Reinventing the (Water) Wheel

Contemporary design theory

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1 Introduction

Keywords— Design, Biomimetics, Ecomimetics, Graph Theoretic, Ecosystem Sustainability, Energy Systems Language, Reductionism, Holism, Environmental Accounting

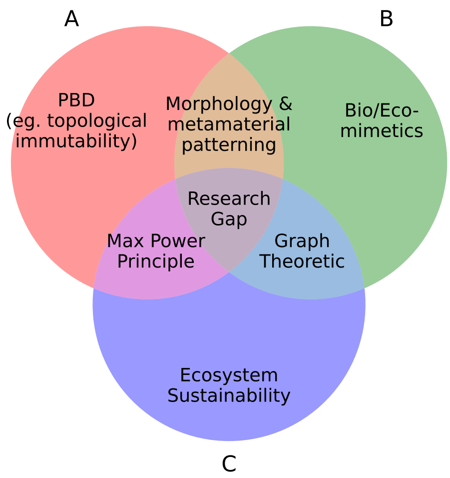


Figure 1: Venn chart of the interacting conceptual framework used in this thesis.

This chapter is Part A of the literature review. With reference to the conceptual framework given in the Introduction (reproduced in Fig. 1 for convenience), the present chapter is concerned with the 'Eco/Biomimetics' literature, the 'Ecosystem Sustainability' literature and the overlap between these domains through the methods of ecological Graph Theoretics. Part B of the literature review is concerned with the concept of 'Principle' as a basis of 'Principle Based Design' (PBD), and overlaps that PBD has with Ecosystem Sustainability and Eco/Biomimetics. Part B will focus on the *Cestibique Engine* (an ancient type of waterhweel) as a design case for demonstrating the concepts motivating PBD.

Part A of the literature review will begin here by looking briefly at the origins of Biomimetics in the works of Schmitt. It will then progress to consider the emergence of 'Ecomimetics' as an ecological enhancement of Biomimetics introduced in the literature to respond to the criticism that Biomimetics is too reductive. The review will consider how some scholars consider Ecological Engineering, Systems Ecology and Ecological Graphs as integral to Ecomimetics, and in particular the ecological scholarship of Howard T. Odum is identified as a key feature of Ecomimetic literature. The review will therefore consider how the ecological Graph Theoretics of Odum have been suggested as a way of addressing the critique of Biomimetics as reductive. The relationship of Ecosystem Sustainability theory to the Ecomimetics domain will then be introduced through the concepts of Environmental Accounting generated in Odum's scholarship. In so doing the review will also breifly introduce the recent work of Keena et al. who attempted to develop a novel Grasshopper add-on, 'Clark's Crow', which enables the kind of Ecological Accounting analysis of CAD designs envisioned by Odum. Part A will conclude by considering the gaps in the literature as presented here, particularly with reference to the concept of 'Principle'.

2 Bioimetics

> "MIMETIC 1. Having a particular aptitude for mimicry or imitation; habitually practising imitation or mime." OED (2002)

In the field of design, the concept of mimetics appears to be most closely associated with the ideas of Schmitt that reference to the term, "Biomimetics". For the purpose of this review, a brief background to Schmitt concept of Biomimetics will be given with emphasis on three different aspects of Schmitt's thinking; '*in the image of life*' (Sec. 2.2), '*information transform models*' (Sec. 2.3) and '*meeting the machine halfway*' (Sec. 2.4).

2.1 Background to biomimetics

According to Harkness (2002) the concept of Biomimetics originated in the scholarship of the American (Bio-electrical) Engineer Otto Herbert Schmitt (1913-1998 CE). Harkness says it is uncertain when Schmitt invented the word "Biomimetics", but Harkness locates the first textual appearance in the title of a presentation given Schmitt, *Some Interesting and Useful Biomimetic*

Transforms Schmitt (1969).[1] In fact, as early as 1963, Schmitt expressed a preference for the word ‘Biomimetics’ over the term ‘bionics’ in his publication, *Signals Assimilable by Living Organisms and by Machines* Schmitt (1963):[2]

> Let us consider what bionics has come to mean operationally and what it or some word like it (I prefer biomimetics) ought to mean in order to make good use of the technical skills of scientists specializing, or, more accurately, despecializing into this area of research.

Figure 2: (Schmitt, 1963, p. 90)

Authors like Bhushan suggest that the idea of Biomimetics probably arose earlier in Schmitt’s doctoral research (Bhushan, 2009, p. 1445). To this point, Harkness recounts that Schmitt’s graduate research was on the general topic of “biophysical and biochemical methods” which included the study of the molecular organisation of nerve fibre cells and tissues (Harkness, 2002, p.465). But Harkness also says that Schmitt moved his interest towards the idea of building bioelectric systems rather than just biophysical and biochemical ones, and that this may have been because of Schmitt’s background in electrical engineering; “. . . Otto developed a complex electronic device to mimic the generation and propagation of action potentials along nerve fibers” (Harkness, 2002, p.465). It is this aspect of Schmitt’s research which, I suggest, has been somewhat obscured in contemporary discussions of Biomimetics in relation to design, and will be discussed in Section 2.4 below. However, the next section will consider the more popular aspect of Biomimetics under the heading, “*in the image of life*”.

2.2 Schmitt’s ‘In the image of life’

In his 1963 paper Schmitt commented that he preferred the word ‘Biomimetics’ over the word ‘bionics’. This seems to have been partly because for Schmitt ‘Biomimetics’ was a broader term that not only included the ‘man-machine systems’ of bionics, but also ‘biological engineering’

[1] The paper was presented at the Third International Biophysics Congress in Boston. The full text of the document appears not to have been recorded in any textually verifiable sources.

[2] For **?** ‘Biomimetics’ is also synonymous with the words, ‘biomimesis’, ‘Biomimicry’, ‘biognosis’, and with the term ‘biologically inspired design’ (**?**, p. 471).

and 'cybernetics' (Schmitt, 1963, p. 90). Using 'Biomimetics' as a broader term he expressed what he thought might be the common interests of all these disciplines:

> Presumably our common interest is in examining biological phenomenology in the hope of gaining insight and inspiration for developing physical or composite bio-physical systems in the image of life.

