate disposal costs	Cheaper source of Gyproc
2004	Water purification	Kalundborg Municipality	Novozymes/Novo Nordisk	New revenue stream, improved wastewater treatment	Cheaper source of key factor input

Then in 1972, Gyproc, a local gypsum production enterprise entered into an agreement with Statoil, for the supply of excess natural gas from Statoil's production and used the natural gas for drying plasterboard (Kalundborg Symbiosis 2010). In 1973, Dong Energy (Asnaes Power Station) was connected to Statoil’s water pipe. In 1976, Novo Nordisk started delivering biological sludge to neighbouring farms and in 1982 Novo Nordisk and the Statoil constructed steam supply pipelines from the power plant allowing both businesses to purchase process steam from the power plant and shutdown inefficient steam boilers (Valentine 2016). In 1981, Kalundborg municipality also completed a district heating distribution network that utilises waste heat from the power plant (Jacobsen 2006).

By 1989 the partners had formed the most successful, well-known and studied example of IS. Initially, the main impetus behind the partnerships was to reduce costs via finding financial opportunities for waste products, however, over time the companies and Kalundborg citizens began to understand the transactions were also providing environmental benefits (Suarez 2012). Kalundborg now has a central office funded by its members (Valentine 2016).

Awards

Despite its success and significance, to date, Kalundborg has only been awarded one environmental award, the 1991 ‘Danish Environmental Prize’ (Kalundborg Symbiosis 2010).

Assessment Framework

The following section discusses the application of the assessment framework to Kalundborg EIP.

Biomimetic Principles

Humans in industry can adopt the principles by which ecosystems are based upon. For example, zero waste generation, whereby an organism's waste is consumed by others. This is the fundamental concept of Kalundborg, where industries have collaborated to maintain the continuous flow of materials and zero waste generation. Specifically, Kalundborg mimics a rainforest, capturing water and encouraging the flow of nutrients with the Park's commercial, industrial and residential areas connected in a food web akin to an ecosystem or an 'ecomimetic' system (Balle 2010; El Haggar 2010; Petrig 2013). Table 14 provides a breakdown of the environmental benefits achieved at Kalundborg,

Table 14. Annual Environmental Benefits of Kalundborg EIP (Domenech and Davies 2011; Van Renssen 2012).

Emission/Resource Flow	Annual Savings
Ground Water	2.9 million m^3
Surface Water	1 million m^3
Liquid Sulfur	20,000 Tons
Biomass	319,000 m^3
Yeast Slurry	42,500 Tons
Carbon Dioxide (Carbon dioxide) Emissions	272,000 Tons
Sulfur Dioxide (SO_2) Emissions	53 Tons
Nitrogen Oxides (NO_x) Emissions	89 Tons
Waste Water	200,000m^3
Gypsum	170,000 Tons

As Table 14 shows, the Kalundborg synergies have massively reduced the environmental footprint of the partners. For example, they have saved over 270,000 tonnes of Carbon dioxide per year and approximately 3.9 million m^3 of water (Van Renssen 2012).

Table 15 summarises the application of the framework to Kalundborg EIP.

Table 15. Kalundborg Assessment Framework

Framework Principle	**Examples**
Resource Efficiency	• Recycling and reuse of water • Production of Biogas • Recycling of gypsum from desulphurisation • Significant reductions in Carbon dioxide emissions and use of oil and coal • Residual heat recovered and reused. **Presence of Circular Economies** • Waste steam and heat collected from various partners producing power, materials and pharmaceutical products. • Solid waste produces power and organic matter. • Fly Ash[6] production • Reclaimed metals. • Desulfurisation **Level of Self-sufficiency** • Aquaculture • Yeast Slurry
Presence of Biophilic Design	**Biophilic Qualities present:** Biodiversity and Livability and movement (Kellert 2008). **Balance between Nature and Technology** Lack of data – analysis by Google imagery as no literature was present regarding this element. **Psychological Health and Well Being** No evidence found to suggest Kalundborg EIP enhances the Psychological Health and Well Being of its residents.

The following sections analyse the Framework elements applied to Kalundborg.

Resource Efficiency

The following sections discuss Kalundborg's success in incorporating circular economies and self-sufficient systems into its design. The resource efficiency element at Kalundborg can be separated into three categories; water, energy and waste. The following sections discuss these three areas.

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[6] 'Fine solid particles of ashes, dust, and soot carried out from burning fuel (such as coal or oil) by the draft' (Merriam-Webster 2017b, n.p.).

Water

Each year the Park avoids the emission of 800 million gallons of water (3billion liters) (Smith *et al* 2015). For example, Asnaes Power Station has reduced withdrawals of water from Lake Tissø (Figure 24) by 50% and overall its water consumption has decreased by 60%, meaning 3 million m^3 of water saved annually through recycling and reuse (Ground water: 2.1 million m^3, Surface water: 1.2 million m^3) (Kalundborg Symbiosis 2010).

Energy

Between the partners there is an annual Carbon dioxide reduction of 275,000tns and savings of AUD$120m (Peck and Callaghan 1997; Smith *et al* 2015). For example, residual heat from Asnaes power station is reclaimed and used as heating for approximately 4500 households in Kalundborg, eliminating the use of 3,500 oil-fired residential furnaces (Ehrenfeld and Gertler 1997). Further, Gyproc has reduced its oil consumption by 90-95% (20,000 tons) annually after switching to gas supplied by Statoil refinery and the emission of 30,000 tons of coal (Chertow and Lombardi 2005; Ehrenfeld and Gertler 1997; IISD 2013).

Waste

Biogas is generated using yeast slurry from the insulin production by Novozymes (Bragdon 2017). Biogas is also produced using wastewater using a reactor, which produces the equivalent electricity of seven offshore wind turbines (47,000 MWh), enough to power 12,000 homes, reducing Carbon dioxide emissions by 21,000 tons (Novozymes 2017).

The desulphurisation of flue gas by Asnaes replaces the import of natural gypsum, saving 200,000 tons of gypsum per year (Chertow and Lombardi 2005). The gypsum is sold to Gyproc and Gyproc recovered by Kalundborg Municipality is also used by Gyproc, reducing the amount sent to landfill (Hull, Barbu & Goncharova 2007).

Presence of Circular Economies

The origin of the modern circular economy, Kalundorg EIP is an organic, self-organising and spontaneous formation of numerous synergistic solutions (Taddeo *et al* 2017). For this reason, it is difficult to fault Kalundborg with reference to the circular economy framework element. The Kalundborg EIP functions entirely as a circular economy of closed loop transfers of energy, waste and water, however, waste steam, waste heat and solid waste form the basis for the circular economies.

Waste Steam and Heat

Steam and heat is collected from various partners, namely Asnaes Power Station, allowing for a 30% improvement in energy utilisation across Kalundborg EIP (Thayer School of Engineering 2013). Waste steam from Asnaes powers fermentation tanks at Novo Nordisk (pharmaceutical plant), which Novo Nordisk uses to produce enzymes and insulin (Benifand, Ahmed & Church 2014). Statoil refinery also receives waste steam, some of which is used to purify waste gas, but most is shipped to Gyproc, together with a calcium sulfate solution to produce wallboards (Branson 2016). The production of wallboards produces sulphuric acid, which is shipped to 'Kemira', a chemical industry group, who use the acid to produce paper products (Hill 2012). More waste steam from Asnaes power station is used to power 4,500 homes of Kalundborg residents employed by farms, Asnaes, Statoil and Novo Nordisk (Benifand, Ahmed & Church 2014). Lastly, waste heat from the Asnaes power plant is also used for a bio-refinery that produces 5.4 million litres of ethanol annually, from waste materials generated around the site and by local farmers such as straw, left over from harvest (Branson 2011; Brownstein 2014; Siegel 2016).

