Biomimicry as A Design Guide Towards Sustainable Built Environments

Omar Borham[1], Moemen Afify[2] and Sherine Wahba[3]

[1]Department of Architecture, Faculty of Engineering, Cairo University, Cairo, Egypt omar_borham@cu.edu.eg;

[2]Department of Architecture, Faculty of Engineering, Cairo University;

[3]Department of Architecture, Faculty of Engineering, Cairo University.

Abstract: Built environments have great negative impacts on the environment, which further increase as the urban population grows (UNFPA 2007). Efforts have been made in the past few decades to shift towards sustainable urban development, such as aiming for zero environmental impact or 'neutral' buildings in terms of energy, water, carbon or waste. Although these targets are valuable, they are not enough. Research suggests that even if all GHG emissions were stopped at once, the slow Earth's response would mean that the effects caused by past emissions would still be experienced (IPCC, 2007). This implies that the built environment needs to have net positive environmental benefits to remediate the environmental damage rather than just sustaining the current status. Architects, urban designers and planners should explore novel ideas that could lead to such a shift in the way we design our cities.

This paper investigates Biomimicry, where nature's organisms, processes or ecosystems are mimicked in design, and its potential to present a new approach for designing the built environments to be truly sustainable or regenerative. It is important to note that biomimicry is not about the mere copying of nature's shapes, but rather the ideas, functions and principles that lie behind them. The question put forward is: how can mimicking nature be useful in finding a new methodology to design sustainable built environments?

A brief introduction to the definition, levels and principles of biomimicry is followed by the analysis and critique of international biomimetic case studies with the aim of deducing a design framework that could form the basis of a new methodology to design sustainable built environments. It is argued that the incorporation of biomimetic ideas in the design of our cities would lead to creating built environments that are positively integrated into nature rather than dominating over it.

Keywords: Biomimicry, Sustainability, Built Environment, Resource Efficiency.

Introduction

Throughout history, Man has looked to nature as a source of inspiration to find solutions to the challenges he faces. It was not until the modern age and the industrial revolution that the mindset of mankind was deviated away to compete with nature rather than to live in harmony with it. Advances in technologies, together with the discovery of fossil fuels and the invention of the steam engine made way for concepts such as mass production and 'heat, beat and treat'. These concepts not only ignored the fact that resources on Earth are limited, but also, were harming the environment to the extent that threatens our own existence.

Ozone depletion, global warming and rising sea levels were all alarms that an action needs to be taken soon before the damage is beyond repair. Concepts of sustainability began to emerge to reduce the negative impacts on the environment. However, it still lacks the desired impact. One reason is that these concepts have their roots back from the industrial age. Research suggests that these actions are not enough and that there needs to be a shift in the way we think to achieve true sustainability or regenerative sustainability, which does not only try to reduce impact, but instead aims to repair and have a net positive impact on the environment.

This Paper investigates Biomimicry as a new methodology, a new way of thinking to find solutions to achieve sustainability in built environments. It presents an alternative to the current model once described by Le Corbusier, where he said that "Buildings are machines to live in". This paper introduces nature as the design model to look up to if we are to live in harmony with our natural surrounding instead of dominating it.

Biomimicry Definitions

Biomimicry is from the Greek words 'bios', meaning 'life', and 'mimesis', meaning to 'imitate'. Many researchers defined Biomimicry. The first of whom is Benyus, a biologist and a writer who founded the biomimicry movement, she defines it as "a new discipline that studies nature's best ideas and then imitates these designs and processes to solve human problems" (Benyus, 1997).

While that definition links biomimicry to design in general, Guber defined Biomimicry as "the study of overlapping fields of biology and architecture that show innovative potential for architectural problems" (Bar-Cohen Y., 2005).

Pederson Zari notes that there is no clear definition of biomimicry that architects could apply in designing their projects and therefore it is best to focus on analysing the different approaches to Biomimicry to come out with best methods to apply Biomimicry for maximum benefit (Zari, 2007).

The application of biomimicry to a design problem is the answer to the question: 'How would nature solve this design problem?'