Figure 3: (Schmitt, 1963, p. 90)

The idea of makings things that are, "in the image of life", seems to have captured the interests of the secondary literature, where "Biomimetics" has been defined as, "...to imitate (mimesis) life (bios) ..." (Kaufmann and Portmann, 2015, p.54). As Ayre writes, in practical terms Biomimetics is, "...essentially the practice of taking ideas and concepts from nature and implementing them in a field of technology such as engineering, design or computing" (Ayre, 2004, p. 4). In the examples of Biomimetic research given below, we will see that this idea of mimicking biological systems can be done at many different scales of design, from the molecular to the built environment.

2.3 Schmitt's information transform model

A further aspect of Schmitt's Biomimetics is the idea of an, "*information transform model*" (Schmitt, 1969, p. 297). The concept of an information transform model doesn't seem to be fully captured by the idea of mimicry given above, but appears to be what Schmitt also calls "emulation". Emulation is ,in Schmitt terms, the process of building special computers that embody the, "...particular 'bio' properties that we want to measure" (Schmitt, 1963, p. 92). Out of this approach, Schmitt suggested that he had developed a "holographic memory model" that might assist human pattern recognition. However, at the time he was writing, Schmitt noted that he had not yet developed any useful experiments for demonstrating or testing the concept (Schmitt, 1969).

2.4 Schmitt meeting the machine halfway

Another aspect of Schmitt's thinking is the idea of, "meeting the machine halfway" (Schmitt, 1963, p. 91). As noted above, one of Schmitt's intended outcomes of Biomimetics was the potential development of, "...composite bio-physical systems" (Schmitt, 1963, p. 90). Here Schmitt appears to be talking about engineering signal systems that might afford novel bio-machine hybrids. But to make these hybrid Schmitt says we are required to look at three dimensional space, "...for the optimal combinations of man, machinery and the 'figures of speech' or the theoretical models" (Schmitt, 1963, p. 91). Schmitt gives the following example which pertains to the transfer of three dimensional instruction code to the signal processing of the human brain:

> Have we adequately explored the other extremes of this compromise? Suppose we design a visual or auditory code that is physiologically efficient and then spend the necessary time to train an individual to receive and assimilate this code. We could then put into this code a variety of kinds of signals that we would like to get into a man quickly and accurately.

Figure 4: 'Signals into people' (Schmitt, 1963, p. 91)

Schmitt goes on to say that as a part of getting signals into people, "Surprisingly often a human or two can be built into the machine as an active component at startling savings in cost and with greatly enhanced performance" (Schmitt, 1963, p. 92). A human built into a machine is depicted in Figure 5, reproduced from Schmitt's paper on *Biomimetic modeling of the heart* (Schmitt, 1973).

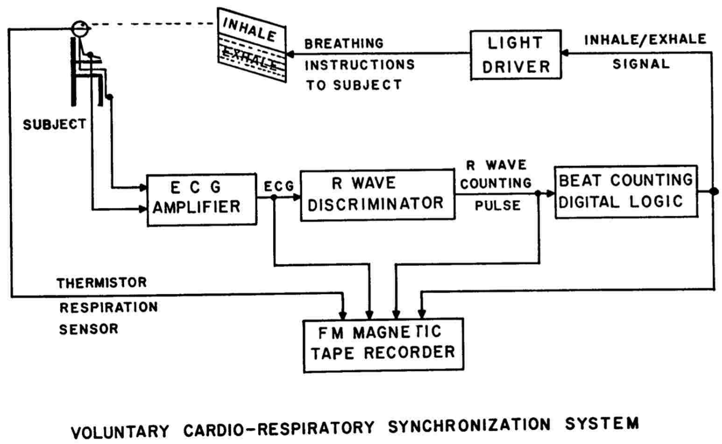


Figure 5: 'Human in the machine' (Schmitt, 1973, p. 487)

In this way 'Biomimetics' seems to have more of the 'bionics' meaning, such that the definition is not only talking about copying or mimicking living systems, but also about the engineering of human-machine composites. As mentioned by Ayre, here Schmitt's familiarity with the methods of electric engineering appear to have significance such that the idea of placing humans and life in the bioelectric circuit made them the subject of the mathematical theorems of circuits. This may be why Schmitt was thinking of a new type of mathematics, and a new type of mathematician:

> The mathematicians we lack are those who understand life science phenomenology personally in an intuitive way and yet are secure enough in their mathematical skills and their theoretical model making to be prepared to create new working mathematics as they go.

Figure 6: 'New mathematicians' (Schmitt, 1963, p. 91)

To elaborate on this idea Schmitt refers to one instance where he used stock mathematical treatments in 'unconventional combinations'. In doing so he arrived at a "functional correlation technique"[3] for the analysis of biophysical data. For Schmitt it appears that the novelty of this technique was not so much that it enabled him to find analogous types, but rather that it required him to treat time as a dependent variable rather than an independent variable. Describing the utility of this technique Schmitt says that the activity of varying the time axis

[3] This is possibly the 'functional analogies' mentioned by ?.

gave him, "...new latitude in recognizing what seems biophysically important in electrographic pattern evaluation" (Schmitt, 1963, p. 91). We shall return to the concept of time as a dependent variable in the discussion of sustainability below. Presently, however, the next section will give some examples of the kind of work that Schmitt's ideas have inspired in various domains and scales of fabrication.

3 Examples of biomimetically inspired designs

3.1 In the image of life

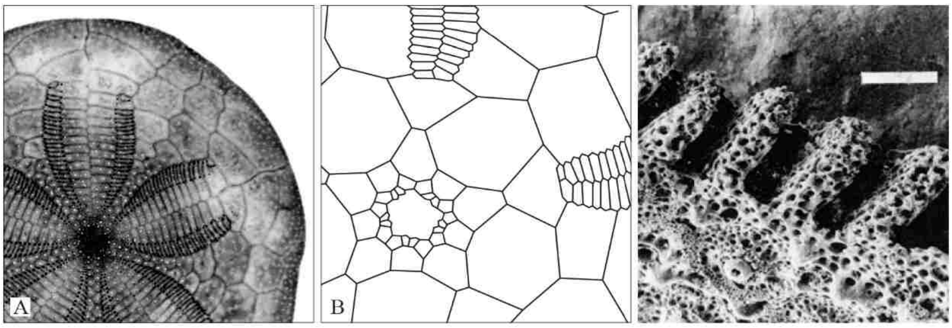


Figure 7: Inspiration: Sand dollar shell (Krieg et al., 2012, p. 524)