Solid waste

Novozymes' enzyme production involves the fermentation of raw materials including cornstarch and potato flour generating 90,000m^3 of liquid biomass and 150,000m^3 of solid biomass annually (Hull, Barbu & Goncharova 2007). These by-products contain lime, nitrogen and phosphorus, which after inactivation and sterilisation are used by local farmers as fertiliser, reducing their need for commercial fertilisers (Grdzelishvili and Sathre 2007).

Asnaes also removes approximately 30,000 tons of Fly Ash from its smoke annually, used as a cement-blending agent by the cement industry, reducing emissions to the atmosphere (Grdzelishvili and Sathre 2007). Fly Ash is also recycled in a plant in the UK where 4,000 tons of iron, nickel and vanadium are reclaimed and sold (Grdzelishvili and Sathre 2007). Further, desulfurisation at Asnaes Power Station produces 100,000 tons of gypsum per year. A by-product of this produces 20,000 tons of liquid fertiliser (equal to the approximate annual Danish consumption of liquid fertiliser) (Thayer School of Engineering 2013).

Level of Self-sufficiency

It could be argued that the entire industrial ecosystem at Kalundborg is self-sufficient, however, there are two specific examples. These examples have some crossover with the circular economy framework element. Firstly, excess cooling water from Asnaes Power Station is used to produce 250 tons of trout, salmon and turbot (a species of flatfish) annually, in tanks adjacent to the power plant, which are shipped as a product and consumed by the town (Benifand, Ahmed & Church 2014). This system was so successful, it was expanded and privatised and clearly demonstrates the recycling of water and flow of nutrients (Branson 2016).

Secondly, yeast Slurry from Novonordisk is distributed to hundreds of local farms to feed 800,000 pigs per year, replacing 70% of the soy protein used by farmers to feed the pigs also reducing the release of toxic substances and encouraging the flow of nutrients (Branson 2016; Grdzelishvili and Sathre 2007).

Presence of Biophilic Design

This element relating to Kalundborg proved the most difficult to analyse due to a lack of available data as there was no literature relating to Kalundborg's balance between nature and technology or whether it enhances the psychological health and well being of its employees. However, an analysis via Google Maps/Earth imagery was performed in order to understand to some degree, the balance between nature and industry. There was an absence of diverse, up-to-date images, however, the results allow for a simple analysis of biophilic qualities within Kalundborg EIP.

Personal communication was also made with Kalundborg Symbiosis (http://www.symbiosis.dk/) regarding the presence of biophilic design, however, Kalundborg to date has not been studied in this manner.

Due to strict air, land and water emissions restrictions in Denmark, lands next to power generation and heavy industry can be used for agriculture and recreation (Bélanger 2016). This accounts for the high level of vegetation situated amongst Kalundborg's partners (Figures 27 and 28). All Kalundborg partners are also within two miles of Lake Tissø (Figure 27) (Robertson 2017). This close proximity to water and vegetation fulfils the 'Biodiversity' and 'Livability and movement' biophilic qualities (Kellert 2008). Table 16 provides a summary of biophilic design elements present at Kalundborg.

Table 16. Summary of Biophilic Qualities present at Kalundborg

Biophilic Quality	**Example(s)**
Biodiversity (vegetation elements)	• Abundant vegetation
Liveability and movement (with real moving water or reflecting surfaces)	• Proximity to Lake Tissø

Figure 27. Aerial view of Kalundborg EIP showing Lake Tissø (Van Renssen 2012, p. 388)

It is difficult to reach any conclusions regarding whether the presence of biophilic qualities (water and vegetation) enhances the psychological health and well being of Kalundborg EIP employees. However, the Park has achieved a good balance between nature and technology with all Partners directly adjacent to farmland or green spaces and close to water (Lake Tissø).

Figure 28. Aerial view of Kalundborg EIP (Google Maps 2010, n.p.)

Conclusion

The only criticism found against Kalundborg is that it relies upon non-renewable energy resources and produces Carbon dioxide emissions (Korhonen 2004, cited in Gibbs and Deutz 2007). Although this is true, Kalundborg's sheer amount of circular economies more than make up for this. The poster child of Industrial Symbiosis, Kalundborg EIP demonstrates a well-functioning ecosystem, where the waste of one partner becomes the resource of another. As energy needs continue to increase due to global population growth, Eco-Industrial Parks will become more important in order for companies to practice sustainability. EIPs like Kalundborg support the mitigation of Carbon dioxide emissions, reduce the use of traditional energy sources via renewable energy systems and reduce soil and air pollution.

Lavasa Hill City, Maharashtra, India

Introduction and Background

Touted as India's first smart city[7], Lavasa Hill City (Figure 29) is a private sector urban development of approximately 100km^2 (25,000 acres), the largest urban infrastructure project in India (Kannarath 2014; Kadam, Patil & Kawale 2017). Lavasa is located in the Indian state of Maharashtra, 40kms outside Pune, Maharashtra's second largest city, located 90kms southeast from Mumbai (Brebbia 2008; Datta 2012) (Figure 31). Lavasa was conceived by the Hindustan Construction Company (HCC) and is governed by a private subsidiary, the 'Lavasa Corporation Limited' (Hadfield-Hill and Zara 2017). Lavasa is the first 'hill station' built since Indian independence in 1947 (Irvine 2015). Hill stations were compounds built by British colonial officers in the cooler highlands to escape the crowds and heat of low-lying cities (Irvine 2015). The building of new hill stations has been encouraged by the state government of Maharashtra as a way to increase tourism, enabling the construction of Lavasa (Irvine 2015).

Figure 29. Aerial View of Dasve, Lavasa (LCL 2012, n.p.)

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[7] 'A city that gives inspiration, shares culture, knowledge and life, a city that motivates its inhabitants to create and flourish in their own lives' (Rios 2008, p. 4).

Figure 30. Location of Lavasa (Google Maps 2017b, n.p.)

Figure 31. Lavasa Site Plan (HOK 2017, n.p.)

Lavasa is one of few urban-scale biomimetic sites and although it hasn't been fully completed, Lavasa can still be assessed using the framework as one town (Dasve) has been fully built (Buck 2017). The overall Lavasa development will include five self-sustaining towns scheduled for completion by 2020 and is the first settlement to use standards based on biomimicry (Balakrishnan 2013; Hua 2016). Figures 31 and 32 shows the envisioned land use master plan for Lavasa. Each town will house 30,000 to 50,000 people with a planned total residential population of 300,000 by 2020 (Datta 2012; NCF 2014). At an estimated cost of USD$30billion, Lavasa will generate 96,500 jobs with a planned two million annual visitors (HOK 2017; Parikh 2015). The first town, ‘Dasve’, was completed in 2011 and construction work began on the second town, ‘Mugaon’, approximately 6kms from Dasve in 2004 (Hadfield-Hill and Zara 2017; Lavasa Corporation Limited 2014; NCF 2014). Mugaon is intended to become a commercial and residential hub to India's research and development companies (LCL 2014).