Biomimicry Levels

When applying Biomimicry to tackle a design problem, it is vital to decide what level of biomimicry is used; that is what aspect biology is to be mimicked. According to Benyus these categories / levels are **form, process,** and **ecosystem** (Steadman 2008). However, Zari introduces a different classification. After analysing existing biomimetic examples, Zari broke down biomimicry into three levels; **organism, behaviour,** and **ecosystem** (Webb, 2005). Zari introduces a framework which suggests five further dimensions within each of these levels (Zari, 2007). It is noticed that both researchers agreed on the ecosystem level, while they differed over the other two levels. This paper adopts Zari's classification seen as more applicable to architectural fields. A brief description of each level is given below:

Organism level

This level includes mimicking the whole or part of a specific living organism such as an animal or a plant. An example is the Sto's Lotusan Paint which was designed after the nanostructure properties of the Lotus leaves. The hydrophobic paint is self-cleaning as droplets of water run over its surface removing dirt particles in a similar way to the self-cleaning lotus leaves.

Behaviour level

This level includes mimicking the behaviour of an organism or how it relates to its surroundings. An example is the East-gate building which mimics the method termites use to ventilate their nests. This example is analysed later in further detail.

Ecosystem level

This is considered the most difficult level of mimicry, since it involves mimicry of a whole ecosystem and the complex relationships between its components and the aspects that enable an ecosystem to function efficiently (Aziz & El sherif, 2015). An example is the selfwatering Pikaplant product, where a plant specimen is sealed in a humid jar biotope. The plant never needs watering, since it recycles and reuses the water in the jar in a similar way to the water cycle in nature.

Kibert (2006) suggests that the complexity in understanding ecosystems makes it impossible for designers to engage modelling ecosystems in their work, since, according to Kibert, human designs are non-complex. However, Zari (2010) argues otherwise. Zari defends that the ever increasing knowledge about nature would enable us to mimic the complex relationships in ecosystems to increase the sustainability of our Built Environments (Pedersen Zari, 2010).

There could be overlaps between the different levels of biomimicry as would be evident in one of the case studies handled in this paper. For instance, a number of systems that relate to each other like an ecosystem is an ecosystem level biomimicry. At the same time the components of those systems may be modelled after organisms or their behaviour in a similar way that a forest ecosystem is home to many interrelated organisms (Zari, 2006).

Nature's Design Principles

The previous section explains how designers could relate to nature, but do not necessarily illustrate what nature is. In her book, Benyus has identified nine statements to be the principles, laws or strategies that nature follows in its designs (Benyus, 1997). The biomimicry institute refined those laws to be ten design principles that are evident in nature's design (Biomimicry Institute, 2015). It is argued that the application of these principles in human designs would make these designs biomimetic and as much sustainable as nature's designs are. That is, they behave in a similar way to nature's designs. These ten principles are defined as follows:

Principle 1: Nature uses only the energy it needs and relies on freely available energy
Principle 2: Nature recycles all materials (finds use for all waste)
Principle 3: Nature is resilient to disturbances (the ability to recover after sudden changes)
Principle 4: Nature optimizes rather than maximizes (no excessive use of material or energy)
Principle 5: Nature rewards cooperation (between organisms and / or their context)
Principle 6: Nature runs on information (to be able to respond to their environment)
Principle 7: Nature uses chemistry and materials that are safe for living beings
Principle 8: Nature builds using abundant resources, incorporating rare resources only sparingly
Principle 9: Nature is locally attuned and responsive
Principle 10: Nature uses shape to determine functionality (form follows function)

So, if we want to look to nature as a design model, we probably need to fulfil as much of these principles in our designs as possible. Fulfilling these principles would result in design that function in a similar way as nature and thus would be as sustainable. The case studies in the following section will be analysed in comparison to these ten principles.

Application of Biomimicry in the Built Environment

This section analyses different international case studies with the aim to identify which level of biomimicry is the most suitable for achieving sustainable built environments that function like nature's designs. The design challenge, the natural model used, the biomimicry level and nature's design principles achieved in each case study are identified. The degree of fulfilment of the ten design principles identified earlier is regarded as an indication to how much a design is able to mimic nature to the best degree possible and therefore is as sustainable.

Case Study 1: East-Gate Center, Harare, Zimbabwe

A frequently cited example of behavioural level biomimicry in architecture is East-Gate Center by Mick Pearce (Shown in Figure 1).

Figure 1: Exterior facade of East-Gate Center, Zimbabwe. Source: archnet.org

Mimicry level : Behavioural level

Challenge : Passive Ventilation of a large structure to achieve thermal comfort

Natural model : Termite mound

Analogy between termite mound and East-Gate building:

The architect examined the nest's natural ventilation system to come up passive techniques to regulate indoor temperatures and passively ventilate the building to maintain the interior environment within comfort levels (Kowaltowski et al. 2010).