An example at the scale of the built environment is Krieg et al. (2012)'s case study which took inspiration from the skeletal structure of the sand dollar shell shown in Figure 7. The mimicry pavilion fabricated by Krieg et al. is shown in Figure 8:

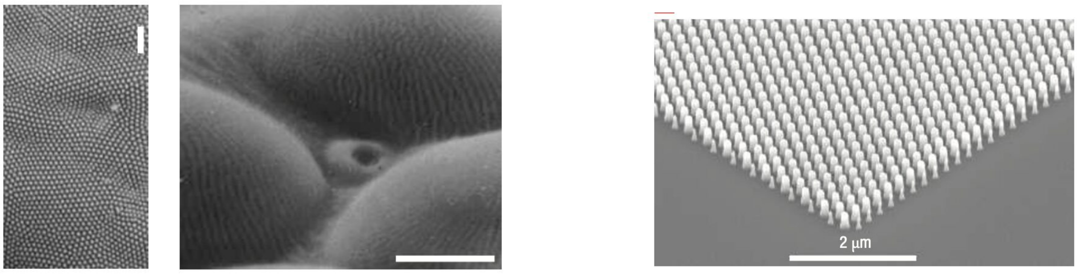
Figure 8: Fabrication: Research pavilion (Krieg et al., 2012, p. 522)

The pioneering research of Menges, Hensel and Weinstock has attempted to 'up-scale' life's small-scale generative design strategies. Indeed, Menges, Hensel and Weinstock say that biomimetic engineering was the core of their morphogenetic approach to design. In this approach, material (and biological) systems are generative drivers, or forcing functions, of design:

> Based on concepts of developmental biology and biomimetic engineering, the core of such a morphogenetic approach is an understanding of material systems not as derivatives of standardised building systems and elements facilitating the construction of pre-established design schemes, but rather as generative drivers in the design process.

Figure 9: (Menges, Hensel and Weinstock, 2012, p. 165)

Some other examples of the attempt to mimic biological structures in built environment design are, Knippers and Speck (2012), Krieg et al. (2012), Erdine (2013), Magna et al. (2013), Castriotto (2019). At the small scale, examples of Biomimetics are evident in the work of Parker and Townley, who, for example, were inspired by the anti-reflective properties of moth eye surfaces. Parker and Townley scanned a moth eye shown in Figure 10a, and then attempted to mimic the surface by fabrication with ion-beam etching to produce the result depicted in Figure 10b.



(a) Inspiration: Moth eye

(b) Fabrication: Moth eye replica

Figure 10: (Parker and Townley, 2007, Fig. 1a-c, p. 348)

At the micro-scale, researchers have been concerned with the molecular building blocks. A search of "Nature Reviews" for example, reveals that the term "Biomimetics" has been used across several fields of nanotechnology (Sarikaya et al., 2003, Parker and Townley, 2007), materials science (Sanchez, Arribart and Giraud Guille, 2005, Hou et al., 2017), chemistry (?Levin et al., 2020), water science (Goel et al., 2021), physics (Manna et al., 2022), polymer science

(**?**Hirai et al., 2019), dentistry and oral science (Pandya and Diekwisch, 2019), smart biomaterials (**?**), electronics, microelectronics and microelectromechanical microfabrication (Löthman et al., 2014) and even in Information Systems (Kaufmann and Portmann, 2015).

3.2 Bio-machine hybrids

Schmitt's idea of Bio-machine hybrids appears to have been taken up from two different perspectives. One approach has been through the idea cyborg and the field of cybernetics, and other is from the perspective of materials science. From the materials science perspective, Schmitt, for example, emphasise the hybrid aspect, and has led to the development of a field called "molecular biomimetics". As Sarikaya et al. wrote, molecular biomimetics is a, "...marriage of materials science engineering and molecular biology for development of functional hybrid systems" (Sarikaya et al., 2003, p. 579). Sarikaya et al. focused on proteins as bio-control structures, under the premise that, "...inorganic surface-specific polypeptides could be used as binding agents to control the organization and specific functions of materials" (Sarikaya et al., 2003, p. 578). Figure 11 is how Sarikaya et al. represent the domain of molecular biomimetics as an integration of biology with the synthetic materials from the materials sciences to form genetically engineered and self-assembling materials:

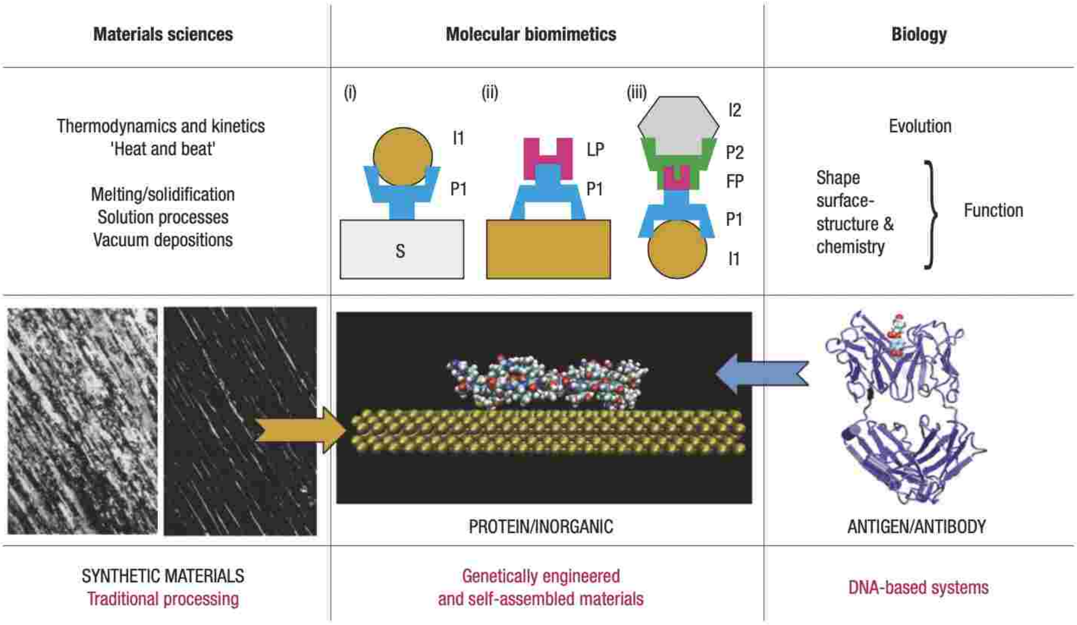


Figure 11: Molecular biomimetics (Sarikaya et al., 2003, Fig. 2, p. 579)