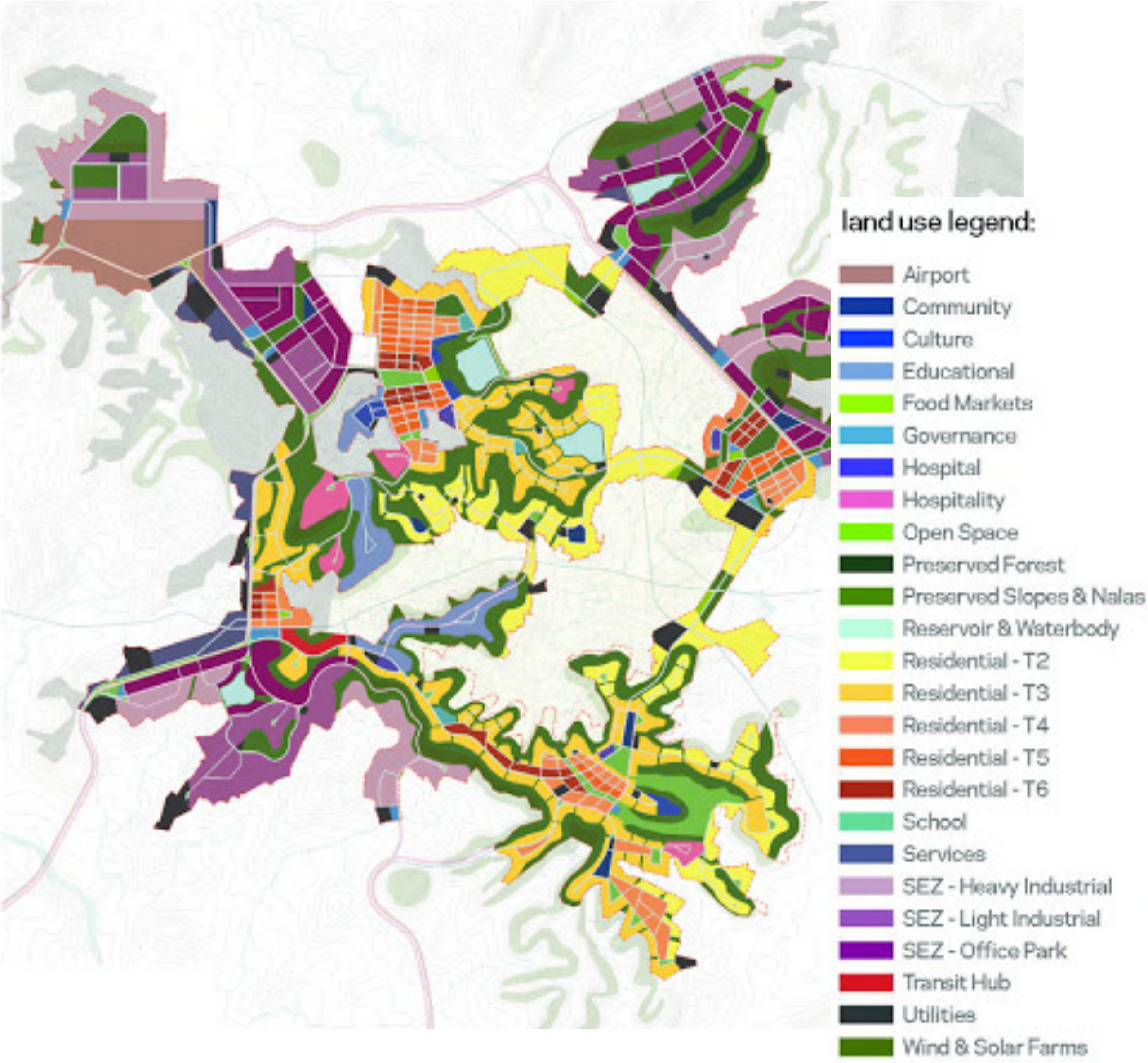

Figure 32. Lavasa Land Use Master Plan (Peters 2011, p. 51)

As Figure 32 indicates, Lavasa will comprised of large areas of preserved forests and hills.

Lavasa will comprise apartments, a retail district, hotels, an international convention centre, education and information technology facilities, biotech parks and recreational facilities including a golf course and theme park (HCC 2017; Parikh 2015). The main economic drivers for Lavasa are home sales and rentals with apartment prices ranging from US$17,000 to $36,000 (South 2015). Further amenities including, shopping centers and sparse development of the surrounding hills will also contribute to Lavasa's success (Gandhi 2007). The vision of Lavasa can be best summarised from the citizen brochure,

> Life in Lavasa has been envisioned as energetic yet calm, aspirational yet affordable, hi-tech yet simple and urban yet close to nature…Here, residents and visitors can access state-of-the-art amenities while enjoying the tranquility of wide-open expanses and a scenic natural waterfront… Lavasa aspires to establish a new benchmark in India of a fully planned city based on innovation and rejuvenation such that what is finally delivered is a balanced life (LCL 2012, p. 4).

Prior to the start of construction, Lavasa's natural habitat was destroyed by slash-and-burn agriculture for over 400 years (Knittel 2013). Lavasa was designed and planned by 'HOK' (Hellmuth, Obata & Kassabaum), USA architects, among the world's largest architectural firms and is being developed and built by the Hindustan Construction Company (HCC) Group (Datta 2012). HOK partnered with 'The Biomimicry Guild' to integrate sustainable design into the daily functioning of Lavasa, with the ultimate aim of reducing the city's ecological footprint (Balakrishnan 2013; Nogja 2011; Rossin 2010). Further influences include the Italian town of Portofino, which provides the name to some of Lavasa's buildings and streets (Parikh 2015).

Lavasa is the first Indian city to be built solely by a corporation and is the creation of billionaire industrialist Ajit Gulabch, known for mega-projects such as highways and dams (Kennard and Provost 2015). Gulabch created the project to feed the exploding demand for housing and work environments caused by rural to urban migration, as annually 15 million people migrate to Indian cities for jobs and 400 million people are expected to migrate into India's heavily overcrowded cities by 2040 (Gulabch Interview with North 2015; Miklian and Hoelscher 2014; Nogja 2011). Devised by global branding firm, 'Landor', the name 'Lavasa' has no meaning, but was designed to invoke images of exoticism and mystery with its hint at Hindi and abstract poeticism (Kennard and Provost 2015). At present, 500,000 people visit Lavasa annually, however, only 100 families have relocated to Lavasa (Miklian and Hoelscher 2014).

New Urbanism

Lavasa was modelled on the urban design movement, 'New Urbanism', which promotes walkable communities with most of the land designated for green and open spaces (Datta 2012). Further, (Srivastava 2013, p. 7) lists the principles of New Urbanism,

- Commuting and Connectivity: The city plan is in such a way that all the spaces lie in a ten kilometre radius and people can easily travel from home to work and vice versa as they are connected by a network of streets.
- Mixed Use and Diversity: A healthy mix of residential, commercial and recreational spaces for the people from all walks of life.
- Mixed Housing: A wide range of housing to cater to the needs of people.
- Architecture and Urban Design: Detailed attention to aesthetics and human comfort
- Neighbourhood Structuring: The city is planned in such a way that there are public spaces, which can be used for interaction and be made use of by the people.
- Smarter Transportation: Cost effective and technologically advanced travel network
- Sustainability: Minimal impact on the environment

The integration of these principles ensured biomimicry was incorporated throughout the design of the city. For example, the Sustainability principle ensures ‘minimal impact on the environment’ (Srivastava, 2013, p. 7). Figure 32 highlights a commitment to this principle with large areas designated as preserved forests, slopes and nalas (ravines or gullies).

