USING EMERGENT TECHNOLOGIES TO DEVELOP SUSTAINABLE ARCHITECTURAL COMPOSITES

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I hereby declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person (except where explicitly defined in the acknowledgements), nor material which to a substantial extent has been submitted for the award of any other degree or diploma of a university or other institution of higher learning.

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ABSTRACT

The intention of this project is to research the potential of emergent technologies for developing sustainable composites for the building industry. It is divided into three parts:

Part 1 Identifies emergent practices which are being applied to the development of new sustainable building prototypes such as developments using nanotechnologies, the influence of biomimetics, the development of intelligent interactive systems and the use of digital technologies to generate complex cellular structural systems.

Part 2 Outlines existing processes involved in selecting and manufacturing prototypes, as many existing processes have been opportunistically applied to emergent practices to generate innovative sustainable prototypes.

Part 3 By synthesising the research gathered in the previous parts of this thesis, this section documents the design process for developing a sustainable building system. The design is based on a minimal surface structure to reduce materiality and to optimise strength and its manufacturing process exploits emergent and existing technologies for its generation.

INTRODUCTION

"All possible branches are real." (Borges, *The Garden of Forking Paths*, 1941)

This project commenced with an intention to scope out a strategic plan for the development of structural composites. For anybody involved with designing built environments, and interested in developing new building systems, one has to become aware not only of existing processes and material selection strategies, and implications of their use, but also of emergent technologies, collaborations with wider specialised fields, as well as a consideration of sustainability. Existing strategies and manufacturing processes for developing sustainable building systems have been well documented by writers such as Brenda and Robert Vale (1991), who outline comprehensive "how to" processes for achieving sustainable solutions, mostly based on good practice, such as positioning for solar gain and building energy efficient, thick walled, super insulated houses, using traditional sustainable materials such as straw bale or mud brick. But the shortcomings of these methods are their limitation to small-scale development, lack of engagement with emergent technologies and materiality which struggles to compete with modernist preoccupations obsessed with steel, glass and concrete. While newer buildings constructed out of glass and steel can become more sustainable by improving energy efficiency with double-glazing and insulation, this only partially resolves their sustainability in terms of overall environmental impact.

The other shortcoming of traditional modes for designing and manufacturing buildings is a top down approach preoccupied with form and uniformity, which does not take into account wider contexts such as the impact of variable environmental conditions or the diversity of material structures. Traditional approaches to manufacturing buildings do not engage with emergent and collaborative practices especially in relation to developing opportunities for manufacturing more sustainable alternatives. While this research does not attempt to offer a definitive solution for how new technologies can be applied to new building systems, it is relevant to researchers and designers as it raises an awareness of how emergent technologies might be used, alongside existing technologies, to develop better and more sustainable building systems.

Sustainability and its relationship to developing new building systems covers a broad spectrum

of complex and interrelated areas. The research commences with an outline of key thematics raised in consideration of sustainability in relation to the selection of materials and manufacturing processes for the production of building systems, which reduce waste and are less dependant on fossil fuel consumption and nonrenewable resources for their generation and long term serviceability. Following this introduction to sustainability the work is ordered into three sections as follows: Emergent Technologies, Processes and Documentation.

Part one (Emergent Technologies) covers four main areas: Nanotechnologies, Biomimetics, Immateriality and consideration of Collective Intelligence in relation to applications of Digital Technology. The first section on Nanotechnologies discusses the influence of this technology in developing better and more sustainable building systems and its relevance in the development of nano-enhanced biocomposites. The second section examines Biomemetics and considers how research in this area has led to the development of intelligent building systems and the production of prototypes which behave more like biological systems in terms of their self-organisational properties and adaptive qualities. Inspired by the efficiency and adaptability of natural systems in terms of energy consumption and use of resources, the third section focuses on materiality, or rather, strategies which look towards dematerialisation and lightness driven not only by aesthetic concerns but also by the desire to produce more sustainable buildings through the conservation of resources, a reduction in waste and improved performance through the generation of cellular lattice-like minimal surface structures. The fourth section considers collaborative strategies in the development of flexible solutions using morphogenetic digital design processes and the potential to advantageously combine digital processes with rapid prototyping manufacturing techniques to generate new building systems.

The second part of this thesis (Processes) briefly outlines the tools used by designers and researchers to assist in making decisions for material selection such as Classification Systems, Selection Processes and Manufacturing Techniques used for the construction of building systems.

The final part of the thesis (Documentation) traverses the boundaries between design process and research through the investigation into the development of a minimal surface structure for a design prototype, extending the first parts of this research through synthesising the potential

raised by the written component.

Research usually begins with the task of reading a series of texts that are related to an abstract that sets out a proposal. In this case, the research was initially concerned with an investigation to determine where the horizon lies for the development of future structural composites. Key texts referred to at an early stage were works written by Ashby (2005), Fernandez (2005) and Addington (2005) who outline the various selection and manufacturing processes and classification systems for researchers interested in developing new materials based on existing methodologies. However, it became apparent that a focus was needed on issues of sustainability in relation to the development of new building systems and materials. This shift came with recognition of the significant impact of sustainability occurring globally, influenced internationally by writers such as McDonough and Braungart (2002) who are the authorities behind a movement towards intelligent design that considers the long term effect of what we produce, and more locally, Alcorn (2003) and Boyle (2004) who have written about sustainability in consideration of New Zealand's commitment to the Kyoto Protocol. Sustainability has become such a pressing issue to New Zealand that it has lead to legislative changes to the New Zealand Building Act evident in the regulations relating to improving energy efficiency through insulation and double glazing and reducing carbon emissions in relation to fuel efficient heating systems. The raised awareness of the ongoing impact of carbon emissions means that sustainability will profoundly affect all future building development both locally and globally. This research into the development of future structural composites could not be responsibly undertaken without making sustainability a key consideration.

Research into sustainability, architecture and the related development of building systems, in relation to New Zealand contexts has already been extensively conducted by authors such as Brenda and Robert Vale (1991), Mithridate et al (2004), Alcorn (2003), Nobel (2006) and Boyle (2004) and others, particularly in relation to designing energy efficient building systems using solar design, thermal mass and energy efficient construction methods based on materials with low emergy ratings such as rammed earth, adobe and straw bale. Rather than regurgitating existing material based on these more traditional methods to produce sustainable design, the focus for this research is on emergent practices; that is: how would emergent practices impact on the

development of more sustainable composite building materials. Could emergent technologies be applied to produce composites which have better performance abilities in terms of strength/ durability/energy efficiency and self sufficiency? This shift in direction came with recognition of the limitations of traditional top down approaches that might be overcome through emergent practices and the development of new technologies. While some of these technologies such as nanotechnology have not been fully developed, and aren't promoted here as a definitive solution, it is apparent that opportunities exist to exploit emergent processes to develop innovative prototypes that are sometimes superior to those constructed and designed using existing and less sustainable methods.

By looking at emergent technologies, we encounter processes and methods that can in certain instances bring us closer to aspirations of producing products or building systems that are more sustainable. Once this direction had been identified, there emerged a problem of actually defining practices that related to sustainability. This was an area that did not seem to follow a distinct and logically defined pathway. It spread across a range of distinct areas that began with Nanotechnologies: (instigated by writers such as Drexler 1991 and Wegner 2005) and Biomimetics (largely influenced by an issue of *Architectural Design*, Techniques and Technologies in Morphogentic Design, guest edited by the Emergence and Design Group, 2006). This publication outlines the impact of biological systems on the generation of material systems and has had a huge impact on recent research carried out by the Architectural Association through the AADRL, MIT and Columbia University who have all been focused on the development of generative material systems based on Algorithmic Codes and Digital Technologies (Silver 2006, Andrasek 2006, Hensel et al 2006). It was also important to consider the impact of Intelligent Systems which adapt and respond to various conditions rather than remaining fixed (Addington and Shodek 2005), as many of the innovations in new building systems are based on the development of smart materials and a closer understanding of material science. While emergent technologies have the potential to generate innovative processes and materials, many of the most recent developments have relied on the modification of existing processes in relation to material classification systems, selection strategies used to select materials for the generation of new building prototypes and also manufacturing processes. This was most clearly articulated in Ashby's book, *Materials Selection in Mechanical Design* (2005). Good selection strategies are not

only critical to the design process, but have been advantageously applied to emergent practices to optimise material selection. Ashby's approaches to selection strategies are discussed in more depth in the second part of the thesis (Processes). All these diverse fields have an impact on sustainable practices but each area is unconnected in terms of how the issue of sustainability is addressed.