But although Sarikaya et al. seems to implement a kind of hybrid system, from the bionic perspective of Schmitt's bio-machine hybrids, the idea seems to be more concerned with the transfer of a 3D instruction set (perhaps something like G-Code) to a living system, like the human brain. In simple terms the concept appears to view humans like 3D-printers, and as a kind of target system for Computer Aided Manufacturing. To that end, DARPA[4] has researched bio-machine hybrids such as the, "cyborg beetles". That is, beetles whose flight is controlled by implanted electrodes and a wireless radio receiver (Singer, 2009) (See Fig. 12):

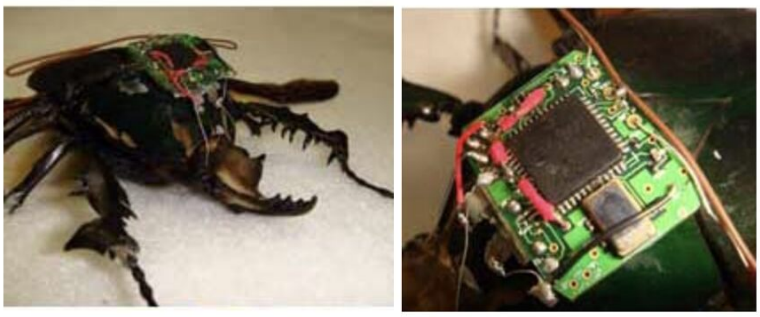


Figure 12: Bio-machine hybrid beetle (Singer, 2009)

[4]Defense Advanced Research Projects Agency

3.3 Emulation and an example from Systems Ecology

As noted above, Schmitt himself did not appear to find good experimental examples to demonstrate his concept of emulation and his associated 'information transform models'. It is possible, however, to find some discussion of emulators but just not with reference to Schmitt's biomimetics. It appears to have required a dialectical paradigm shift away from the 'human in the machine' and more toward the 'machine in the environment'. The science of Systems Ecology was one domain that appeared to make such a paradigm shift and used the concept of emulation to refer to 'microcosms' (Beyers and Odum, 1993, p. 187). Beyers and Odum, for example, cited **?**'s depiction of a microcosm as a specific instance of Emulation (Beyers and Odum, 1993, p. 238). **?**'s depiction is reproduced in Figure 13, and presented here as an example of the kind of emulation system that Schmitt may have been thinking of.

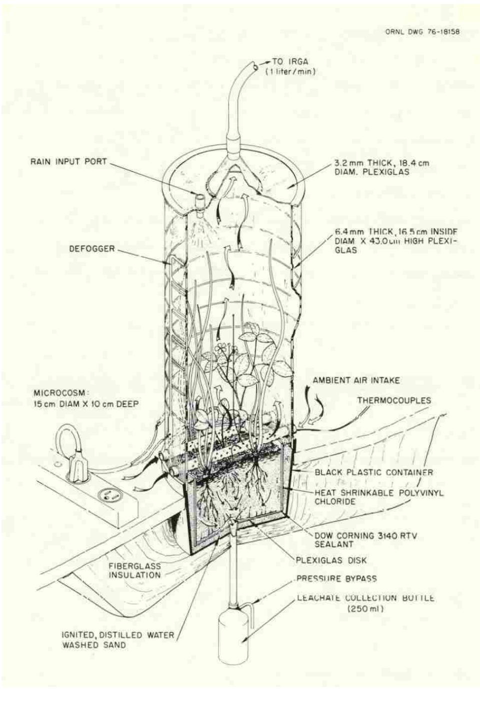


Figure 13: Microcosm 'emulation' (**?**, p. 12)

The intention of **?** and Beyers and Odum was to create a small scale ecological system that had all the inputs and outputs controlled so that test conditions could be created to understand the input requirements of the ecological system, and its outputs. This type of ecological mimetics pre-dates the concept of 'Ecomimetics', however would seem to apply as a nascent form of Ecomimetics. It is not clear whether the process of creating small ecological systems as emulations led to the development of the concept of Sustainability in the Systems Ecology of Beyers and Odum, however, it seems that Schmitt's biomimetics does not itself inherently contain a concept of Sustainability, and the next section will briefly introduce critical questions for Biomimetics in this regard.

3.4 Reductionist criticism of Biomimetics

Gamage and Hyde argue that an examination of Biomimicry literature reveals a reductive mindset that makes it difficult to apply the concept, "...as a complete design approach within architecture" (Gamage and Hyde, 2011, p. 1). The problem with the reductive mindset here is that a design can be considered in and of itself, like a closed system, irrespective to any environmental context. The above presentation of Schmitt's Biomimetics and the associated examples of Biomimetic research can be seen to display reductionist characteristics in that they have not explicitly involved the concept of 'Sustainability' or transactions with an environment. This is not to say the concept of Sustainability cannot be a key pillar of Biomimetics, but, rather, that Biomimetic designs can be fabricated in the absence of any measure of ecological Sustainability.

To this point, when reviewing Schmitt's original ideas of Biomimetics above, an increase in design sustainability did not appear to be an explicitly intended outcome. For instance, the examples of cybernetic control of beetle flight and the combination of material science and biology in molecular Biomimetics do not present any associated Sustainability metric against which the "Sustainabilityness" of the research outcomes might be evaluated. If we consider the Biomimetic pavilion design of Krieg et al. (Fig. 8) for example, we can question how the Biomimetic features improve the design Sustainability. Although aesthetically impressive, there does not appear to be any metric that can be used to show how the design was any more or less Sustainable due to its Biomimetic features. The review will now turn to look at the concept of 'Ecomimetics' which has been introduced in response to this criticism. It will also consider the 'Graph Theoretic' implications of the Ecomimetic approach as it is used by Holguera et al. (2014) and Garcia-Holguera (2018).