Awards

Although the project is still in development, Lavasa has received a number of awards. Firstly, design firm HOK, Lavasa’s architects, received three international awards for Lavasa’s master plan (Carpi and Brebbia 2010). Firstly, the American Society of Landscape Architects ‘Award of Excellence and Honor’ in 2005 for the Dasve and Mugaon Master plans respectively. Secondly, the ‘Best Master Plan Award’ given by the Congress for New Urbanism (USA) (Gandhi 2007). Lavasa also received a Leadership in Energy and Environmental Design (LEED) certificate from the Indian Green Building Council for its energy saving features (Datta 2012). LEED is recognised as the international standard of excellence in green building (USGBC 2017).

Biomimetic Principles

Lavasa was planned around nature, implementing ‘urban advantages in a natural setting’ (HCC 2017), practicing biomimicry at the ecosystem level, known as ‘Ecomimetics’. Working with ‘The Biomimicry Guild (U.S.A)’, the HOK design team classified the six most important ‘ecosystem services' provided by the indigenous forest prior to deforestation Lazarus and Crawford 2011; Peters 2011). These ecosystem services are described in Table 17,

Table 17. Definition of Ecosystem Services emulated at Lavasa

Ecosystem Service	**Description**
Carbon sequestration	The ability of an organism to store or recycle carbon (Zari 2015a).
Evapotranspiration	The process whereby water is transferred from land to the atmosphere by evaporation from the soil and other surfaces and plant transpiration (FAO n.d.).
Solar Gain	'Also known as 'passive solar gain', refers to the increase in temperature in an object or structure resulting from the sun's heat' (Yeang and Woo 2010, p. 177).
The Nitrogen and Phosphorus Cycle	The continuous cycle of nitrogen and phosphorus in various forms between air, organisms, soil and water (Yeang and Woo 2010).
Water Collection and Storage	The process by which water is collected and stored in the soil and organisms.

Mimicking these ecosystem services inspired the urban design as the local forest environment minimises evaporation and erosion with leafy canopies and complex root systems, retains soil and stores water (Buck 2015; Gendall 2009). HOK then created 'ecological performance standards'[8] for each ecosystem service (Parikh 2015). The key concept informing the Lavasa master plan was the role of the native forest in the region's soil and water cycles, demonstrating the application of 'Regenerative Design', by remediating past environmental damage and restoring the natural ecosystem (Lazarus and Crawford 2011).

<u>Assessment Framework</u>

The following sections discuss the application of the assessment framework to Lavasa.

Table 18 summarises the application of the assessment framework to Lavasa,

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[8] A tool that measures '…the environment of a building or community in comparison with the surrounding ecosystem' (Rossin 2010, p. 568).

Table 18. Lavasa Assessment Framework

Framework Principle	**Example(s)**
Resource Efficiency	**Presence of Circular Economies** • Organic waste converter, city-wide vermicomposting (worm composting). • Excess crops from villa owners sold to restaurants and hotels (Ardhanari 2016). **Level of Self-sufficiency** • Green roofs • 'Permeable pavements' (Nallathagia 2015, p. 14). • Rainwater collection • Soil biotechnology • Wastewater recycling for irrigation • Solar technology • Reduction of landfill waste via recycling and education programs (Ardhanari 2016; Biomimicry 3.8 2016; NCF 2014) • Reforestation and hydro-seeding[9] (Hua 2016) • Micro wind turbines (Nagargoje *et al* 2016).
Presence of Biophilic Design	**Biophilic Qualities present:** Biodiversity, Livability and movement (Kellert 2008). **Balance between Nature and Technology** • Constructed with locally available materials (Pandey and Vishwakarma 2017). • Anthill inspired roads. **Psychological Health and Well Being** • 70% of land is designated as natural landscape (HOK 2017).

As Table 16 shows, Lavasa performs best in the 'Resource efficiency; Self-sufficiency' element with nine sustainable technologies in total.

The following sections discuss each framework element in detail.

Resource Efficiency

The following sections discuss Lavasa's success in incorporating circular economies and self-sufficient systems into its design.

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[9] 'Planting process that uses slurry of seed and mulch that helps in mass plantation, prevent soil erosion and facilitates quick vegetation' (Hua 2016, p. 270).

Presence of Circular Economies

Lavasa incorporates three different circular economies. Firstly, Lavasa utilises an organic waste converter whereby the biosolids resulting from wastewater treatment are reused as compost for landscaping and plantations and 100% of the sewage effluent is treated using soil biotechnology and used for irrigation, flushing, construction and cooling of buildings (Pandey and Vishwakarma 2017; Srivastava 2013). Further, all non-biodegradable waste is recycled and Lavasa has achieved a 95% reduction of landfill waste via recycling and education programs such as citywide vermicomposting (worm composting) (Biomimicry 3.8 2016; Nallathiga *et al* 2015; NCF 2014). Lastly, excess crops from villa owners are sold to restaurants and hotels, forming another closed loop system of resource sharing (Ardhanari 2016).

Clearly, Lavasa performs very well in this framework element as these initiatives all serve to encourage the flow of nutrients and reduce the flow of toxic substances. Although, as the population of Lavasa increases over time, it remains to be seen whether this level of landfill waste reduction can be sustained.

Level of Self-sufficiency

Lavasa's sustainable technologies can be separated into two categories, Power; and Water Collection and Storage.

Power

Lavasa utilises three sources of renewable energy generation using micro wind turbines, solar power and hydroelectric power from 'The Bhira Hydroelectric Project', 115kms Northeast of Lavasa (Ardhanari 2016; Google Maps 2017; Nagargoje *et al* 2016). Solar power is used for water heating purposes and street lighting and the city is also exploring the use of hybrid wind and solar technology to power site trails (Ardhanari 2016). Using these renewable energy sources has allowed for a 30% reduction in Carbon dioxide emissions compared with using conventional energy sources such as coal (Ardhanari 2016; Biomimicry 3.8 2016; Pandey and Vishwakarma 2017).

Water Collection and Storage

One of HOK's major aims was to prevent soil erosion caused by nine meters of annual monsoonal flooding (Buck 2017). Complicating the process, the area Lavasa occupies remains dry the rest of the year (Gendall 2009). Collaborating with engineering consultants 'Buro Happold', HOK designed '…a building foundation system to store water, as the indigenous trees once did' (Gendall 2009). The aim was to 'break' rainfall using a 'structural canopy' to slow drainage off buildings, allowing for collection (Buck 2017). This water storage mechanism was based on the 'Hydraulic Redistribution[10]' displayed by native Manilkara trees (*Manilkara zapota*), whose roots pull rainwater into the soil as storage for the dry season (Buck 2017). Trenches dug on the sides of roads allow rainwater to percolate into the soil. Mass plantations were also completed to raise the region's water table (Nallathiga *et al* 2015).