The termite mounds protect the nest and royal chambers and the combs containing fungus which is their main source of food. Although the outside temperatures fluctuate widely between 2 and 40 degrees Celsius, the termites manage to maintain a thermally stable environment kept within a range between 30 and 32 degrees Celsius, which is perfect for this fungus growth (Klein 2009).

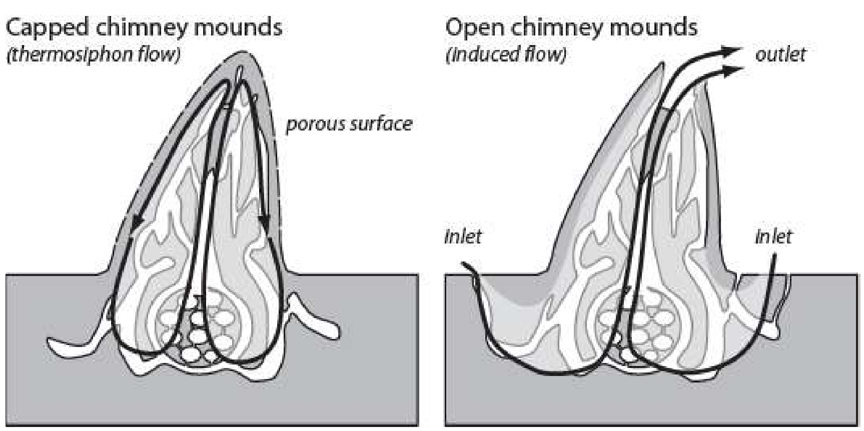

Figure 2: Termite mound models with capped and open chimneys. Source: www.projects.science.uu.nl

Termites build a network of perfectly located vents that induce air flow through convection currents. Air flows through enclosed underground vents with muddy walls which cause them to cool down. As shown in Figure 2, cooled air enters the mound at the bottom of the mound. Then air is channelled as it warms to the peak of the mound where exits through chimneys. Surprisingly, termites open or plug these vents to maintain the required conditions. Termites constantly build new vents and plug old inefficient vents.

This behaviour inspired the architect’s design. As shown in Figure 3, the design consists of exterior buildings with a glass center connecting them. First, similar to mud, he used concrete, which has a high thermal mass and is available locally. The external air is channelled through the building mass where it is passively cooled or warmed depending on the temperature of the building mass. The conditioned air passes through the building floors, from where it is pulled by chimneys (seen in Figure 1) using stack effect (Maglic 2014).

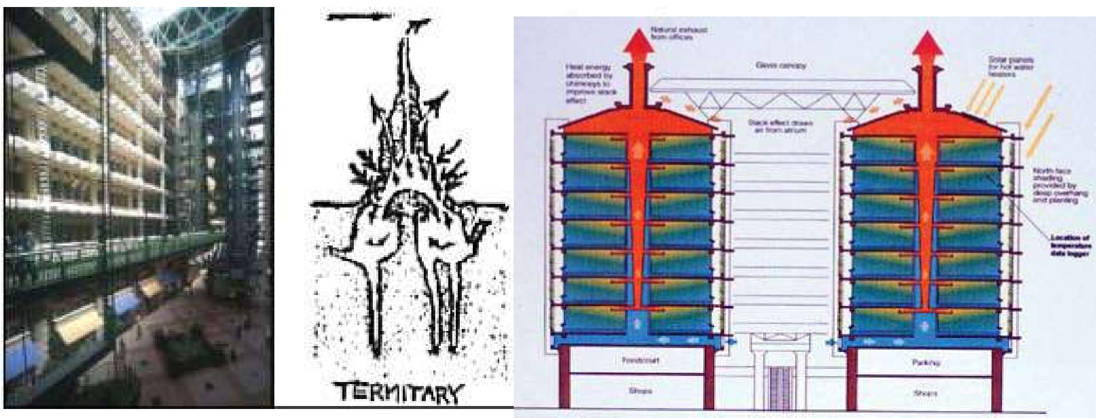

Figure 3: a. East-gate building, b. Ant nest, c. Ventilation System. Source: www.archnet.org/

The result was a reduction in energy consumption of up to 52% in comparison with conventional buildings of the same size in Harare, Zimbabwe (Smith, 1997; Baird, 2001).