3.5 The Ecomimetics response

In response to the reductionist criticism of Biomimetics, some scholars like Gamage and Hyde argue for an "ecological Biomimetics" which they call "Ecomimetics". Ecomimetics, say Gamage and Hyde, is based on a holistic view of Biomimicry that, "...goes beyond mimicking a particular organism, process or ecosystem" (Gamage and Hyde, 2011, p. 1). The aim of this kind of holism is to situate a design in an environmental context. A design, then, is as an open system which seeks to understand the inputs and outputs between a design and its environment. As a part of this holistic view a design is understood to be dynamic and transformed by its environment, but also transforming its environment through exchanges of matter, energy and information. Gamage and Hyde anticipate that such a holistic Ecomimetic design philosophy might start a design revolution for many disciplines, "...based on principles of ecology that studies the relationship of flora and fauna" (Gamage and Hyde, 2011, p. 2).

It is noteworthy here that Gamage and Hyde don't elaborate on the definition of the word 'Principle', nor how it might be related to ecological systems, ecological Biomimetics or Sustainable design. Nevertheless, for Gamage and Hyde, an Ecomimetic design philosophy would need to integrate ecological ideas that view nature's adaptation and integration strategies as transformations (Gamage and Hyde, 2011, p. 1). Indeed, Gamage and Hyde's focus on nature's transformation strategies here seems to partly align with Schmitt's concept of 'information transformation models'.

Holguera et al. has presented theoretical outlines for an Ecomimetic methodology (Garcia-Holguera et al., 2013, Holguera et al., 2014, Garcia-Holguera, 2018). For Holguera et al. Ecomimetics and the Ecomimetic methodology uses concepts and tools from several disciplines in the attempt to, "...build bridges between ecosystems and building design" (Holguera et al., 2014, p.4). But in taking this approach Holguera et al. direct attention to the often-observed problem of ecological complexity which arises through holistic methods. Holguera et al. make note of authors like Bertalanffy (2008), Barabási and Albert (1999) and Anand et al. (2010) who have developed General Systems Theory and Graph Theoretic methods that attempt to accommodate the challenges presented by ecological network complexity. And in addition to these methods Holguera et al. makes an appeal to the identification of general principles and feedback loops as important features that need to be accommodated in Ecomimetic design practice:

> graph theory (Anand et al., 2010) indicates that complex systems share structural features, and Von Bertalanffy (2008) affirmed that there are general principles that are common to many systems independent from the components of the system or the interactions among those components. These ideas are especially relevant because the ecomimetic methodology tries to compare ecosystems with buildings, two types of systems with apparently few things in common. Developing building designs with similar feedback structures to those shown by certain ecosystems is central to the success of the method.

Figure 14: (Holguera et al., 2014, p. 4)

Earlier, Garcia-Holguera et al. identified Ecological Engineering as a key discipline that may have methods to assist Ecomimetic design with the problems posed by ecological network complexity. They cite the scholarship of Mitsch and Jorgensen together with Odum as key works involved in the development of tools that attempted to integrate qualitative with quantitative approaches to ecological complexity. For instance, Garcia-Holguera et al. bring specific attention to Odum's diagramming method known as the 'Energy Systems Language'.[5] One of Odum's early descriptions of the language is given below (Fig. 16):

> **Retaining the natural thinking of flow networks, but also including differential and difference equations, is a language of energy circuits used in several places in this book to clarify the systems interaction of many parts. Since all phenomena have energy flows, they can be expressed in the common denominator of energy flow.**

Figure 15: (Odum and Pigeon, 1970, p. A6)

Odum's Energy Systems Language was developed to afford the comprehension of ecological network complexity by a method of systematically arranging qualitative ecological concepts captured in the symbols of the langauge (Fig. 16) into schematic-like graphs.[6] The purpose of the ecological graphs was to subsequently afford designers to generate a quantitative simulation of the energy flows, storages, and limiting-factors in an ecosystem. A further description of the use of these symbols and language will be given in the Thesis methodology section, however,

[5] Holguera et al. refer to Odum's qualitative tool as Energy System Diagrams. Odum, however, referred to it by various names such as Energy Circuit Language, Energy Systems Language and *Energese*. It will be referred to here as the 'Energy Systems Language'.

[6] See Odum and Pigeon (1970, pp.A5-A11) and Odum (1972, pp. 139–211).

as an introduction, the key symbols of the Energy Systems Language are depicted in Figure 16 with an example of their usage in Figure 20:

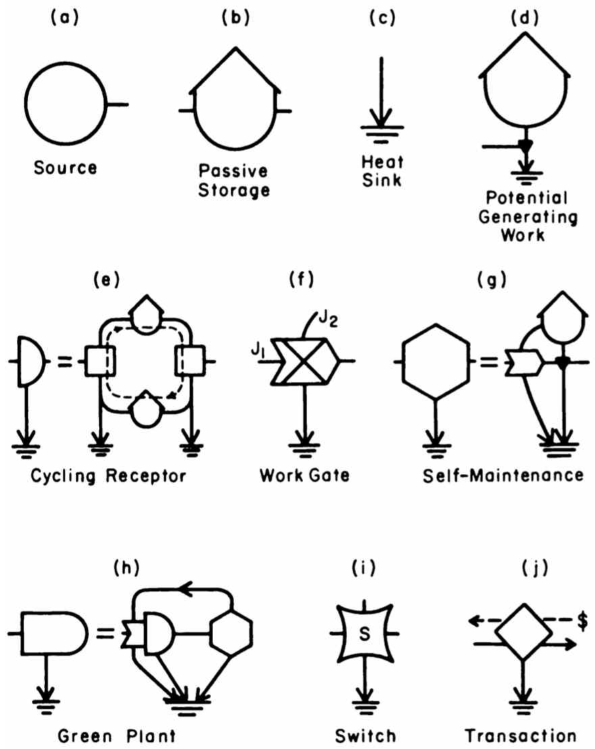


Figure 16: Key symbols for the Energy Systems Language (Odum and Pigeon, 1970, p. A6)

Holguera et al. note that Odum (2003) attempted to pioneer the application of his ecological schematics to the discipline of Design, and that this effort has been continued by Srinivasan et al. (2012). In Figure 20, for example, Srinivasan et al. use the Energy Systems Language to depict all the inflows and outflows between a building design and its environment.