To further address the problem of overflows during the monsoon season, HOK emulated local harvester ants, which slow and divert water away from their nests using multipath, low-grade channels (Nallathiga *et al* 2015) (Figure 34). Lavasa's master plan will adopt the ant's strategy channeling water through the city (Gendall 2009). The roads are also biomimetic in that they curve like rivers to slow and intercept rainwater, reducing erosion (Benyus 2015). Future plans include porous cement, comparable to coral, which stores and slowly releases water (Benyus 2015). Further, all rainwater is collected via 10 dams throughout Lavasa and the city uses pavements that allow rainwater to permeate back into the ground (Nallathagia 2015). This rainwater is collected and has seen a 65% reduction in potable water consumption (HOK 2017).

For Lavasa's rooftops, HOK emulated the morphology of the local banyan fig leaf (Figure 33), specifically, the pointed spear at the leaf's end or 'drip-tip', that cleans its own surface and doubles water run-off (Gendall 2009). Emulating the fig leaf, HOK is developing tiled shingle rooftops that remove water in the same way (Gendall 2009).

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[10] '…the passive movement of water via roots from regions of wetter soil to regions of dryer soil' (Ryel 2004, p. 413).

Figure 33. Leaf of Banyan Fig tree (*Ficus religiosa*) (HOK 2017, n.p.)

Further, a planned 'hydrocanopy' of '…green roofs angled to mimic the rolling shape of the nearby forests' (Benyus 2015) will collect monsoonal rainfall and evaporate approximately a third, further preventing soil erosion (Benyus 2015).

Figure 34. The Indian Harvester Ant Nest, Maharashtra, India (Rushil 2012, n.p.)

As Figure 34 shows, the ant nest is designed to divert water away from the mound in times of monsoonal rainfall (Nallathiga *et al* 2015). To further prevent soil erosion, HOK designed a polymer product that hardens soil to create the same stabilising effect as the nests of Cliff Swallows (*Petrochelidon pyrrhonota*), a small species of bird native to Western North America (Peters 2011). The birds mix saliva with mud to create 'mortar' that adheres their nests to buildings (Peters 2011).

Finally, other environmental initiatives include artificial water holes, wildlife corridors and the release of aquatic birds, deer and fish into dams to maintain biodiversity (Nallathiga *et al* 2015).

Presence of Biophilic Design

It is difficult to fault Lavasa in relation to the presence of biophilic design as it's clear that Lavasa's residents are in constant connection with nature in the form of water or vegetation (Figures 35 - 37).

Table 19 provides a summary of biophilic design elements present within Lavasa.

Table 19. Summary of Biophilic Qualities present within Lavasa

Biophilic Quality	**Example**
Biodiversity (vegetation elements)	• Abundant vegetation and trees
Liveability and movement (with real moving water or reflecting surfaces)	• Proximity to Lake Warasgaon

Although Lavasa is technologically advanced and can be classed as a 'smart city', it was entirely constructed using locally available materials, primarily bamboo, fly ash bricks, crushed sand and locally available stone (Nagargoje *et al* 2016; Pandey and Vishwakarma 2017). Further, Lavasa restored 70% of previously deforested land to its original ecosystem, a moist deciduous forest, fulfilling the 'Biodiversity' quality of Biophilia (HOK 2017; Kellert 2008). This involved the mass plantation of over 1 million indigenous trees and plants, reviving a variety of ecosystem services including water collection and carbon sequestration (Biomimicry 3.8 2016; Gendall 2009; Kannarath 2014). The area is also being restored using detailed landscaping, slope greening and hydro-seeding (Hua 2016). The hydro-seeding facilitates quick re-vegetation and treats large areas, preventing soil erosion and improves seed germination (LCL 2010). Lavasa also fulfils the 'Livability and Movement' biophilic element with 'real moving water' (Kellert 2008) as the city is situated around a man-made lake (Lake Warasgaon) (Nogja 2011).

Figure 35. Lavasa showing Lake Warasgaon, trees and walkways (HOK 2017, n.p.)

Figure 36. Lavasa's Walkways and Vegetation (HOK 2017, n.p.)

Figure 37. Fortune Hotel, Lavasa (Ankur 2009, n.p.)

Discussion and Conclusion

Although generally viewed as a revolutionary development, Lavasa's developers (HCC) have faced numerous governmental challenges and other criticisms relating to environmental harm and land procurement (BBC 2011; Reuters 2010).

In 2010, the Indian Environment and Forest Ministry requested all construction to stop, claiming HCC violated environmental laws (Kannarath 2014). Social activists have been protesting against the Lavasa project since 2006 for its displacement of tribal populations and degradation of ecologically sensitive lands with 3,000 villagers from 12 villages displaced (Balakrishnan 2013; Kennard and Provost 2015). The Maharashtra state government was charged with granting environmental clearance to the Lavasa project when it did not have the statutory powers to do so (Balakrishnan 2013).

The main challenge facing Lavasa's development has been functioning with minimal state planning as Maharashtra's municipal codes did not anticipate a private city such as Lavasa. Motivating the State Government of Maharashtra to avoid a 'one size fits all' attitude in relation to urban development and attempting to convince the Government that innovative urban developments should be actively pursued. Traditionally, the Maharashtra Government has been hesitant towards such developments.

Further, encouraging local people to live more sustainably is a continual problem requiring culturally-appropriate education. For example, separating waste from recycling is a central facet of any sustainable society but is an uncommon practice for upper and middle classes in India (NCF 2014).

Finally, Lavasa is considered an 'ecocity', defined as an 'urban environment system in which input (of resources) and output (of waste) are minimized' (Register 1987, p. 31). Datta (2012) argues that ecocities such as Lavasa are only marketed as sustainable in order to attract global and domestic capital and Gleckner (2017) views Lavasa simply as a resort city for wealthy urban Indians that does not solve housing and environmental problems. Based on this analysis, Datta's claim can be refuted, as biomimicry/sustainable design was a central design component of Lavasa from its conception. This can also be said of Gleckner's claims, as Lavasa will offer a range of housing options and not only addresses environmental problems but has also attempted to restore the ecosystem.

Lavasa is an ambitious and revolutionary biomimetic development with its scale currently unmatched. Although yet to be fully completed, Lavasa's innovative mimicking of the local environment provides a model for future biomimetic developments and more sustainable cities.

SECTION TWO

Desktop Survey on Biomimicry Educational Offerings

Tables 20 and 21 summarise the findings of the desktop surveys.

Table 20. List of Universities offering Biomimicry Degrees

University	Degree	Description
Arizona State University, Tempe, Arizona, USA.	'Online Master of Science in Biomimicry' (Arizona State University n.d.)	The School of Life Sciences administers the program giving students a good grounding in biomimicry for industry, medical research and application, agriculture, government policy and engineering. Module examples include communication, business, teaching and biomimicry facilitation (Arizona State University n.d.)
University of Akron, Akron, Ohio, USA/ The Cleveland Institute of Art, Cleveland, Ohio, USA.	PhD fellowship	Dedicated biomimicry department offers a PhD fellowship to relevant students with experience and interest in biomimicry (The University of Akron 2017).

Table 21. List of Universities offering Biomimicry related Courses (The Biomimicry Institute 2017, n.p.)