Encountering the different emergent technologies that are influential to the development of sustainable prototypes was like crossing a vast river delta, that meandered into a labyrinth of interconnecting fields and cross-disciplinary tributaries, each tributary revealing its own distinct qualities, and contributing its own nuance in response to sustainability. Added to the difficulty of navigating this territory was the fact that the research bridged between two disciplines: architecture and engineering, which gave the written component to this research a quality that became quite distinct from a thesis written purely from an engineering perspective (which would have required more in depth quantifiable data) or, if it had been written as an architectural thesis (would have demanded a stronger contextual positioning). Each discipline follows its own expectation and definition of what research is considered relevant. Belonging to neither strictly architecture nor engineering came with an inherent risk. Was the approach too generalist? Too multidirectional? Not specialised enough? This became more of a concern as the research widened into territories of computer science, materials science, mathematics, biology, nanotechnology, all areas that have significant implications in terms of the potential for developing future sustainable building systems. Rather than offering in depth scrutiny of one particular approach, this research has scoped out a broader picture presented as a series of interconnected parts, each offering different insights into current and emergent practices in relation to sustainability.

METHODOLOGY

"Thanks to the linguistic nature of all interpretation every interpretation includes the possibility of a relationship with others. There can be no speech that does not bind the speaker and the person spoken to." (Gadamer, *Truth and Method*, 1989)

In an essay entitled Faking it: Pregnant Pauses and Other Constructions of Delay, Francesca Hughes (1998) described the research process as a fragmentary process, where all coherence becomes lost. Ideas slide past, disappear, reappear, delaying any precipitation into a sensible outcome. Within this process pockets of resistance form, leading us astray into other avenues of enquiry. These activities collectively make our practice. The rubbish generated through this process collectively constitutes our product.. So if this research project commenced by reading texts related to sustainability and emergent practices in relation to developing sustainable structural composites with any particular initial expectation, each understanding or revision has lead to radically shifting horizons and a continual revision of understanding. Many of the texts referenced were sourced from cross disciplinary contexts – for instance, readings on emergent architectural practice combined with readings on engineering, alongside the development of sustainable composites, alongside biomedical contexts, mathematical and evolutionary computational applications and developments in relation to nanotechnologies. These cross disciplinary contexts aggravated shifts in interpretation, which has meant that any process of interpretation and reading of texts has not been through a rational process, but rather, through an emersion into a range of ideas which has evolved with each revision and new encounter. Sometimes these shifting horizons have lead to dead ends or competing interpretations, which have randomly jostled each other for supremacy or some sort of sense of overall cohesion. Interpretations of this reading material are represented in this text. As such, any sense of cohesion reflected in this text is in itself a reflection of the limitations within the context which have been engaged with. In setting these limits this interpretation inevitably carries with it, its own distortions and prejudices.

One of the most important aspects of this research into emergent practices was to determine how relevant different emergent technologies were to sustainability, in terms of creating energy

efficient building systems using readily available sustainable materials, and how were these technologies applied to real world contexts. It became apparent as the research developed that many emergent practices linked to digital production were reliant on old technologies in terms of use of materials and energy making them unsustainable. So the first part of this research primarily looked at emergent technologies that privileged either the improvement of materials sourced from renewable resources, or which reduced material consumption through improving structural strength, or through conserving energy.

Nanotechnologies through the manipulation of material at a molecular level provided one of the most interesting areas for future development. But, while it was tempting to optimistically dream about the potential nanoassemblies have for generating sustainable prototypes, through the manipulation of cellulose fibrils, the reality is that there are significant technological obstacles to be overcome in economically being able to extract these elements before this technology can be relevantly applied. Another area of research, that has been applied to generating sustainable prototypes is through biomimetics, which has influenced the development of intelligent systems and also the development of complex cellular structures, which mimic biological models in terms of optimisation of materiality. The impact of optimal material structures has recently seen significant advances in development mainly through advances using rapid prototyping technologies, which has enabled complex morphogenetic structural systems to be physically modelled. But, while rapid prototyping processes can easily make complex forms that optimise material structures, the scale of these productions is always limited to small-scale applications, and the materials used in these productions aren't sustainable. This means that the generation of complex materials systems through rapid prototyping faces problems in terms of how the technology can be applied affordably and sustainably to manufacture things at the scale of buildings.

Many of the emergent technologies discussed in the first part of this thesis, are embryonic. They either have not been fully realised yet or face technical difficulties in terms of how they are applied. Some rely on active on-going and highly specialised maintenance to optimally perform which also becomes impractical when compared to passive low technology sustainable building systems such as straw bale or adobe. Bearing in mind the technical teething problems faced by emergent technologies in producing sustainable solutions, existing practices were also researched,

as while some existing processes aren't sustainable there have been occurrences where existing technologies have been opportunistically applied to emergent practices to generate more sustainable building prototypes.

The final section relating to a design component was significantly influenced by research in the first section on biomimetics and studies of minimal surface structures that optimise materiality. This research lead to a design strategy that focused on mathematical models of triply periodic minimal surface structures, as these structures seemed optimal in relation to material composition. Minimal surface structures were analysed to determine if they could be applied to the generation of a structural system that used significantly less material than traditional systems. This was applied to a design for a concrete block . From a myriad of possible materials, concrete was selected based on an intuition that a concrete block might become more sustainable if the quantity of material required to produce the block could be reduced through optimising the design without impacting on its structural performance. The decision to use this material for making the structure was also based on the awareness that while concrete is not sustainable (it generates significant carbon emissions in its production); it remains predominant as a primary building material in New Zealand contexts. The design was implemented, and documented through the generation of a series of physical and digital models. These models were used to determine how a minimal surface structure could be formed and moulded into a blockwork system. Through digital and physical iterations, the design was modified in response to a range of criteria, such as assessing strength, formation, mouldability, the size of aggregates, wall thickness the type of admixtures, the limitations in scale of the rapid protyotyping machine, and the ability of the design to be assembled into a larger system. The design was then manufactured using rapid prototyping in combination with silicon moulds, and was also tested to determine its structural capability.

While the first part of this research began looking at a wide field of knowledge which prejudiced the more extreme end of emergent development in relation to nanotechnologies and intelligent, interactive systems in favour of traditional sustainable practices, the shift to applied practice with the development of the prototype lead to a radical re-assessment of emergent technologies in terms of relevance. In spite of the brouhaha of technological advances, technologies which leveraged the experience of traditional practices were applied. The blocks were made using cast

moulds, not too dissimilar to moulds used for making adobe bricks, and were manufactured using a concrete not too dissimilar to that used by the ancient Greeks. Their crenulated formation reminiscent of 13th century Gothic or Moorish architecture.

DEFINITION OF KEY TERMS

Sustainability

Sustainability: from the verb to sustain, meaning: to hold up; to bear; to support; to provide for; to maintain; to sanction; to keep going; to keep up; to prolong; to support the life of. (Chambers *Concise Dictionary*, 1999, p1303) In the context of this research sustainability refers to strategies to minimize the negative environmental impact of buildings by enhancing energy efficiency and moderation in the use of materials, in the development of built environments. Rather than looking at mainstream strategies to produce sustainable architecture which has been well documented by previous researchers, this project focuses on emergent areas which have not been so well addressed though outlining the impact the construction industry has on global warming and describing sustainable strategies for improving energy efficiency, reducing waste and toxic manufacturing processes and carbon emissions in building applications.

Emergence

This term refers to two conditions. The first relates to the application of new technologies in the development of novel prototypes and building systems. These are technologies whose principles are understood, but which have not been fully developed or applied to general building systems, such as nanotechnologies, biomimetics or morphogenetic processes using digital technologies to generate new materials and structures. The second context in which emergence is used is in relation to emergent patterns and complex systems that occur in nature through self-organisation as a result of multiple yet relatively simple interactions.

Nanotechnology

Nanotechnology involves the manipulation of matter on a scale smaller than 1 micrometer (a very small unit of length equivalent to one millionth of a meter), and has been used for the development and fabrication of new materials from the bottom up, leading to improved performance qualities and a radical shift in relation to how things are constructed.

Considers the manipulation of matter at a microscopic scale using atoms and molecules to construct stronger and more durable, energy efficient, lighter and intelligent products. Describes how nanotechnologies will significantly transform the way in which buildings are constructed and how this could positively effect the development of more sustainable building systems. Also identifies how biocomposites using nanotechnologies will replace existing processes sources from non-sustainable resources.

Biomimetic

This is a strategy used to develop new prototypes, which draws on the analysis of natural biological systems. It is based on the notion that natural systems self assemble using minimal resources in relation to optimised effect. Research into biomimetics has lead to the development of intelligent building systems and the production of new prototypes, which behave like biological systems in terms of their self-organisational properties and flexible/adaptive qualities. They also are constructed using minimal materials. Considers the design of more efficient adaptive, self-generative and intelligent systems. Outlines how natural biological systems generate form. Discusses the development of intelligent materials and building structures, which mimic the biological in terms of their adaptive qualities. Considers the impact of biomimetic studies in the development of more adaptable, structurally efficient and sustainable building systems, and identifies approaches that exploit the potential of self-generative systems in the development of building prototypes.