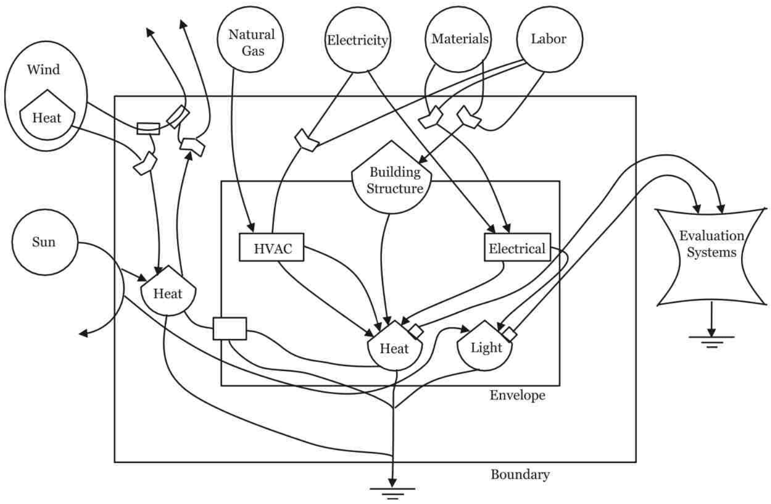


Figure 17: Diagram of building environmental design showing energy pathways (Srinivasan et al., 2012, Fig. 3, p. 304)

Holguera et al. themselves in 2013 produced an ecological graph of a passive solar family house in Hudson (USA) using the Energy Sysetms Language (Fig. 18):

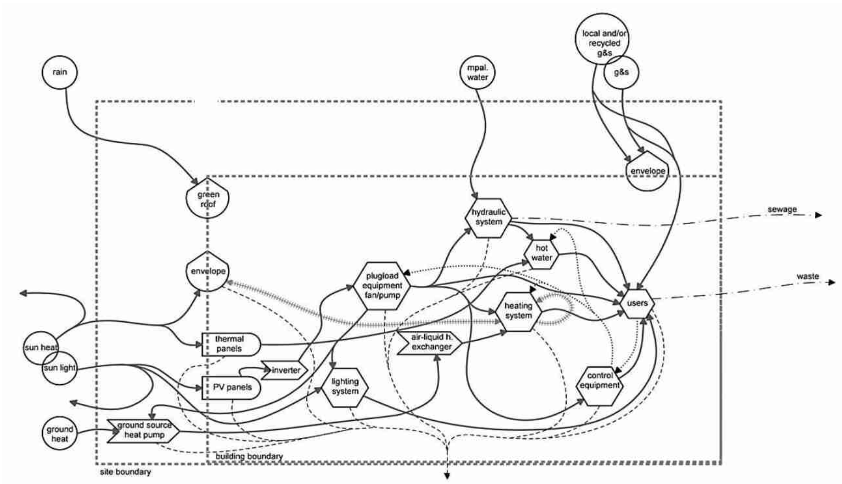


Figure 18: Ecological graph of passive solar family house (Garcia-Holguera et al., 2013, Fig. 4)

A further example that might be more graphically illustrative is the work of Keena et al. who has attempted to apply the Energy Systems Language method but using more qualitative pictograms and graphic design to visualise the Ecological inputs into the Farnsworth house (Keena et al., 2016) as shown in Figure 19:

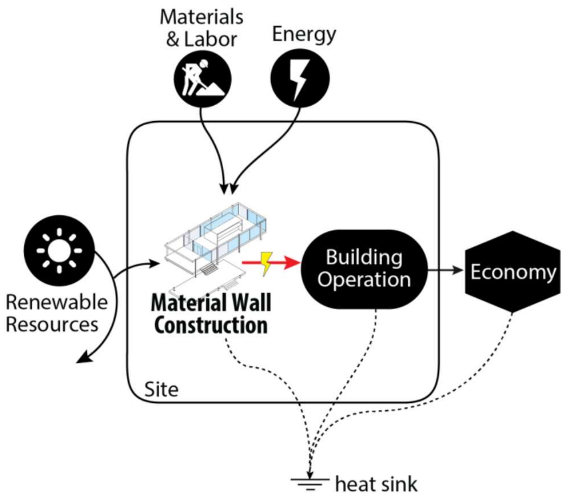


Figure 19: Ecological graph visualisation of Farnsworth house by Keena et al. (2016, Fig. 4, p. 134).

3.6 Summary of Ecomimetics

In all of the examples of using the graph theoretic method of Odum to generate holistic concepts of design, a number of quesions and issues seem to remain. For while the concept of Ecomimetics has arisen out of the attempt to make Biomimetics holistic in scope, and despite the efforts of Srinivasan and Moe, the graph theoretic methods of Odum do not appear to have been used widely as a part of design methods. Part of the evidence for this assertion is that although Odum has given several computational examples for the Energy Systems Language method (Odum, 1972, 1989, 1994), the key symbols and simulation methods have not been integrated into commonly used Computer Aided Design tools like Rhino3D and Grasshopper. And even although Holguera et al. have sought to integrate the methods of Ecological Engineering the question of how to evaluate the Sustainability of an ‘ecological Biomimetic’ design using the Energy Systems Language still remains opaque. How, for instance, do Odum's diagrammatic methods show ecological Biomimetic designers the Sustainability of their design? These questions motivate the next section which will review how the Ecosystems Engineering literature has attempted to provide answers.

4 Sustainability

Before we consider how the Ecomimetic use of Odum's graph theoretic methods might enable an evaluation of a design's Sustainability, we will first consider the definition of terms. Unfortunately, however, it is difficult to provide a canonical definition for the word SUSTAINABILITY. The OED gives three distinct origins all formed within English by derivation; 1. A legal origin pertaining to the, "... quality of being sustainable by argument; the capacity to be upheld or defended as valid, correct, or true", 2. An economic context pertaining to the longevity of economic growth, and 3. An environmental context relating to, "... the degree to which a process or enterprise is able to be maintained or continued while avoiding the long-term depletion of natural resources" OED (2022). Whilst the idea of sustainability referred to in this thesis is most closely aligned with the third definition, it should also be acknowledged that even within the environmentally oriented scholarship the concept means different things to different scholars. This is partly because there has not been a universally agreed upon metric for the evaluation of a design's sustainability.

4.1 Ecosystem Sustainability

The discussion that is of most interest is that arising out of what will be identified as the 'Florida School'.[7] Although several branches of scholarship emerged from the Florida School, it has been the work around the sustainability indices and bookkeeping methods which has been most developed, and yet, as Grönlund has observed, has also been the most difficult to communicate.