University	Course(s)	Description
Minneapolis College of Art and Design, Minneapolis, Minnesota, USA.	'Innovation Tools and Techniques', 'Elements of Sustainable Design', 'Practice of Sustainable Design', and 'Geometry of Thinking' (Minneapolis College of Art and Design n.d, n.p.)	Biomimicry concepts and tools are integrated into several online Sustainable Design Masters and Certificate courses (Minneapolis College of Art and Design n.d)
Stellenbosch University. Lynedoch, South Africa.	Masters' degree in Sustainable Development	Week-long advanced studies biomimicry module (Biomimicry SA n.d.).
Ontario College of Art & Design University, Toronto, Ontario, Canada.	'Biomimicry 1: Points of Departure 'and 'Biomimicry 2: Application' (The Biomimicry Institute 2017, n.p.).	Two biomimicry courses within the Environmental Design Major that combine studio-based learning with critical inquiry (The Biomimicry

		Institute 2017).
University of California, Berkeley Center for Green Chemistry, California, USA.	Postgraduate course – ‘Greener Solutions’ (University of California, Berkeley n.d., n.p.)	Designed to introduce students and potential future researchers to biomimicry methodology through real world examples offered by some of the country's and the world's largest and most successful businesses (University of California, Berkeley n.d.)
Universidad Iberoamericana (Architectural Design School), Mexico City, Mexico.	‘Sustainable Design & Construction’ and ‘Sustainable Communities Design’ (The Biomimicry Institute 2017a, n.p.).	Forms the closing subject for two, four-month diploma courses (The Biomimicry Institute 2017a).
University of South Australia, Adelaide, South Australia.	‘Morphology and Biomimicry in Design’ (The University of South Australia 2017, n.p.).	Undergraduate architecture students morphology and processes including biomimicry via observation, drawing, and research to design products, spaces or architecture (The University of South Australia 2017).

University Scholarships/Prizes/Programs related to Biomimicry

The only University prize/scholarship related to biomimicry found during the desktop survey on biomimetic educational offerings was The University of New South Wales’, School of Civil and Environmental Engineering ‘Acacia Program National Sustainability Competition’. The purpose of the Program is to provide further sustainability education for Australian university students and to celebrate and recognise student projects that address challenges and opportunities relevant to sustainable development (UNSW n.d.). The 2017 Program accepts projects that propose original ideas across many themes, one of which is ‘Biomimicry technology’ (UNSW n.d.).

Design and Consulting Firms offering Biomimetic Approach

A desktop survey was also completed globally to investigate whether any design or consulting firms incorporated the biomimetic approach. Overall, a total of 11 firms were found to incorporate the biomimetic approach. Table 22 lists the design firm’s name and location and Biomimicry related concept(s) practiced. A number of firms practice biomimicry generally, meaning the firm does not incorporate specific biomimetic design concepts, in these instances; 'Biomimicry in General' is listed.

Table 22. Design and Consulting Firms offering Biomimetic Approach

Name and Location	**Biomimicry Related Concept(s) Practised**
'Biomimicry Switzerland', Zürich.	*Biomimicry in General*
'Exploration Architecture' (design, innovation and strategy company), London, UK.	*Biomimicry in General*
'Azul seven', Minneapolis, Minnesota, USA.	*Biomimicry in General*
'Biomimicry NYC', New York, USA.	*Biomimicry in General*
'Biomimicry 3.8', Missoula, Montana, USA.	*Biomimicry in General*
'HOK' (design, architecture, engineering and urban planning firm) St. Louis, Missouri, USA.	*Biomimicry in General*
'Symbiosis Group', Yosemite National Park, California, USA.	*Biomimicry in General*
'55-5 Consulting', Seattle, Washington, USA.	Regenerative Design (See pg. 19)
'Energy Architecture', Adelaide.	Ecologically Sustainable Development[11] Design
'Outer Space', Adelaide.	Green Infrastructure[12]
'Envirotecture', NSW.	Passive Design (See pg. 10) Biophilic design (See pg. 16)

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[11] 'Using, conserving and enhancing the community's resources so that ecological processes, on which life depends, are maintained, and the total quality of life, now and in the future, can be increased' (Department of the Environment and Energy n.d.).

[12] 'A design philosophy that seeks to maximize the quality of the built environment, while minimizing or eliminating negative impact to the natural environment' (McLennan 2004, p. 4).

DISCUSSION AND CONCLUSION

The aim of this study was to evaluate the uptake of Biomimicry towards more sustainable cities. This was completed by fulfilling a number of objectives, first of which was to explore the benefits of biomimicry in architecture and building design. This objective was primarily achieved by developing a framework for evaluating the benefits of selected biomimetic sites and applying the framework to four existing biomimetic sites at a range of scales, in order to fully understand the benefits and limitations of Biomimetic Architecture compared with traditional architecture The results yielded many important findings in support of the aim and objectives of the study.

The Assessment Framework

Firstly, the results of the assessment framework clearly established and demonstrated the benefits of Biomimetic Architecture over traditional architecture. As climate change worsens, biomimicry is a viable alternative to the traditional practices of the building industry. For this reason, this study was important, as it directly addresses the substantial negative environmental impacts, namely in the form of Carbon dioxide emissions, caused by the building sector. These impacts will only worsen due to an increasing global population and influx of people into urban areas. Biomimetic Architecture provides a method for reducing the energy and water used and waste produced by buildings and cities, leading to major improvements in resource efficiency, energy efficiency and occupant health and wellbeing. These improvements will enable the development of more sustainable cities.

Four case studies were chosen from the literature that purported to be ideal biomimetic buildings or sites, Council House Two (CH2) Melbourne, Australia, The Eastgate Centre, Harare, Zimbabwe, Kalundborg Eco-industrial Park, Kalundborg, Denmark and Lavasa Hill Town, Maharashtra, India. An assessment framework was applied to each case study to assess this claim. This Framework is useful for professionals/businesses wishing to build biomimetic buildings, as it will allow them to assess the degree to which biomimicry has been successfully integrated into its design. The four case studies examined, clearly highlighted the potential and pitfalls of Biomimetic Architecture and how biomimicry can lead to a resource and energy efficient, sustainable built world.

The design of the framework was a success in that it enabled a thorough analysis of all biomimetic features of each case study. The framework separated the biomimetic features of each site into discreet, easily understandable units, allowing for comparison between each case study. The results of the assessment framework support the literature, demonstrating the advantages of biomimetic architecture over traditional architecture. Incorporating circular economies, sustainable technologies and biophilic design all serve to enhance the efficiency and sustainability of the built environment.

When comparing the four case studies, Council House Two (CH2) clearly incorporated biomimetic design the most successfully and to the greatest extent when evaluated by the assessment framework. This is perhaps because it is the most recently built of all the case studies but more likely it is because of the clear vision of the project. Biomimicry was kept at the forefront throughout the conception and design of CH2. This is a key lesson for future biomimetic architects as the translation of biology into the design process can be troublesome as discussed in the literature review.

CH2's investment in sustainability features yielded significant improvements in employee productivity and outstanding energy savings. CH2 was the only case study proven to improve the psychological health and well being of its occupants. Webb (2012, p. 5) writes 'through projects like CH2, a new 'living architecture' is slowly emerging that expresses climate and culture and aims at creating environments that integrate people and buildings with the natural world.' CH2 can be defined as a 'living building', functioning like an organism interacting with its environment. CH2 is a successful biomimetic building because it took a 'ground up' design approach, with recycled products, energy saving and sustainable products used throughout (C40 2007).