Immateriality

Minimal surface structures based on soap bubble studies have been used in the past by architects such as Otto Frei and Buckminster Fuller to optimise the generation of large-scale structures. New materials and new structural prototypes have been developed using principles of minimal surface structures to reduce materiality and improve performance capabilities. Considers the strategies that have been used to reduce materiality in architectural applications. Outlines how voids have been applied to develop lightweight and energy efficient building systems. Considers the impact of thin-skinned building components, use of voids/foamed /honeycombed elements

and their relationship to minimal surface structures.

Digital

The development of digital technologies and manufacturing processes has revolutionised form making. Hyped by the potential limitlessness of these technologies, how will they be used in a sustainable way to reduce overall excess and consumption? Discusses the translation of parametric data into building systems that behave more like biological organisms in their generation. Considers the impact of rapid prototyping techniques which link data input to the generation of form, and the harnessing of a collective intelligence to generate more sensitive design solutions.

1.1 CONSTRUCTING A SUSTAINABLE FUTURE

"Buildings account for one-third of the planet's CO_2 emissions and as a consequence are a key contributor to human-induced climate change". (O'Connell, 2003, p4)

Faced with a growing concern over global warming and issues of sustainability, as researchers and building designers, we have a choice to move in two quite distinct directions. We can either embrace proven traditional sustainable, zero energy building design technologies, by focusing on the construction of self sufficient houses positioned for solar gain and built using traditional techniques and sustainable materials (rammed earth, adobe, straw bale houses) to create thermal mass for energy efficiency, or alternatively, we can look towards the potential for creating sustainable buildings that are more flexible and lightweight, utilising emergent technologies and manufacturing processes and alternative materials. These emergent technologies not only have the potential of allowing buildings to become more self sustaining and capable of generating their own energy sources, but they could radically alter how buildings are actually generated.

For anybody working on the development of new building prototypes, sustainability has become of primary consideration. The focus on global warming has lead to a strong emphasis on sustainability in terms of energy consumption, durability, recycling dynamics and non-toxicity. In order to become more sustainable, future building systems will need to become more self sufficient and capable of generating their own energy sources. Goldsmith, (Architect and Principal of FTL Design Engineering Studio), suggests that the ultimate aim for designers would be to develop "a long lasting structural fabric. ……that would be 100 per cent sustainable (recyclable with no toxic off-gases from the chemical manufacturing process), and that would be able to act as a photovoltaic surface to generate its own power." (Beylerain, 2005, p260).

The following outlines the impact of the building industry on energy consumption and strategies used to identify sustainable building materials, and sustainable manufacturing processes. It also considers the potential for developing biocomposites to replace materials sourced from non-renewable resources.

Statistical evidence from numerous studies has demonstrated that the building industry is notorious for its flagrant consumption of resources. For many years, issues of sustainability in the building industry have been primarily driven by economic concerns expressed in the dematerialisation of buildings, rather than focusing on wider issues such as a building's environmental impact, toxic manufacturing processes, carbon emissions or energy consumption. With dwindling natural resources, global warming, economic and other factors to consider, there is a greater awareness and urgency applied to how materials, energy and natural resources are used more efficiently and considerately. Sustainability raises an awareness of how these resources are consumed to meet present requirements and also how natural resources can be preserved indefinitely for future generations. In the past sustainability has typically been accomplished through designing explicitly for site conditions, integrating basic principles of passive solar design, moderating the use of materials drawn from non renewable resources and by significantly reducing energy consumption through better design, which takes into consideration not only the energy required to extract and process raw materials but also considers long term energy consumption and environmental impact.

In New Zealand, concerns about sustainability have lead to a revision of the Building Act (2004) to incorporate the principles of sustainable development in terms of enhanced energy efficiency, health and consideration of sustainable attributes. These policies have also been ratified by New Zealand's obligations under the Kyoto protocol, which obliges New Zealand to significantly curb carbon emissions to 5 percent below the level they were in 1990. Data from 2003 shows that carbon dioxide emissions were about 37% higher than they were in 1990 (O'Connell, 2003). With the on-going rise in carbon emmisions New Zealand has to earn carbon credits to compensate for our inability to meet the Kyoto quota (govt.nz). In order to reduce carbon emissions in the building industry one has to reconsider the environmental impact of the materials that go into building manufacture in the first place and also how they are used. Studies have indicated that if materials are selected on the basis of low environmental impact, and buildings designed with a stronger ecological focus in terms of energy consumption and waste, the resulting carbon emissions would be significantly reduced (Nebel, 2005).

Sustainability is measured by Emergy. This measure assesses the energy used in the production

of building materials based on and environmental impact. M.T.Brown (2003) defined the energy used in building construction processes and other industries, in 1997, as embodied energy (often referred to as emergy), that is, the energy required for extracting and using materials. This is measured as a quantitative sustainability index, and represented as a ratio of the emergy ("embodied energy" yield ratio) to the environmental loading ratio. The "Sustainability Index", is "an index that accounts for yield, renewability, and environmental load. Emergy is used as the main indicator of sustainability in buildings". (Brown et al 2003)
This is formulated as the following relation:

$$\text{Sustainability Index} = \frac{\text{Emergy Yield Ratio}}{\text{Environmental Loading Ratio}}$$

The sustainability index is also effected by "Life Cycle Analysis" or "Cradle to Grave" analysis (Jacques, 1998). This is a quantitative method developed to systematically analyse the environmental impact of a building material at every stage of its life cycle from extraction, to manufacture, to transportation, to installation, to lifetime use, to recycling and disposal. Life Cycle Analysis has been used to give a detailed evaluation of materials and their impact and to develop tools to assist designers in the selection of materials. For example, sustainability indexes such as BASIX, GaBi and SimaPro (Nebel, 2006) and other environmental management systems have been developed based on life cycle analysis to measure standards of sustainability so that specifiers can more accurately predict the environmental impact of materials. A New Zealand version of these comparative selection systems include the NZIA Environmental Impact Comparison Charts (1996) and a more recently established Greenbuild (2007) website developed by Warren and Mahoney which can also be used to assist designers in selecting materials with low emergy ratings. There are however some limitations to the reliability of the data represented on these websites. The registration of materials on the Greenbuild website is costly. As a consequence the materials listed reflect traditional materials, practices and processes, which aren't necessarily that sustainable.

When the emergy figures of major building materials are compared (refer table 1), these levels can become significantly reduced depending on the type of materials selected. In this table,

materials with emergy ratings over 50Mi/kg have been highlighted grey (these are materials to avoid or consider in relation to more sustainable alternatives, such as using painted timber instead of aluminium for joinery). Materials with emergy ratings under 1 Mi/kg have been highlighted green (the sustainable choices). BRANZ has responded to this data by setting up a project (ZALEH) to test the potential to develop houses using low energy technologies such as straw bale, adobe, and straw clay along with wood fibre insulation, and alternative energy applications with significant results. (Nebel, 2005)

EMBODIED ENERGY FIGURES FOR COMMON NZ BUILDING MATERIALS
(After Alcorn (2003) and Jacques and Sheridan (2006)

MATERIAL	EMERGY MJ/KG	MATERIAL	EMERGY MJ/KG	MATERIAL	EMERGY MJ/KG
Adobe block straw stabilised	0.5	Concrete block-fill	1.4	Plaster gypsum	4.5
Adobe, bitumen stabilised	0.3	Concrete block-fill pump mix	1.5	Plasterboard	7.4
Adobe, cement stabilised	0.4	Concrete precast double T	1.9	Plastics HDPE	51
Aggregate, general	0.1	Concrete grout	1.7	Plastics LDPE	51
Aggregate, Virgin rock	0.04	Concrete 17.5 MPa	0.9	Plastics polystyrene, expanded EPS	58.4
Aggregate, River	0.02	Concrete 30 MPa	1.2	Plastics polystyrene, extruded XPS	58.4
Aluminium, virgin	191	Concrete 40 MPa	1.4	PVC	60.9
Aluminium, Extruded	201	Copper, virgin sheet	97.6	Rubber, natural latex	67.5