However, there are limitations to the design. While the building is successful in terms of thermal stability, thorough analysis of the termite mounds explains that, to regulate temperatures there are complex interactions with surrounding environments than was thought at the time of the design. This suggests that a more in-depth analogy could lead to higher benefits in terms of energy consumption (and thus GHG emissions) and help in creating ‘living’ buildings that mimic the termites mound with a deeper understanding. (Turner and Soar, 2008)

The following Table 1, represents an analysis to this case study and how much it fulfills the ten design principles explained in the previous section. The degree of fulfillment of these principles is considered a measure of how much a design is behaving in a similar way to nature and therefore should be as sustainable. A principle is either fulfilled (Y), Not fulfilled (N) or Partially fulfilled (P).

Table 1. Nature's Design Principles Fulfilment-Case study 1, Source: Author

Nature's Design Principles	Fulfilled (Y/N/P)	Notes
Principle 1	P	50% reduction in energy consumption
Principle 2	N	Not made of recycled materials
Principle 3	N	Not resilient to disturbances
Principle 4	P	Only ventilation was tackled using passive methods
Principle 5	N	
Principle 6	N	
Principle 7	N	Requires deeper analysis of used materials
Principle 8	Y	Use of locally available materials eg. Concrete
Principle 9	Y	Adaptive ventilation system inspired by local organism
Principle 10	N	Requires deeper analysis

A few principles have been fulfilled or partially fulfilled which indicates that there is still room for improvement in the design methodology to reach better results.

Case Study 2: Biomimetic Office Building, Zurich, Switzerland

Unlike East-gate building, which was classified as biomimetic only after completion, the Biomimetic Office building, shown in Figure 4 is the first building to be designed comprehensively with biomimicry in mind from the very first design steps. The architecture firm, Exploration Architecture, aimed to design a class leading environmental office building by incorporating several biomimetic features.

Figure 4: The Biomimetic Office, Zurich, Switzerland. Source: http://i.vimeocdn.com

Mimicry level : Organism and Behavioural levels

Challenge : Daylighting, structure, shading and material efficiency

Natural models : A number of models including spook fish, brittle star, stone plant, cuttlefish bone, birds' skull structure, termites, beetle wings, mimosa leaves

Analogy between natural models and the inspired design:

The building was designed to maximize the environmental performance, while making use of local materials and climate. Daylighting was the driving force that shaped the building form in such a way that daylight could reach all floor areas. The design team looked to several examples in nature for inspiration on how to enhance the use of daylight:

- The Spook fish which lives in water with low level of daylight use a mirror structure in its eyes which focuses low-level bioluminescence onto its retina as shown in Figure 5. This inspired the design of a reflective structure in the middle of the building's atrium to reflect light back into the darkest parts of the building's floor slabs as in Figure 7.

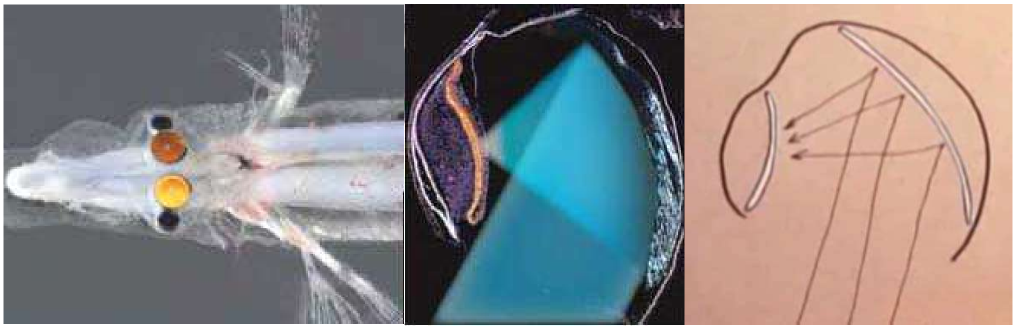

Figure 5: Spook fish eye structure. Source: http://i.vimeocdn.com

- The brittle-star is a star fish living 500m below the ocean, where light levels are minimum. It has developed optically perfect lenses that collect and focus light onto its receptors for early prediction of predators as seen in Figure 6. This has inspired the design of a canopy covering the atrium that directs light into the atrium and onto the reflective mirrors.