CH2 performs best in the 'Level of Self-Sufficiency' framework element achieving outstanding efficiencies in many areas including water consumption, energy generation and waste management. Although CH2 was overall very effective in this framework element, it only possesses one circular economy in the form of the water mining plant. Although an additional $11m was spent on CH2's sustainability features, this saw substantial energy savings and financial pay back was between five and seven years (Torgal *et al* 2015). Notably, CH2 performed better than its predecessor, CH1, a conventional building, proving a biomimetic building can be more efficient and sustainable than a traditional building.

CH2 balances well, the integration of technology with presence of natural surroundings and enhances the psychological health and well being of its occupants by integrating a number of biophilic qualities including its abundant use of indoor plants and green spaces, providing an optimum working environment. Staff productivity increases were seen as a result of these features. CH2 should inspire future architects to pursue biomimicry as a central design concept for these reasons.

CH2 demonstrates the importance of understanding the relationship between the natural world and the built environment and investing in sustainability. The conscious effort of CH2’s designers to integrate the natural world into the daily lives of its occupants via Biophilic Design, e.g. natural lighting, enabled a more productive workforce and lead to financial and energy savings.

Although Eastgate was a pioneering biomimetic design at the time of its construction, when comparing Eastgate with the other three case studies, it’s clear that it possesses the least amount of biomimetic properties, is the most simplistic in its design and is the least successful biomimetic building when evaluated by the framework. This was a somewhat unanticipated result as although Eastgate’s design was based on an oversimplification of termite mound functioning, it is still revered and heavily cited in the literature (e.g. Royall 2010; Turner and Soar 2008; Vierra 2016). It was expected that Eastgate would perform well overall when assessed by the framework.

In the ‘Resource Efficiency’ element its only sustainable technology and circular economy was its passive ventilation system, however, it does contain a number of biophilic qualities. Despite its simplicity when interpreted by the framework, using only fans and innovative design, Eastgate achieves the same amount of cooling as a conventional industrial air conditioning system, involving considerable electricity consumption and equipment. Eastgate’s pioneering design has achieved substantial energy and financial savings.

There was just one, yet significant criticism found against Eastgate. Turner and Soar (2008) argue Eastgate is modelled on a flawed interpretation of how termite mounds function and ‘fails’ theoretically. The authors contend the termite mound functions in a more sophisticated way than Eastgate. My analysis of Eastgate’s design supported this finding too. This relates to the literature as one of the main barriers found to the uptake of biomimicry was a generalisation of complex biological functions that miss the significance of underlying principles (Buck 2015). In this respect, Eastgate represents a major lesson for future biomimetic building design, demonstrating the importance of fully understanding the biological design being emulated.

Eastgate's incorporation of biophilic design is undervalued by the literature as the majority of the literature concerning Eastgate focussed on its flawed design, however, the results of this study show that it can also serve as a model for biophilic design. According to Kellert (2008), Eastgate incorporates four different biophilic qualities, e.g. fountains and indoor plants and is worthy of further analysis. As demonstrated by Paevere and Brown's (2008) study of CH2's biophilic design, Biophilia can lead to improvements in occupant psychological health and well-being and productivity.

Despite being modelled on an oversimplification of termite mound functioning, Eastgate still achieved its objectives, namely passive ventilation and functions efficiently and effectively, serving as a model for future biomimetic buildings.

Both CH2 and Eastgate share the same core biomimetic concept; the emulation of the termite mound's self-cooling system, allowing for direct comparison. They both demonstrate how just one behaviour of a single organism can inspire the design of two entirely different buildings. This highlights the potential significance of biomimicry when applied to architecture.

Valentine (2016, p. 66) describes Kalundborg as 'one of the few examples in the world of an organically-evolving network of strategically unassociated economic entities that continue to collaborate in order to improve utilization of resources and share knowledge.' The collaboration between the partners provided continuous, valuable high-volume by-products (Marinova, Annandale & Phillimore 2008). As Kalundborg is an Industrial Ecosystem and not a single building like CH2 and Eastgate, it is difficult to directly compare the Park with these other case studies or even Lavasa which although on a similar scale, is comprised of discrete buildings.

Kalundborg demonstrates best practice as it shows how sustainability can be assimilated into economic *and* environmental systems. The Kalundborg EIP shows that natural systems can function as models for human systems in terms of efficient use of energy, resources and waste. Kalundborg represents a model for future Eco-Industrial Parks and for biomimicry at the industrial scale, amounting to tons of recycled waste resources and reduced waste emissions annually. This will be critical in the future as the world population continues to rise, the demand for energy, water and materials will only increase along with the output of waste. EIPs such as Kalundborg will provide important models of sustainability for industry.

Although Kalundborg succeeded when assessed by the 'Resource Efficiency' element, its success relative to the 'Presence of Biophilic Design' element was difficult to assess due to a lack of available data, especially 'Psychological Health and Well Being'.

When applied to Kalundborg, the 'Presence of Circular Economies' framework element identified significant economic and environmental benefits whereby participating companies collaborated to enable 20 different by-product exchanges including gas, steam and water in a closed loop cycle. This collaboration lead to significant financial and resource savings.

In support of the literature, Kalundborg demonstrates the importance and significance of circular economies (e.g. Mendoza *et al* 2017; Saidani *et al* 2017). The presence of circular economies also heavily influenced the success of CH2 and Lavasa, as both the case studies also incorporated a number of circular economies. The ability for cities to challenge the make-use-waste model will become integral if they are to remain sustainable as more people migrate from rural to urban areas.

Future research should include a survey of Kalundborg EIP employees in order to determine whether the presence of biophilic qualities has any effect on their psychological health and well being and whether a balance between nature and technology was considered in the design of the various partners located within Kalundborg. It is acknowledged that perhaps this could have been completed as part of my study and is a limitation of this thesis.

Coupled with CH2, Lavasa has the most number of sustainable, self-sufficient technologies. Lavasa also has a number of circular economies and biophilic design elements and has been able to successfully integrate biomimetic concepts even at a vast scale. Like CH2, biomimicry was central to the design of Lavasa, which has undoubtedly contributed to its success thus far.

Lavasa is just one of over a thousand planned global cities (Miklian and Hoelscher 2014). In relation to the overall aim of the study, Lavasa shows that perhaps a city sized biomimetic development is achievable and that if future city developers understand and incorporate biomimicry into design, then a more sustainable city can be developed. Importantly, Lavasa was the first settlement to use standards based on biomimicry and is one of few current urban-scale biomimetic sites. Lavasa demonstrates that new cities can address increases in urban populations, while remaining regenerative and sustainable. Sites like Lavasa will become more important as countries attempt to cope with increasing urban populations while remaining sustainable. Cities will need to produce more than they consume and not be reliant on conventional energy generation, i.e. fossil fuels.

Lavasa utilised just two species in its design, the Indian Harvester Ant and Banyan Fig Tree for its most significant and effective sustainable designs. Like Eastgate's use of a single organism, the termite, this again shows how one or two species can inspire the design of entire buildings or cities.

Lavasa also highlights Governmental issues that may be encountered by proponents of biomimicry. The developers of Lavasa, HCC, received some resistance from the Maharashtra State Government but evidently were able to continue building. Similarly, as Loosemore (2017) identified, the inertia of thought, sustaining the traditional, tried and tested designs and technologies of the building industry will need to be overcome in order for the widespread uptake of biomimicry to occur.