EMBODIED ENERGY FIGURES FOR COMMON NZ BUILDING MATERIALS (After Alcorn (2003) and Jacques and Sheridan (2006)					
MATERIAL	EMERGY MJ/KG	MATERIAL	EMERGY MJ/KG	MATERIAL	EMERGY MJ/KG
Aluminium, Extruded anodised	227	Copper, virgin rod wire	92.5	Sand	0.1
Aluminium, Extruded powder coated	218	Copper, recycled tube	2.4	Soil, rammed cement	0.8
Asphalt (paving)	3.4	Glass, float	15.9	Steel, recycled	10.1
Bitumen (fuel)	2.4	Glass, toughened	26.2	Steel, reinforcing, sections	8.9
Bitumen (feedstock)	44.1	Glass, laminated	16.3	Steel, wire rod	12.5
Brick, new technology	2.7	Gypsum plaster	3.6	Steel, virgin general	31.3
Brick, old technology	7.7	Insulation, cellulose	4.3	Steel, galvanised	34.8
Building paper	25.5	Insulation, fibreglass	32.1	Straw baled	0.2
Cellulose pulp	19.6	Insulation, polystyrene (expanded)	58.4	Timber, air dried, rough sawn	2.8
Cement, average	6.2	Insulation, polystyrene (extruded)	58.4	Timber, air dried, dressed	3.0
Cement, dry process	5.8	Insulation, polyester	53.7	Timber, gas dried, dressed	9.5
Cement, wet process	6.5	Insulation, recycled wool	14.6	Timber, biofuel dried, dressed	4.1

EMBODIED ENERGY FIGURES FOR COMMON NZ BUILDING MATERIALS (After Alcorn (2003) and Jacques and Sheridan (2006)					
MATERIAL	EMERGY MJ/KG	MATERIAL	EMERGY MJ/KG	MATERIAL	EMERGY MJ/KG
Soil/cement	0.4	Paint acrylic water based	88.5	Timber, mouldings	3.1
Fibre-cement board	11.0	Paint alkyd solvent based	98.1	Timber, Plywood	22.2
Concrete block	0.94			Timber, MDF	11.3

Table 1. Embodied emergy ratings for common New Zealand building materials. (After Alcorn (2003) and Jacques and Sheridan (2006).

One way of reducing environmental impact is through recycling, reusing, or reducing materials. Recycling is the reprocessing of materials into new products in an effort to prevent resources from being wasted, by reducing the consumption of raw materials and energy consumption required when compared with initial extraction processes (Boyle, 2004 and Morel et al, 2001). This is particularly true for metals such as copper, iron and aluminium. Other materials that are routinely recycled include crushed concrete, rubber, glass, asphalt, wool and clay. However recycling can be problematic in that it can often be more expensive and environmentally detrimental than initial extraction processes and the products produced can be inferior to the initial product thereby limiting its effectiveness. (McDonough et al., 2002) It has been also argued by researchers (Addington, 2005 and Moe, 2007) that rather than reducing consumption, recycling and reusing materials can have adverse effects through increasing overall consumption.

Another way of reducing the environmental impact is through using the Cradle to Grave analysis. This model for assessing environmental impact of manufacturing processes and use follows a linear cycle from extraction to use to disposal. It assesses traditional manufacturing processes, which are mostly reliant on fossil fuels and the use of toxic chemicals to opportunistically extract raw materials. The solutions produced by these manufacturing processes become discarded once they are considered obsolete thereby creating waste or what have been referred to as

"monstrous hybrids" that cannot be recycled further or can only be recycled through down grading – a result of "bad design." By contrast, Cradle to Cradle (McDonough et al., 2002), is a term which refers to the development of production techniques that are essentially waste free, where material inputs and outputs are seen either as " technical or biological nutrients" that can be recycled or reused. Cradle-to-Cradle rejects the on-going utilisation of destructive industrial processes in favour of processes, which are "eco effective." In Cradle to Cradle/Remaking the way we make things, McDonough and Braungart argue that a clear understanding of a materials flow though various life cycle stages from extraction, production, manufacturing, use, recovery/ reutilisation and impact on environment and health alongside the utilization of solar energy in manufacturing processes, leads to more intelligent design decisions that bring about long term positive benefits. (McDonough et al., 2002)

Over the last few years, driven by concerns over global warming, our commitment to the Kyoto protocol and legislative changes in the building industry, New Zealand has introduced a number of sustainable strategies for producing carbon neutral houses which have mainly focused on reducing energy consumption through increased insulation, using passive solar heating, adding thermal mass to reduce energy consumption and using low emergy materials such as straw bale and adobe to reduce carbon emissions. While the technology already exists to radically reduce carbon emissions, these strategies need to be embedded at the commencement of any design process interested in developing new building products. This can be achieved in the following ways:

At the material selection stage for developing composites, the embodied energy or emergy for materials proposed for the development of buildings should be considered. (Boyle, 2004). It is short sighted to mainly focus on developing materials drawn from non renewable resources, which are already known to have excessively high emergy rankings, such as steel or aluminium, when sustainable alternatives exist, unless they can radically improve their manufacturing processes and energy efficiency and be effectively recycled and reused. The alternative is to focus on developing materials with lower emergy rankings. This is a strategy used by BRANZ. Composites developed using materials with low emergy ratios, e.g. bio materials such as plantation grown timber, bamboo, straw, and flax, or recycled materials such as paper or glass are far more sustainable than those constructed using materials with higher emergy ratings drawn

from non renewable resources. These low emergy materials achieve strong results, as evidenced in the production of zero energy houses (ZALEH), built using traditional methods of straw bale and adobe. In order to select the best materials for composite development, life cycle assessment techniques identify the best options for material selection in terms of technological processes, construction methods, implementation and recycling/reuse capabilities, as well as consideration of the impact on the environment from pollutants, energy consumption, fossil fuel consumption, water consumption, land degradation/consumption, resource consumption, waste production from raw material extraction, processing, construction, and building operation (Boyle, 2004). To encourage an informed process in material selection, the Waitakere City Council has developed a free on line system "Tool for Urban Sustainability – Code of Practice" (TUSC) for assessing the lifecycle of materials and building systems, so that designers/consumers can more easily assess the environmental impact of their design.

Another important consideration is the durability of a material or building system. This involves calculating how buildings age in terms of maintenance, occupancy and visual appearance. Buildings constructed in materials which last longer and which require less maintenance are considered more sustainable than those which need regular resurfacing or repainting. Most materials specified for external applications in building construction have a limited life expectancy with regular repairs or replacement required throughout its lifespan. Over time, weather acts on these materials breaking down the constituent parts so that eventually without maintenance the building becomes a ruin. To avoid this process, buildings are either routinely replaced or conserved, such as through recoating external surfaces with paint. Both strategies are expensive and wasteful in terms of natural resources (Jacques et al., 2006) In order to avoid maintenance, developing composites using materials and fixing procedures capable of lasting for the lifetime of a building (at least 100 years or more) or which weather without detriment to the overall aesthetic or structural integrity is more sustainable.

The durability of materials also has an impact on aesthetic considerations. Newness is conventionally associated with novelty and cleanness, while agedness has connotations of degradation and disease. The negative associations of agedness are emphasised by a concern with hygiene, and epitomised by the clean lines and white facades of modernist architecture.

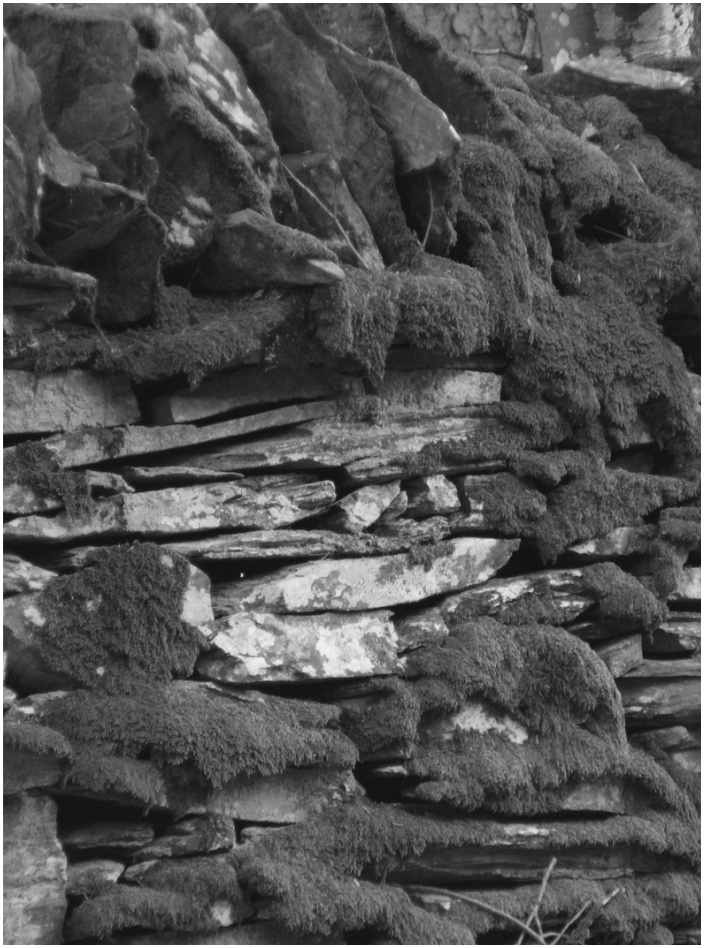


Fig. 1 The most sustainable approaches to building use materials that are locally available, which can transform over time through weathering without detriment to performance as in this example of a dry stone wall covered in moss.