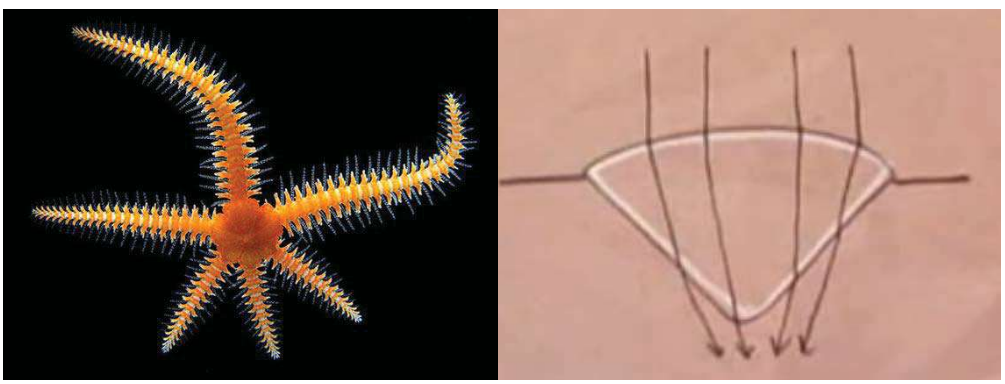

Figure 6: Brittle Star fish and the structure of its light receptors. Source: http://i.vimeocdn.com

From the mechanism of the spook fish eye and the brittle star cell structure, Pawlyn designed a canopy that focuses light into the building and a reflective surface in the courtyard to reflect day light to the areas which otherwise be in shade.

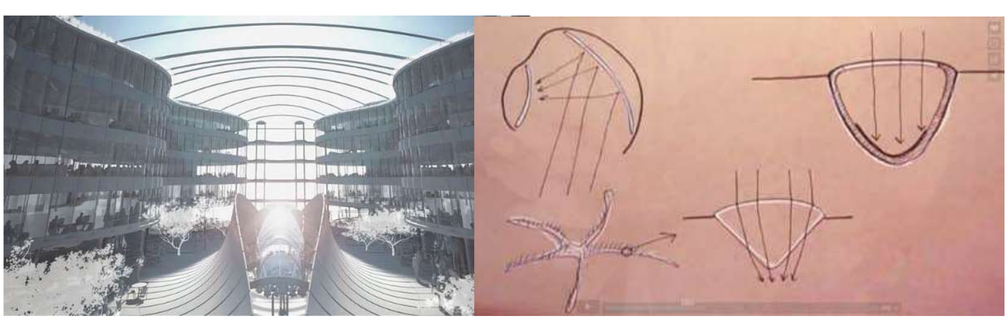

Figure 7: Designed atrium and architect's concept sketches. Source: http://i.vimeocdn.com

Another important aspect of the design is the building's structure system. The design team aimed at reducing the use of materials without compromising structural strength. Again, they turned to nature for design models:

- Birds skulls and the cuttlefish bone, both efficiently place material to the parts where they only needed as illustrated in Figure 8. Therefore, material is reduced, while creating a very rigid structure with very thin walls at the top and the bottom.

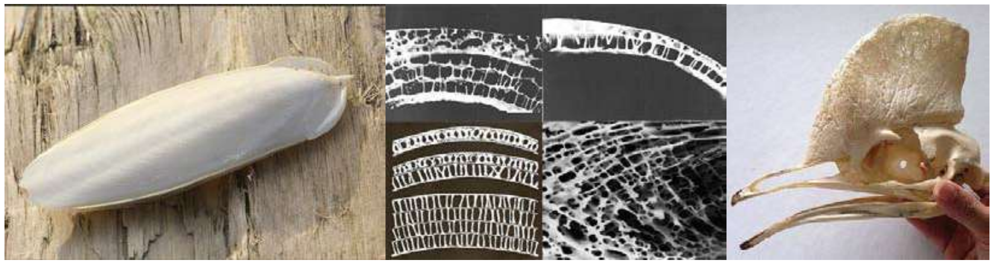

Figure 8: Cuttlefish bone and birds' skull structure. Source: biomimetic-architecture.com

After a structure loads analysis, the floor slabs and columns were consequently designed in such a manner that concrete is allocated only where there are forces and excluded where they are not useful as shown in Figure 9. This allowed certain structure elements to be hollow where they can accommodate wiring or ventilation elements.