In 1994, Ulgiati, Odum and Bastianoni attempted to comunicate a definition of Sustainability with respects to the Environmental Accounting paradigm they were developing as a part of the holistic methods of Systems Ecology and Ecological Engineering emerging from the Florida School:

[7] For a root-branch depiction of the lineage of those scholars associated with the Florida School, see the fronticepiece of Hall's Festschrift for Howard T Odum Hall (1995).

> The interface of environment and human society is often in the marketplace where resources are exploited and sold. In the process, the environment sustains some transformations that may or may not lead to long-term stability. As the population expands, it is increasingly important that humans consider the long-term environmental consequences of their economic decisions. A long-term perspective and macroscopic view are needed to adequately factor in questions of long-term sustainability in our public policy decision process.

Figure 20: Ulgiati, Odum and Bastianoni (1994, p. 215) on long-term sustainability

The key idea that will be emphasised here is that of an environment[8] 'sustaining transformations' for some duration of stability. In a design context, the question of defining Sustainability seems to be one of an environment's design-affordance. Grönlund attempted to communicate this idea of environment's design-affordance with reference to the concept of a hierarchical 'triple-bottom-line', and Grönlund (2019, Fig. 3, p. 41) then used the Energy Systems Language to depict such (Fig. 21):

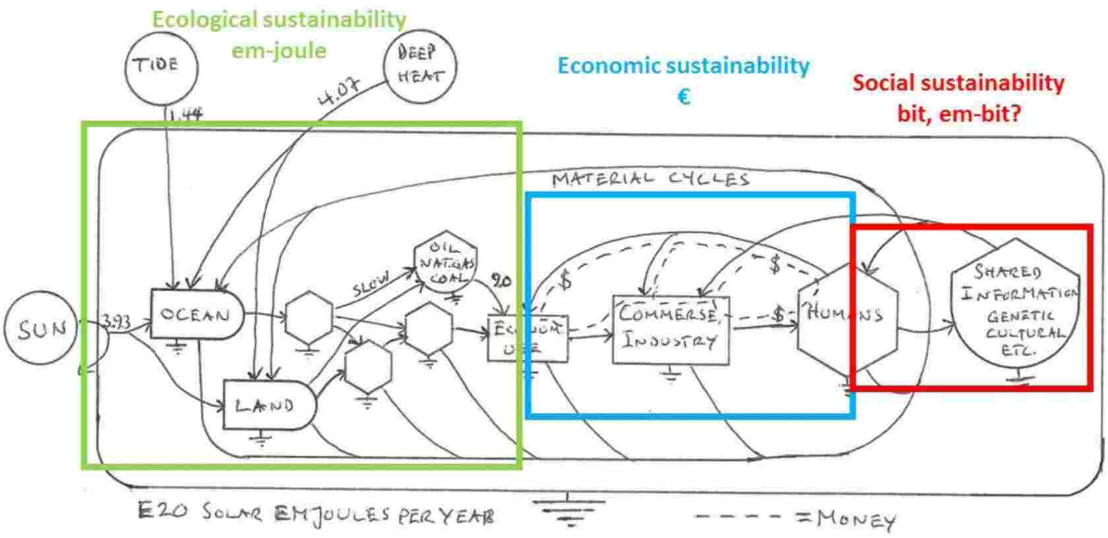


Figure 21: Triple-bottom-line in the energy hierarchy Grönlund (2019, Fig. 3, p. 41)

We can see that on the left-hand side of Figure 21, Grönlund uses a green box to ring-fence the concept of ecological sustainability. Grönlund does this to show that the ecological system make a contribution to the economic system (the blue box), which in turn makes a contribution

[8]Following Odum (1994) the word 'environment' will be used interchangeably with the word 'ecosystem' without loss of meaning.

of information and services to the social system (the red box). It is in this sense that the ecosystem affords certain economic designs, and an economy affords certain social designs. One question for a designer of artefacts here, is whether their design matches the affordances of the ecosystem inputs, and the material cycle that the design and the design fabrication processes feedback to the ecological system. This material cycle feedback from the economy of design fabrication is depicted by Grönlund in Figure 21 with arrows that exit from the bottom of the blue box and return around through the red box to circle back around above the blue box back to the ocean and land of the ecosystem.

4.2 Clark's Crow and Total Environmental Accounting

Although it was noted above that Odum's Energy Systems Language and methods had not been integrated into popular CAD packages, there has been an attempt to integrate the accounting methodology of the Florida School into Grasshopper. In the period leading up to their 2018 paper for instance, Keena et al. developed a novel Grasshopper add-on for the Rhinocerous 3D CAD software package. Keena et al. called their add-on 'Clark's Crow' (Fig. 22), and described it as a tool that could be used during the design decision-making process to evaluate the socio-ecological impact of different design options (Keena et al., 2018, pp. 42-44). In the development of 'Clark's Crow' Keena et al. leveraged the existing Grasshopper add-on called 'Ladybug'[9], which in turn uses 'Honeybee'[10], to import OpenData on energy for the modelling and analysis of designs (See also Fig. 23).

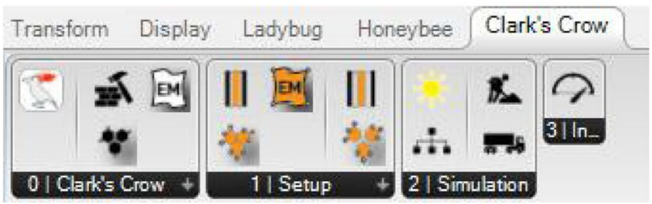


Figure 22: Clark's Crow Grasshopper Add-in (Keena et al., 2018, p. 46).