Modernist buildings require regular repainting to maintain their crisp lines and aesthetic appeal of newness. Leatherbarrow et al. (1993) argue that buildings are inherently temporal structures that inevitably change over time due to weathering. The consideration of transformation of a building's materiality registered through a patina of weathering or marks of occupation emphasises a significant shift in considering a buildings materiality, with signs of agedness being associated with character and added value. Materials that have long lasting durability such as stone register traces of occupation and weathering as they age. The gradual accumulation of dirt, water stains, surface erosion and gradual occupation of pits and crevasses by lichens, mosses and grasses (fig. 1) transforms inert facades into living surfaces that are always transforming.

Another important consideration for developing sustainable solutions is through developing flexible building systems that last. Buildings are usually designed to meet certain performance criteria and budgetary constraints, for a fixed or limited occupancy. Closely linked to notions of durability are strategies to build more flexible building systems that allow for changes in occupancy over the duration of a lifetime that spans well beyond initial contexts. A plethora of conflicting constraints inevitably effect the outcome of a building project. But if we are designing buildings to last, we need to consider longer-term strategies and have a deeper awareness of future growth patterns, and socio economic considerations that may not be initially apparent, but which will effect how a building is used. Developing an awareness of long-term serviceability demands a change from current practices of designing for the short term. For designing building composite systems, this would mean manufacturing products that can easily be dissembled or adjusted in relation to changing requirements.

Buying locally manufactured products instead of importing from global sources is another approach to being more sustainable. Most of the energy consumption and negative environmental impact of materials used in buildings occurs during the extraction and processing and transportation of raw materials. Studies (Morel et al., 2001) have proven that significant reductions in energy consumption occur when local materials rather than imported materials are used. This leads to the conclusion that local materials readily available in New Zealand rather than those imported from overseas should be used for developing more sustainable building materials.

In order to become more sustainable, buildings and new generations of materials should become more energy efficient. Depending on where they are located and how they are designed, future building systems will be able to not only passively absorb and store heat, but also draw heat away from overheated spaces as well as act as a self sufficient energy sources. By using new technologies, sustainable prototypes can generate enough power to meet changing environmental conditions or even supply energy to neighbouring houses. Self sufficiency can be achieved by designing houses using materials that are thermally efficient, which actively respond to solar heat gain, and which harvest daylight, air and solar energy. Recent studies by scientists at Waikato University (Newzedge 2007) have been investigating the development of alternatives to silicon-based solar cells based on chlorophyll dyes. Innovations like this could make solar generated power sources more cost effective and more reliable, as unlike silicon based solar cells, these systems are able to generate power on overcast days (Newzedge 2007). Energy saving design at all levels of the design process has a significant effect on energy consumption, and strategies to reduce energy consumption have already been applied to changes in the building code mostly in relation to preventing heatloss through insulation.

Existing manufacturing and extraction processes also need to be re-evaluated and alternative methods used to minimise impact. This means that in future, processing plants will use alternative power sources (solar or wind power) and consideration will be given to minimising disposal and waste through recycling (McDonough et al., 2002). Other strategies include setting up smaller portable manufacturing systems close to construction sites thereby reducing transport requirements from centralised manufacturing plants.

One of the greatest impacts in developing more sustainable buildings and building materials is through the application of Cradle-to-Cradle analysis, which considers how buildings or their materials are either reused or recycled. If a building is expected to last for a certain number of years, how can it be designed so that it accommodates different uses? How can it be designed in such a way that once it has been decommissioned, the materials can easily be dissembled and recycled?

Biocomposites derived from a combination of biobased materials and synthetically produced

polymer resins such as polyester and polyethylene is another area that has seen significant developments in recent years in developing sustainable prototypes (Drzal et al, 2004). Our rapidly diminishing stock of fossil fuels and evidence of increasing oil consumption has lead to a stronger worldwide focus on developing more environmentally friendly products and processes using wood and biocomposites. Fibres from plants such as bamboo, cotton, jute, kenaf, flax or hemp, and plastics from soybean, wastepaper, corn and sugar have all been used to manufacture strong lightweight building materials, which, through advances in innovative manufacturing processes, have become stronger and cheaper to produce than composites manufactured using traditional plastics and glass fibres. Natural fibres have many advantages over other materials: as not only are they cheap to produce, they are less dependant on fossil fuels for extraction and processing, they come from a renewable resources which are easily grown, and they can be biodegradable thereby reducing potential future harmful environmental effects.

Sustainability in building construction, effectively considers the environment, site, location, availability of materials and the manufacturing processes. This section has introduced the key concepts that are considered in relation to developing more sustainable building prototypes. Consideration of sustainability in relation to future building systems will not only better serve the environment, but will provide better foundations for the long-term serviceability and viability of future building systems. In this respect, sustainability is considered as a critical component to the development of any future building prototype.

The following sections consider sustainability more specifically in relation to emergent technologies and generative processes which intelligently interlink material systems and energy flows in response to environmental impact.

1.2 THE IMPACT OF NANOTECHNOLOGY

"Six years ago they began to get invisible, glass or no glass. Nobody has ever seen the last five I made because no glass is strong enough to make them big enough to be regarded truly as the smallest things ever made. Nobody can see me making them because my little tools are invisible into the same bargain. The one I am making now is nearly as small as nothing." (Flann O'Brien, *The Third Policeman*, 1939).

Future composites will embrace nanotechnologies in their ability to be "self-contained, self-propelled, programmable, intelligent, and regenerative." Karim Rashid (Beylerain, 2005, p269)

Perhaps the most profound advance in the future development of new building components will come with the exploitation of nanotechnologies. Nanotechnologies reduce elements down to a scale measured in nanometers. The ability to manipulate matter at a microscopic scale using atoms and molecules to construct things was first imagined by Feynman in 1959. Although still in its infancy, many bottom-up technologies using nanotechnologies have already been developed to manufacture nanocomposites for the building industry, such as self cleaning windows, flexible solar panels, concretes that self heal/clean/bend and panels that emit light or sense and respond to environmental changes. (Addington/Schodek, 2005).

The term nanotechnology comes from the Greek *nanos* meaning dwarf, hence of microscopic size, one thousand millionth (10-9), *logos* relating to science or discourse and *techné* which refers to the art or craft of how something is made.

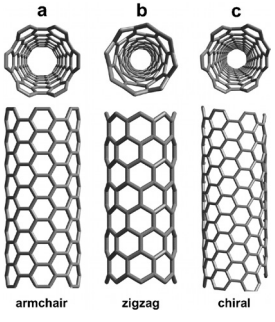
The internal makeup and bonding forces between different materials is the main determining factor in the performance ability of a material. If the molecular structure of a material can be manipulated from scratch it is possible to significantly alter the performance of a material without even changing the initial components. By manipulating substances at a molecular scale nanotechnologies radically transform the performance of existing composite materials, making them stronger more durable, more energy efficient, lighter and more intelligent in terms of an ability to respond to stimuli. This is achieved by either manipulating the molecular bonding

between atoms or developing composites with the addition of carbon-nanotubes, (one of the most important and strongest materials available) or other nano materials. Carbon nanotubes (Fig. 2) are members of the fullerene structural family. They are formed as a cylindrical or spherical arrangement of carbon atoms (bucky balls and tubes). Carbon nanotubes can be used to strengthen the material properties of composites at a molecular level. They also have electrical properties which enable them to generate energy or act as sensors to find cracks in structural components or sense temperature changes which can then be relayed to operative systems.

Research investigating the potential of nanotechnologies in housing applications includes projects such as the "nanohouse" a case study house developed as a joint project by the University of Technology, Sydney, and the CSIRO to demonstrate its use in the creation of a more sustainable and environmentally friendly living environment. The "nanohouse" has innovations such as: self-cleaning windows which block heat and ultra-violet radiation, or which can change transparency as required. It also has self cleaning/sterilising bathroom and kitchen surfaces coated with thin coats of titanium-dioxide to repel dirt and kill bacteria, and long lasting nano-enhanced timber joinery that does not require regular repainting. Inside, light is pumped through the house like water in "energy efficient polymer nano-composite light pipes." (Davis, 2003) The walls are coated in paint with a powdered nanoparticle additive, which operates as a sensor to pick up temperature changes, while "nanoscale chromophores" allow the walls to change colour or transparency (on glass) as required. Minute solar cells in the paint generate so much energy that surplus energy can be transmitted to neighbouring houses.

The Leeds NanoManufacturing Institute (NMI) has also developed a house using nanotechnologies designed to withstand earthquakes in Greece through its self-healing properties. This house is built using an intelligent sensor network and nano polymer particles added to a concrete matrix which turn to liquid under pressure, but which self heal when the liquid flows into cracks and hardens to a solid material again.