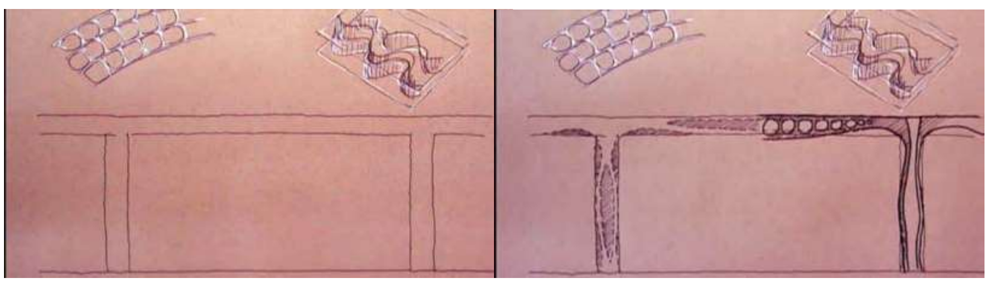

Figure 9: Architect's concept sketches showing conventional vs design structure elements. Source: http://i.vimeocdn.com

Other natural models that were used include termites for passive cooling, beetle wings and mimosa leaves for a shading system that allows only adequate amount of light. When completed, it is to be one of the world's leading low energy office buildings.

However, there are limitations to the design. While the design addressed the issues of resource efficiency, structure, daylighting and energy efficiency; it lacked the higher level of biomimicry (ecosystem level). Of course, this is difficult to apply on a building level and would require a larger scale to be applicable. However, on the building scale, there could have been an understanding of how this building would interact with the surrounding context whether other buildings or local environment. This could have brought a deeper level of biomimicry opening the gates to maximum sustainability potential.

Table **2**. Nature's Design Principles Fulfilment- Case study 2, Source: Author

Nature's Design Principles	Fulfilled (Y/N/P)	Notes
Principle 1	Y	To be one of the world's lowest energy office buildings
Principle 2	N	Not made of recycled materials
Principle 3	N	Not resilient to disturbances
Principle 4	Y	Significant Reduction in construction and envelope materials
Principle 5	N	
Principle 6	Y	Adaptive shading system responds to lighting level information
Principle 7	P	Requires deeper analysis of used materials
Principle 8	Y	Use of locally available materials
Principle 9	Y	Responds to local climate
Principle 10	Y	Form was driven by daylighting constraints

In comparison with table 1, it is evident from Table 2 that when both levels of biomimicry (organism and behavioral) were included in the design process in its initial stages more design principles of nature were covered. This design has the potential to be more sustainable than the previous case study.

However, some principles require application of biomimicry on a larger scale to be applicable. For instance, Principle 5, *nature rewards cooperation,* need to be applied on interrelations between different buildings that are the building blocks of the larger scale urban context. This shall be examined in the next case study.

Case Study 3: District Rieselfeld, Freiburg, Germany

The Previous two examples were architectural. Even though, the second case study included biomimicry since the initial design stages, it still experiences limitations in terms of sustainability. This case study explores ecosystem level biomimicry and how it could be more useful to design on an urban level rather than designing individual buildings.

District Rieselfeld in Freiburg, Germany (Figure 10) was planned in 1992 with aim to contain mixed-use high-density buildings (Figure 11) with courtyards in between along with recycling points and open play areas. It features cycling paths and non-vehicle friendly streets. On-site water management ensures collection and reuse of storm water (Spiegelhalter & Arch 2010).

Figure 10: Aerial view of district Rieselfeld. Source: Google Earth

Mimicry level : Ecosystem level
Challenge : A district that is solar powered and recycles water and waste
Natural models : Trees, water cycle and nutrients cycle (ecosystem level models)
Analogy between natural models and the inspired design:

Water cycle in nature inspired the storm water management techniques in the district such as onsite storm water collection in underground tanks in a similar way that water is infiltrated and stored in underground water tables.

Nature uses only the energy it needs and runs on freely available energy. This inspired planners to determine energy targets for the buildings in the district such that they could be covered by renewable energy sources. This would force building to apply building envelopes of increased efficiency. Subsidies are granted on the use of PV cells, passive and active solar thermal heating and cooling.