Like CH2, Lavasa demonstrates the importance of understanding the relationship between the natural world and the built environment. Its numerous biophilic elements, namely proximity to water and abundant vegetation, will ensure residents have a constant connection with nature.

Although CH2 proved to be the most successful when assessed by the framework, Lavasa's engagement with and understanding of, the local environment, was best out of the four case studies analysed. From its inception, HOK designers deduced the most important functions of the local environment and designed Lavasa's sustainable technologies and circular economies based on an understanding of the native ecosystem. A common theme in the literature and supported by the results of this study is that 'ecomimetics' will be pivotal in biomimicry creating sustainable cities (Garcia-Holguera *et al* 2013; Ning 2015; Pan and Ning 2014; Woo 2011). Despite their conceptual differences, Kalundborg and Lavasa demonstrate the emulation of an ecosystem, on a scale applicable to future cities.

Although both Lavasa and Kalundborg implement ecomimetics, direct comparison is difficult, as Kalundborg is an ‘Industrial Ecosystem’ comprised of commercial partners and Lavasa is a residential development. Further, it’s clear that biophilic design was an integral part of Lavasa’s conception and at Kalundborg there was no literature relating to this area.

The results of the assessment framework have implications for other areas of study. For example, the sustainability and resource efficiencies demonstrated by the case studies could serve as further verification to other industries that biomimicry is worthy of costly research and development. As the benefits of biomimetic architecture are further demonstrated via sites such as those discussed, its merit as a genuine design tool will be strengthened.

Desktop Survey of Biomimetic Courses and Degrees

An investigation into the availability of professional development courses and degrees for biomimetic design was completed via a desktop survey. The results of this survey supported the literature review, finding a definitive lack of courses and degrees available for design professionals (e.g. Dahl 2013; El Zeiny 2012; Gruber 2011; Helms, Vattam & Goel 2009).

The survey found just six courses and two biomimetic architecture degrees globally. Two of the courses are available in the USA and one in Australia, Canada, Mexico and South Africa respectively. Both degrees are only available in the USA. These findings were not overall surprising, however, it was not expected that the number of courses and degrees would be so low. It was thought that in an era of increasing acceptance of alternative, green/sustainable concepts and practices that biomimicry would be more at the fore or demonstrated in a greater number of courses and degrees.

Further restricting the uptake of biomimicry, the only two biomimicry degrees and two of the six biomimicry courses, are only available to post graduate students. Evidently, for biomimetic architecture to become more accepted and widespread, there must be more undergraduate and secondary courses and degrees available.

These findings were central to completing the aim and objectives of this study. The amount of professional courses and degrees must increase and they must educate professionals early on in their careers, so the ways of the traditional building industry and the ‘business as usual’ approach can be supplemented and challenged with the benefits of Biomimetic Architecture.

While researching biomimicry courses and degrees, only one University prize/scholarship related to biomimicry was found globally, The University of New South Wales’, School of Civil and Environmental Engineering ‘Acacia Program National Sustainability Competition’ (UNSW n.d.). The presence of only one University prize/scholarship related to biomimicry further indicates a lack of focus on biomimicry by educational institutions.

The findings of the desktop survey help address knowledge gaps in the literature. For example, there has been no research conducted on evaluating biomimicry teaching and training methods. Although the desktop study does not evaluate the biomimetic courses and degrees identified, it helps inform the literature by listing the location and basic information of all current biomimicry courses and degrees globally. This information had not been previously exposed or described in the literature.

Desktop Survey of Design Firms

The desktop survey of Design and Consulting Firms identified just 11 green design firms incorporating biomimicry into their design approach globally. Evidently, this represents a significant barrier to the uptake of biomimicry, as if architects can not access information related to biomimetic design, then they can not incorporate it into their design approach. Like the desktop survey of biomimetic courses and degrees, the results help inform the literature by listing the location and basic information of all current design and consulting firms practicing biomimetic architecture globally. This information had also not been previously exposed or described in the literature.

The results of the survey found that seven out of the 11 firms identified, practice biomimicry *generally*, meaning they do not incorporate specific biomimetic design concepts such as Regenerative Design or Biophilic Design. Like the courses and degrees identified, the results indicated little geographic diversity of firms. Six firms are located in the USA, three in Australia and two in Europe. Clearly, this is a very small number of firms globally. These are not particularly surprising results as the USA is the country most active in the field of biomimicry and the field's most influential proponent, Janine Benyus, operates a number of highly successful biomimicry organisations in the USA as discussed in the literature review.

The two desktop surveys have a clear and direct relationship and support the literature. For biomimetic architecture to be accepted and widely recognised as a viable alternative to conventional architecture, a greater number of design firms must embrace it. For this to occur, design professionals must be exposed to or made aware of, a greater number of biomimicry courses and degrees. Importantly, there are limited examples of true biomimetic architectural sites because of this lack of education and awareness.

This thesis set out to evaluate the uptake of Biomimicry towards more sustainable cities. The study yielded a number of important implications. Firstly, the assessment of the case studies demonstrated that biomimicry can achieve fundamental improvements in resource efficiency and enhance the quality of life of the building's occupants. Secondly, biomimetic architecture represents a widely unacknowledged solution to reduce the vast environmental impacts of cities and climate change. Overall, the findings of this thesis serve as further testament to the literature in support of biomimicry as a valuable design tool.

The literature on Biomimetic Architecture promotes this field as a fundamental paradigm shift in our relationship with nature and the built world. This is significant because as the world population increases, cities will be placed under further resource stresses, exacerbating the effects of climate change, namely via an increase in Carbon dioxide emissions. The sustainability of the built world has never been more important.

The significance and importance of this research was principally the design and application of a novel framework for assessing the success of biomimetic sites, as no such framework is currently present in the literature. Also, no other study has analysed and compared biomimetic case studies in such detail. The development and application of the framework informed the key findings of the thesis, allowing for the identification of flaws in supposed prototypical biomimetic sites, as well as highlighting the benefits of biomimetic architecture, namely improvements in resource and energy efficiency.

Further, no other literature was found that lists and interprets the full range of biomimetic courses and degrees available globally to professionals or the number of design firms incorporating biomimicry into their design ethos.

There are a number of areas that require further research in order to advance the literature on biomimetic architecture. Firstly, research is required into the attitudes of architects and design firms towards biomimetic architecture, ideally in the form of a survey or personal interviews. This will allow for a greater understanding as to why biomimicry is not being adopted more commonly. This represented another limitation of this thesis as it was beyond the scope and means of the study to interview academics and professionals in the field of biomimicry and architecture. Had I been able to do so, potentially more meaningful results could have been produced.

Secondly, other supposed biomimetic buildings and sites should be evaluated using a framework such as that developed during this study, so that our understanding of successful biomimetic architecture can be improved. The assessment framework should also be refined and improved and other frameworks should be developed in order to further assess biomimetic sites and ensure best practice.

Biomimicry has been heralded as a powerful design tool for increasing the sustainability of the built world by mitigating the vast proportion of materials, waste and energy use attributed to buildings and cities, which exacerbate the effects of climate change. However, the widespread uptake and acceptance of biomimicry is thwarted by a number of barriers and knowledge gaps. The results of my study support this view of biomimicry, showing it can lead to more sustainable buildings and cities. My results provide an important foundation for evaluating the sustainability of biomimetic sites and further support the literature showing that education is the key to biomimetic architecture truly challenging conventional views and attitudes towards architecture.

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