While it is apparent that there are significant improvements in terms of material performance capabilities and sustainability using these technologies, the applications in the above examples do not significantly break from past practices in terms of how buildings are actually built. At this



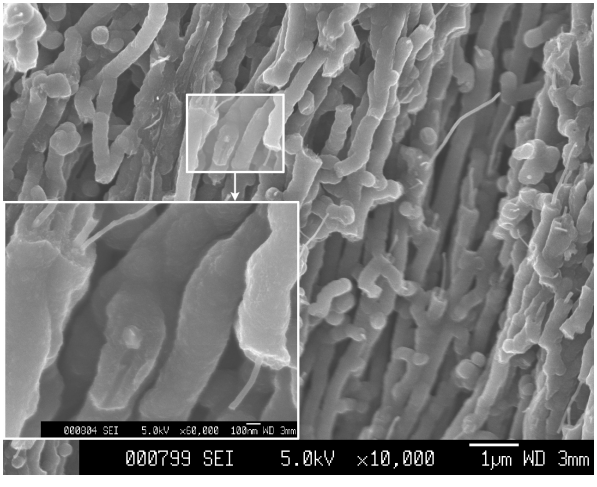


Fig. 2 Structure of carbon nano tubes.

stage, the real potential of nanotechnologies are only just beginning to be understood. Eventually nanotechnologies could fundamentally alter the way buildings are manufactured, as buildings will no longer be assembled on site from a series of different parts manufactured in off site factories. Instead Hosey writes:

"Experts anticipate that within the next few decades, large-scale objects, including buildings, could be fabricated using microscopic robots called assemblers, which would join to make a cybernetic glue, able to assume any shape and size. Such an instrument would eliminate traditional constraints of design and construction. Standard, irreducible components, such as the 2 X 4, the brick, steel shapes, nails and screws, will be replaced by microscopic parts. Form, texture, color, and strength would be defined at the cellular level. Orthogonal geometry, demanded for efficiency by standard frame construction, could disappear altogether." (Hosey,2003).

While Hosey's prediction that this might happen in the next few decades may be overly optimistic, this radical shift in the generation of form making, means that buildings will be freed from the constraints of orthogonal construction through innovative manufacturing processes which will organically grow the building on site with fully integrated self generated skins. For the uninitiated, developing buildings through self-assembly and replication borders between the realms of science fiction and reality. Through nanotechnological assemblies, a delicate intricacy can be achieved that is impossible using any other process. Freitas and Merkle (2004) have compared our current manufacturing processes to "trying to build lego wearing thick gloves". The real potential with this technology comes with the development of processes of self-assembly and self-replication. Self-assembly refers to molecules or even structures that can build themselves. While this happens in natural systems, and is starting to be applied in biomedical fields using cells to artificially grow organs such as skin, the real challenge in relation to architectural practice is how can we replicate self assembly and self replication processes artificially so that for instance a house could be assembled from a pile of dust: or that "We design the components of the house, such as the 2-by-4s and cement blocks, so that they will interact with each other in such a way that when you throw them together randomly they self-assemble into the desired house" (Torquato, 2006). Although they have not yet been applied at to the scale of a house, nanomanufacturing techniques have been proposed to assemble small-scale structures. These nanomanufacturing

processes use molecular assemblers - devices programmed to build form molecule by molecule. These molecular assemblers are in turn linked to larger scale robotic assemblers, which assemble the smaller components into larger scale components until eventually we get to meter sized or maybe eventually in the future building scaled components.

But will the inherent freedom associated with nanomanufacturing techniques produce sustainable architecture? While nanotechnolgies have the potential to be applied to produce more sustainable building systems in terms of generating more flexible, durable and energy efficient building systems, Hosey cautions that this freedom could radically change the role of architecture practice, to one driven by a mechanised self replicating technological excess rather than one driven by a more meaningful consideration of what it is we are creating. So that, rather than creating more sustainable buildings, captivated by the ease at which they can be applied, nanotechnologies could be adversely used to continue a legacy of over-consumption. Added to these concerns, with this technology also comes inherent risks of contamination through the absorption of nanoparticles into air/water food systems or through direct contact with components made using nanofibres. Fernandez has cautioned that the small particles make it difficult to predict how they become dispersed (Fernandez, 2005). Although concerns about the environmental risks have been countered by beneficial environmental applications where nanoparticles have been used to break down toxic carcinogens.

In *Unbounding the Future: The Nanotechnology Revolution*, Drexler et al (1991) speculated on the impact of molecular nanotechnology. In this text the authors optimistically predicted that one of the additional advantages of nanotechnologies is the potential to reduce our dependency on natural resources through mining carbon molecules from the atmosphere to generate materials for houses such as carbon windows and wall systems.

> The best structural materials use carbon, in forms like diamond and graphite. With elements from air and water, carbon makes up the polymers of wool and polyester, and of wood and nylon. A twenty-first-century civilization could mine the atmosphere for carbon, extracting over 300 billion tons before lowering the CO_2 concentration back to its natural, pre-industrial level. For a population of 10 billion, this would be enough to give

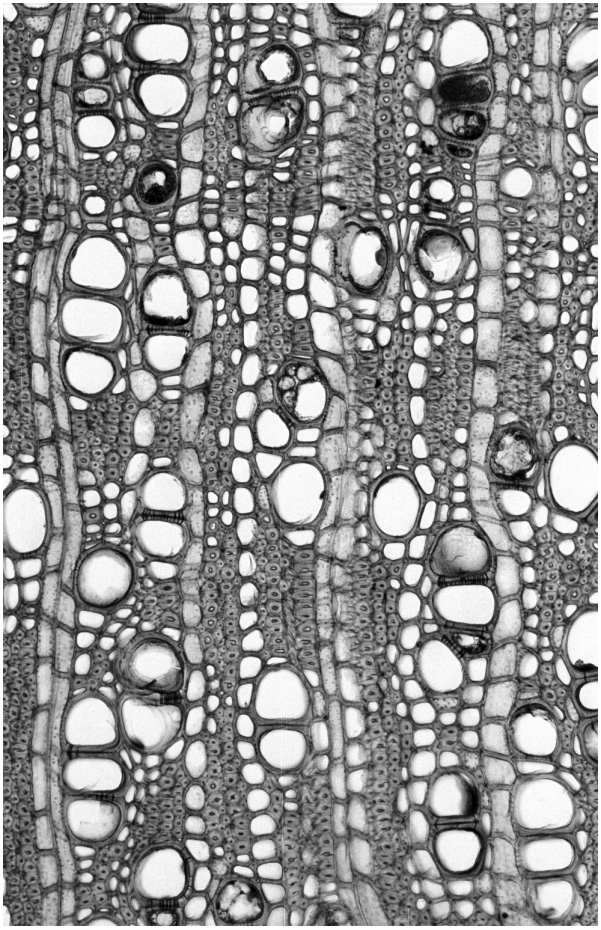


Fig. 3 Microscopic cross section of Olive wood showing variations in wall thicknesses, cell thicknesses and perforations.

> every family a large house with lightweight but steel-strong walls, with 95 percent left over. Atmospheric garbage is an ample source of structural materials, with no need to cut trees or dig iron ore. (Dexler et al, chapter 9)

While concepts such as mining carbon atoms from the atmosphere will only eventuate in a long distant future, driven by concerns of sustainability, nanotechnology is expected to have its most profound influence on the development of bio-based and wood based composites. In the past, biocomposites have had significant problems with moisture absorption, which has effected their long-term stability in building applications. To remedy this, nanotechnologies have already been used to produce thin films and protective coating systems, and advances using "nanoenhanced and nanomanipulated fiber-to-fiber and fiber-to-plastic bonding" have begun to exploit the material potential of bio-based products to produce new prototypes which are more durable, lightweight and strong. Nanotechnology also has the potential to develop intelligent hyper performance bio composites, which have nanosensors to generate electricity, self, repair, measure forces, loads, moisture levels, temperature, pressure, and chemical emissions (Wegner et al. 2006) Wegner argues that these technologies are expected to lead to the generation of smart building bio based products that not only address a reduction in carbon emissions compared to conventional manufacturing systems using glass concrete and steel, but which will be superior to traditional building systems. Carbon nanotubes can radically alter the weak elements of materials sourced from natural/biological and renewable resources such as wood and plant fibre materials, giving wood based composites performance qualities that Wegner claims are equivalent to steel or carbon based products. He suggests that this will make them durable yet at the same time biodegradable at the end of their life cycle. The enhanced performance of biopolymers and bio composites using nanotechnologies will make them extremely competitive as sustainable substitutes, although many claims made regarding how nanotechnologies can be applied have yet to be proven in real world applications.