The intention of using 'Honeybee' and 'Ladybug' was to enable 'Clark's Crow' users to eval-

[9] See Ladybug (2016)
[10] See Ladybug (2022)

uate the sustainability of their design by accounting for all the energy flows, starting with energy flows into the geo-biosphere from the sun. The novelty here is the (attempted) implementation of an ecological accounting method known as 'emergy evaluation'. The word 'emergy', spelled with an 'm', is a shorthand for the term 'embodied energy', and is used specifically to refer to a distinctive ecological accounting approach pioneered by Odum (1996).[11]

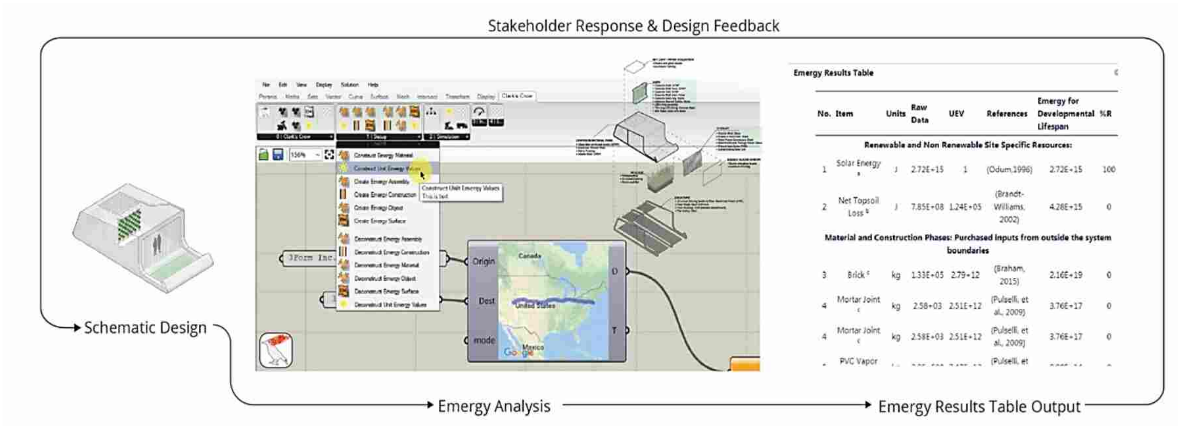


Figure 23: Keena, Raugei and Dyson (2019, Fig. 1, p. 61) visualising an integration of Environmental Accounting and Grasshopper.

The accounting method behind the emergy nomenclature was intended to be holistic in scope, which means that it aimed track all the potential and actual inputs into a system design using the energy available from sunlight hitting the geo-biosphere as a common base unit.[12] In Figure 24 Keena et al. depicted the holistic scope of the emergy method in contrast with other life cycle analysis methods which operate on a restricted part of the system as a whole.

According to Keena et al. the Honeybee Grasshopper add-on in particular includes many of the prerequisites required for the calculation of the emergy values detailed in Odum's book, and was therefore leveraged in the development of Clark's Crow. An example of the novelty

[11] The emergy nomenclature (the words, method and terms used together with the word 'emergy') was developed by Odum, his students and colleagues—especially an Australian fellow by the name of David Scienceman—which is what I'm referring to collectively as the 'Florida School'.

[12] This unit is referred to as the 'solar emergy joule', or 'semj'. However in the tradition of using surnames to refer to a scientific unit the 'Odum' might be a better way to refer to the solar emergy joule as a common base unit.

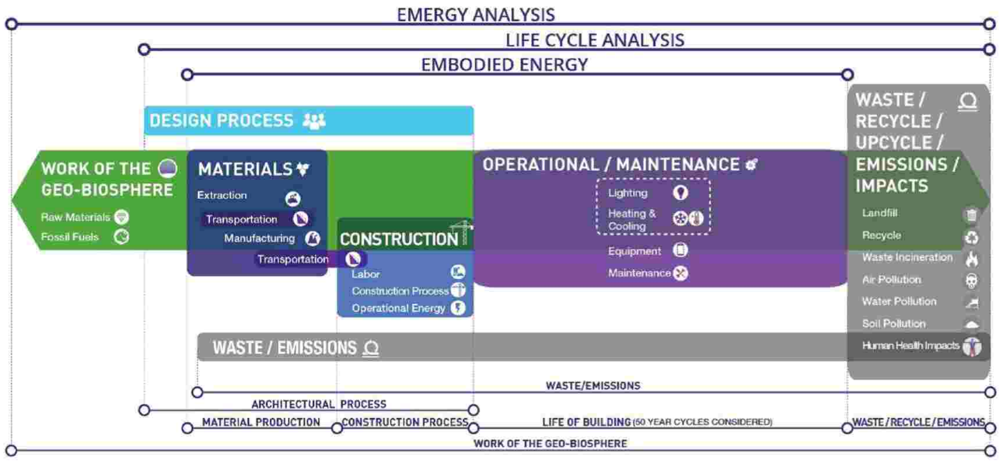


Figure 24: Relationship of different accounting methods compared to holistic 'whole of system' emergy method (Keena et al., 2018, p. 43).

provided by Clark's Crow, prior to its development researchers like Tabony (2021) used the Systems Dynamics[13] simulation platform called STELLA for the task of modelling sustainability of Urban Design. However, at the time of writing, the STELLA software package was not integrated with Rhinocerous 3D/Grasshopper. Furthermore, the STELLA software uses hydraulic analogies based on stock-flow algorithms (Tabony, 2021, p. 100, Fig. 3.43) which seems to have meant that Tabony was unable to use the 'track-summing'[14] process of the emergy method in the simulation of system designs. Hence Clark's Crow was novel both in the use of the emergy method and in the integration with Grasshopper, and with further feature enhancement may be able to replace the STELLA product in the simulation of system designs in Rhino 3D.

Keena et al.'s development of Clark's Crow is of interest in this thesis because, not only is it another attempt[15] to build a tool to facilitate the somtimes controversial[16] ecological accounting method of Odum (1996), but also because it aims to relate the output of Computer Aided Design with the "life cycle" requirements of the design and its materials, including the scale of Earth's geo-biosphere. As Keena et al. (2018) write:

[13] See Forrester (1999)

[14] For mathematical treatments of the track-summing methods see the discussion in; Tennenbaum (1988, 2015*a*,*b*), Le Corre, Truffet and Lahlou (2015).

[15] See for example Valyi (2005, 2004*a*), **?**,*b*,*c*), **?**, and Extend™shown in Odum and Odum (2000).

[16] See, for example, the commentary in valyi$_{u}ser_{2}005'thesis.Seealsothediscussionin?Tennenbaum$ (1988, 2015*a*), *Le C*

> "How we process, recover, restore and regenerate both the technical "nutrients" of the techno-sphere and the biological nutrients of the geo-biosphere within urban ecosystems is thus a crucial question when considering sustainable urban development." (Keena et al., 2018, p. 42)

The adoption of Odum (1996)'s accounting method by Keena et al. is also of interest here because of a prevailing gap in this type of analysis.

5 Gaps

TO APPEAR

6 Summary

TO APPEAR

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