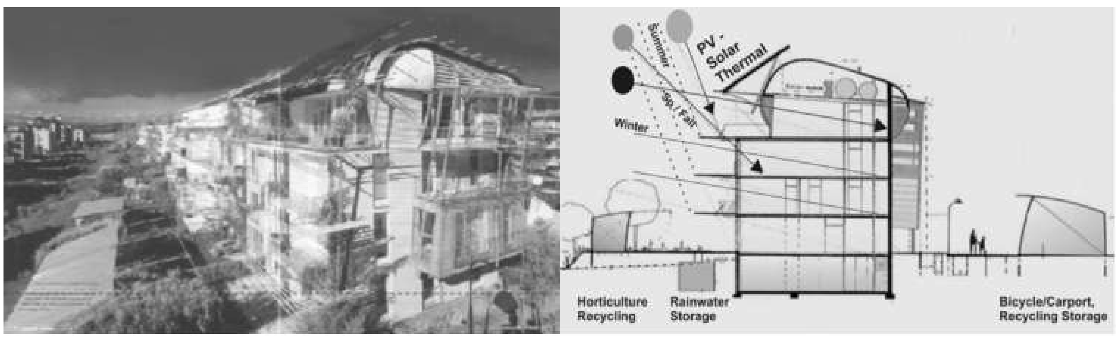

Figure 11: Solar-powered low-energy town-houses of Rieselfeld. Image: Thomas Spiegelhalter

Nutrients cycle inspired the reuse of waste produced from households and saw mills' waste dust to fuel the heat and power plant. Biogas is produced from landfills and is used to power the district-heating system. The biogas could be also used for public transport. Other design aspects to reduce the carbon foot print include traffic calmed streets where no vehicles are allowed, to encourage pedestrian and cycling movement.

This resulted in a balanced circular metabolism that uses renewable energy as the primary power source and recycles waste into an energy source.

Table 3: Nature's Design Principles Fulfilment- Case study 3, Source: Author

Nature's Design Principles	Fulfilled (Y/N/P)	Notes
Principle 1	Y	All town houses are solar powered + biogas district heating
Principle 2	Y	Recycles waste to productive energy source
Principle 3	N	Not tested
Principle 4	Y	No excessive use of energy or materials
Principle 5	Y	Beneficial relationships between neighbourhood elements
Principle 6	Y	Adaptive shading system responds to lighting level information
Principle 7	P	Requires deeper analysis of used materials
Principle 8	Y	Use of locally available materials
Principle 9	Y	Responds to local climate
Principle 10	Y	Form was designed to reduce heat gains/losses

In comparison with previous tables, it is clear from Table 3 that when a higher level of biomimicry (ecosystem biomimicry) was applied on the larger scale (urban scale rather than the architectural scale) almost all design principles of nature were covered. This design methodology has the most potential of all studied case studies to be more sustainable.

However, the district was designed before the biomimicry movement by Benyus and therefore was not designed with biomimicry on the design table from day 1. In the author's opinion that the incorporation of biomimicry (especially ecosystem level biomimicry) in urban design from the initial design stages would have the most potential to create cities that function in a similar way to nature and are therefore as sustainable.

Conclusion

Mankind need to rethink the way they build things in order to achieve a truly sustainable future. Novel ideas need to be explored and tested. The current building design model has failed to ensure a sustainable building trend. A new design model is needed to shift towards a sustainable future. Nature presents a very good potential, since it has sustained itself through billions of years and has developed time-tested strategies that secured its continuum till today.

Biomimicry, the science of imitating natural models presents a good potential when integrated into the design of the built environment. Through the analysis of the above case-studies it was shown that buildings that were designed with biomimicry in mind as a guide throughout the design process present a more promising example than those buildings that were classified as biomimetic after being built. Different levels of biomimicry prove to be more promising than others. Ecosystem level biomimicry gives a more holistic approach to design of built environments. If applied on an urban planning and design level it would give the opportunity of designing cities that behave like forests and that are sustainable.

The more principles the design of the built environment accomplishes, the more likely the design would behave as nature's designs. The genius of place and responsiveness to local environment is very important to set design goals in terms of energy, water and carbon budgets for a given design such that they behave as local ecosystems behave.

Further studies could test how could all levels of biomimicry be applied in a built environment from the largest scale of planning to the very specific detail or architectural element. Biomimicry application in that manner could have even higher potential than the case studies examined in this paper as Benyus suggests that "a full emulation of nature engages at least three levels of mimicry: form, process, and ecosystem".

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