Anticipated benefits that research into the development of wood based composites will bring is apparent by the extensive funding that has been directed into research in this area in other countries particularly in the forestry industry. The development of wood based nanocomposites is particularly relevant to the New Zealand building industry, which predominantly uses timber

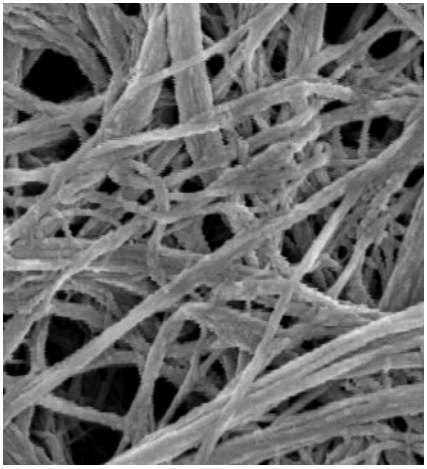


Fig. 4 Microscopic image of cellulose fibrils.

construction for residential developments. In New Zealand, timber construction has advantages over concrete and steel based building processes due to its abundance, cost, ease of construction and flexibility. It also has a positive environmental effect as a carbon sink, it is biodegradable and can be recycled and reused. The main disadvantages in using wood based products is its lack of moisture resistance, combustibility, use of toxic chemical treatments for longevity and lack of weather resistance. Nanotechnologies can rectify these adverse qualities in the following ways:

> New non- or low-toxicity nanomaterials such as nanodimensional zinc oxide, silver, titanium dioxide, and even nanoclays could be used as either preservative treatments or moisture barriers. In addition, resistance to fire could be enhanced by use of nanodimensional materials like titanium dioxide and clays. Nanodimensional barriers could impart long-term weathering resistance, provide ultraviolet light (UV) protection, and provide aesthetically pleasing finishes that will last decades in exterior applications. They could also be used as barrier films and protective coatings (e.g., paints, stains, and other finishes) to provide improved dimensional stability, UV protection, and weathering resistance for wood-based materials used in exterior applications such as windows, doors, weatherboards and plywood panels. Such barrier films and coating could be applied either to engineered biocomposites in the manufacturing process or they could be applied in the field. Either way, the result could be wood-based materials that do not need refinishing for decades. (Wegner et al, 2005)

Two main processes have already been applied to the development of nanobased wood composites. The first uses nano materials or nano sensors to improve existing wood based products; the second exploits the qualities of nanocellulose fibrils that wood is composed of to develop completely new materials that have an equivalent strength to steel or other high performance materials. Nano cellulose fibrils (Fig. 4) have 25% the strength of carbon nanotubes, and are much cheaper to produce than carbon nanotubes. Wegner argues that if nanocellulose fibrils could be extracted from a woody biomass, their high strength could be used to develop inexpensive and more competitive composites of great strength and durability. The only problem at this stage which prevents nanocellulose fibrils being universally applied is developing ways to extract them in the first place. Although an extraction process may already have been developed,

as Peter Testra is currently involved with developing a biodegradable building system called CYAN with EMPA in Swtzerland using nano-cellulose along with engineered composite wood. (Burke et al, 2007)

Once the many technical processes have been overcome, as a sustainable substitute for steel based building components, wood based nanocomposites would aesthetically transfer the built environment so that rather than being masked by paint emulsion to protect a timber substrate, there would be options for timber quality of wood to be expressed. Because of their enhanced performance capabilities, these wood based products would not be limited to residential applications but high rise buildings and sky scrappers would be built out of timber structural components and clad in long-lasting timber panels making commercial construction processes easier to build and less costly to erect than steel or concrete buildings. The ease and flexibility of working with timber based products would lead to a more expressive architecture manifestation. Extending this scenario further, instead of concrete jungles, sustainable cities would be transformed into urban wood scapes.

Nanotechnologies, as an emergent discipline, is still highly theoretical and in its embryonic phase of development. While some of the more extreme ideas surrounding nanotechnology discussed here are intriguing, they mostly remain in a fantasy realm in terms of real world applications as there are significant technological difficulties to be overcome with manufacture and processing. In the building industry, nanotechnologies have mainly been limited to surface applications. But if the problems with extraction and manufacture can be resolved nanotechnologies could have undisputable implications for the future development of sustainable structures. Case studies and examples of nanotechnology merge into some of the following sections of this work demonstrating the far-reaching implications of this technology and how it interweaves with a number of other principles related to the future of sustainable structures.

1.3 DESIGNING MORE EFFICIENT, ADAPTIVE, SELF-GENERATIVE AND INTELLIGENT SYSTEMS BASED ON BIOMIMETIC STUDIES.

In an endeavour to design more efficient building systems researchers have attempted to mimic biological systems in architectural applications. This has become more prevalent with the development of buildings, which behave more like biological structures through using digital technologies, intelligent systems and advanced building materials. Rather than being fixed or static, these biomimetic structures have strong flexible skins, which can be formed into an endless array of compositions. While this may seem like wishful thinking, advancing this concept further, future buildings will be able to transform at will. They will be clad in a "sophisticated architectural skin that can be twisted, stretched, bent and wrapped around in which ever imaginable way and which at the same time can be self supporting, and take any surface quality or colour one can think of" (Zaha Hadid and Beylerain, 2005,p 261). These flexible systems will make buildings chameleon like. They will be able to adapt and transform to varying conditions and environmental loadings, their surfaces will change colour and they will have the capability of being able to shift from translucent to opaque, or become either permeable or impermeable in response to user interactivity. Any anticipated degeneration due to environmental factors could be resolved through inbuilt regenerative, self-healing/cleaning capabilities using nanotechnologies.

This chapter examines processes used by natural systems to produce efficient structures, and considers how these strategies have been applied to the development of building systems which are becoming more adaptable, more intelligent and self generative and therefore as a consequence more sustainable.

Biomemetics comes from the Greek *bios* meaning life and *mimesis* meaning imitation. Biomimicry is generally seen not as a direct imitation of natural forms, but of the systems and patterns used in nature to generate forms that are self-generated from readily available materials. In general these forms are far more streamlined and aerodynamically efficient, responsive, manoeuvrable and lightweight in relation to man made versions. Natural systems have advantages over conventional artificial systems, as they have an ability to adapt to external forces and self-repair. They also use a minimum amount of material in relation to structural effect. Typical examples of natural forms

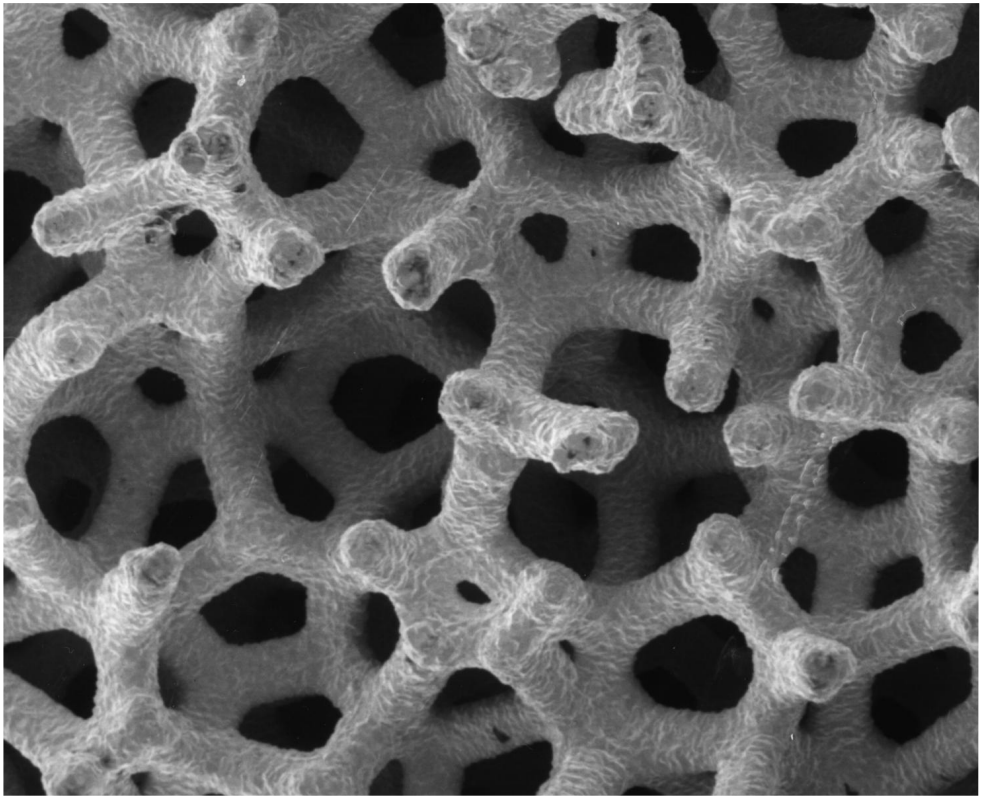


Fig. 5 Stem cells which self assemble to artificially grow bone marrow.

that are referred to in biomimetic studies in relation to architectural applications include studies of bamboo, birds/insect wings, spiders webs, shells, skeletal/skin structures, and hyperbolic structures.

Predominantly driven by practitioners associated with the Emergence Design Network, and discussed in *Architectural Design*, Techniques and Technologies in Morphogenetic Design (published in 2006), the study of biomimetics has more recently lead to a more complex awareness of the generation of architectural structures based on a fascination for and application of the inherent complexity and variation of biological organisms and natural forms, which coexist and respond symbiotically to surrounding environmental conditions. Drawing on intensive biological studies, the writers of this journal have identified several consistent characteristics that occur in naturally occurring structures, which enable them to adapt and respond to varying environmental conditions. Some of these are listed as follows.

One of the most significant qualities of biological systems is their ability to self organise. At a molecular level, patterns form in natural systems in response to a series of complex interactions of each part to different environmental conditions (Fig 5). Some of these patterns become visually manifest such as in the spiral formations found in shells and broccoli flowers heads. Other patterns are less visually explicit, but over time and with mutation these interactions enable each part to self organise into the formation of natural structures. (Davis 2005, Weinstock 2004) These natural structures have important capabilities in terms of an ability to respond to extreme loads and variable environmental conditions. It is these qualities that make biological systems worth analysing at a macromolecular level, with the intention that some of these attributes could advantageously be applied to the development of more adaptable building systems.

An important term behind the understanding of the processes that control the self-organisation of each component in biological structures is the concept of morphogenesis. Morphogenesis refers to the origin and generation of shape at a molecular level, and the patterns, which occur in response to external conditions exerted over a period of time. It comes from the Greek *morphé* meaning form and *genesis* meaning generation. With morphogenesis, over time natural systems become self organised out of a series of disordered components and form into distinctive and repetitive patterns. The self-organization found in natural systems is "a process in which

the internal organization of a system adapts to the environment to promote a specific function without being guided or managed from the outside" (Hensel, 2006 p. 13). This process of self-organisation allows a system to flexibly adjust in response to ever changing conditions rather than remaining fixed and immutable. It is this flexibility, which gives biological structures a much greater capacity to respond and adapt to changing forces without breaking down. By comparison, although traditional building systems using uniform structures are efficient and simple to build and understand, they can only respond to certain specific conditions, as each component within the structure is determined to perform in a particular way. If these conditions alter or become unpredictable they become vulnerable to failure. To compensate for a lack of flexibility, traditionally built systems are over specified.

When consistent forces act on biological structures, such as when wind acts on trees grown on exposed sites, the trees become permanently bent to create the least resistance to wind. The force of the wind acts on the structure in such as way that the structure eventually becomes conditioned and adapts to suit. Hensel has argued that the conditioning that the structure undergoes is "a learning process in which an organism's behaviour becomes dependant on the occurrence of a stimulus to its environment. In turn this requires a careful calibration between behavioural and by extension, performative patterns in relation to specific ranges of environmental conditions. The capacity for this can be embedded in the makeup of materials and in the logic of material assemblies" (Hensel, 2006, p. 11).

Manmade building components such as composite panels usually rely on the uniform distribution between fibrous and matrix materials to create uniformly strong elements. Uniformity does not exist in natural systems. Natural systems use "redundancy" as an essential development strategy, "without which adaptation and response to changing environmental pressures would not be possible" (Weinstock, 2006, p 27). Weinstock points out that natural structures such as bamboo have inbuilt sacrificial bonds or redundancies, which allow natural structures to organically deform, so that they can withstand external forces. He writes: "Biological systems are self assembled, using quite weak materials to make strong structures." (Weinstock, 2006, p27) This element of redundancy is evident in the patterns that appear in all natural systems in response to stress loadings from gravity. These redundancies enable the structure to elastically deform without

Fig. 6. Image of wasps nest showing cellu;ar units constructed from mud and fibre to form a self-supporting structure.

loosing integrity. Enhancing this element of redundancy is a minimal use of materials. The ratio of void to material components optimises the strength and flexibility of the structure depending on forces acting on it. It is the combination of a minimal amount of materiality coupled with the presence of voids/redundancies, which makes natural systems structurally more efficient (Fig 6).

The question, which emerges from these investigations, is, can the study of biological strategies be applied to develop structural composites capable of responding to greater forces than conventionally constructed components determined by optimisation and efficiency alone? Weinstock argues that similar strategies for building systems should be applied, and while the dynamics of structural systems are complex and variable, there are some factors that could be considered in relation to the following:

- The differential distribution of voids and fibres on response to forces acting on the component.
- The use of flexible jointing systems, which allow for morphological continuous changes rather than mechanical changes between different sections.
- The use of variable asymmetrical sections. This variability and asymmetry produces "anisotropic properties and a graduation of values between stiffness and elasticity" (Weinstock, 2006, p33) which affects the resonance and frequency of vibrations within a structure.
- Torsional softness that transfers bending energy into twisting energy.
- The use of inbuilt sensors and actuators, which enable it to respond to external stimuli.

Another quality associated with biological structures is their ability to be self-generative. Natural systems grow from readily available resources using a minimal amount of energy. The glass sponge is a good example of this efficiency. Its beautiful lattice like glass frame is self generated under the ocean without a glass furnace! If only this natural self-generative process could be replicated artificially. To replicate this process artificially requires an understanding of how natural systems self generate. In natural systems evolutionary processes are contained within a specific species and environment. Small incremental alterations occur over generations with mutations. These mutations don't necessarily enhance the overall population but contaminate it in such a way

Fig. 7 Manifold project, a wall panel investigating honeycomb morphologies by Andrew Kudless for MATSYS.

that only the fittest survive through natural selection and carry on to the next generation. The evolutionary process of natural systems can be replicated through the application of genetic algorithms, which follow similar principles as natural systems using simple codes to generate more complex solutions. The fundamental driver behind this methodology is digital computation, which on its simplest level is a system which processes information and manipulates it recursively in a series of stages to generate outcomes.

Based on an observation by the mathematician Stephan Wolfram (2002) that "All processes, whether they are produced by human effort, or occur spontaneously in nature, can be viewed as computations," Karl Chu (2006) has argued that although the actual computations involve simple processes, the implications are profound and represent a fundamental shift in thinking about how form can be generated. While most existing practices are still entrenched in traditional modes of form making, there is the potential for self-replicating processes to be developed which directly link computational methods with constructional methods. This is most evident in small scale operations within the biomedical fields where scientists have successfully grown artificial skins for medical grafting using advanced computer aided technologies. On a larger scale the technology remains peripheral, although one of the best examples to demonstrate how this technology has begun to be applied to an actual building processes is the Milgo experiment. This is a research project carried out by Haresh Lalvani in collaboration with Milgo/Bufkin a metal fabrication company, interested in developing fabrication processes to test the vocabularies of the curved surfaces found in nature.

By using "AlgorRhythms" a computational algorithm that defined "families of surfaces" and by directly linking software to hardware fabrication processes, Lalvani developed a system that has been used to manufacture a series of variable columns and walls with curved surfaces without deforming the metal or relying on standard methods of sheet forming. Lalvani has argued that eventually, endlessly variable units could be manufactured using this same process. The implications of this technique for generating uniquely curved forms in metal manufacturing and other material applications are considerable, as methods for producing similar forms currently rely on either using expensive dies (which can only produce repetitive, identical forms) or hand manipulation processes (which are labour intensive). Lalvani's work on the Milgo experiment has

Fig. 8 Model (International Pavillion Venice Biennale 2008 BI[r]O-BO[o]T) demonstrating small-scale iterations of programmed modelling that evolves with each generation.

subsequently lead on to the development of "The Morphological Genome" a model for mapping infinite types of form based on a limited number of "morph genes".

The fascination of morphogenetic strategies for generating form has also lead to the development of complex lattice networks (Fig 7 and 8), made physically possible through digital processes linked to rapid prototyping techniques, which enable the generation and evolution of structural systems that have increasingly complex structures. Rather than being fixed or uniformly generated from a singular component (one size fits all), these structures are generated through evolutionary computational methods and evolve or adjust to specific conditions in response to variable data. As evolutionary form generators, structures or material systems they can also merge data from finite element analysis and fluid dynamics. This means that the design process itself becomes one, which represents an integration of multiple diverse systems. An addition to these advances in form generation is also the potential of the application of advanced technologies for these systems to artificially grow through self-replication.

In terms of their structural efficacy, such complex bio-mimetic lattice structures generated through evolutionary computing methods are not only profoundly intricate but they have better performance abilities in relation to their resistance to structural damage. This resistance was demonstrated by Vincent (2006) based on his observations of the molecular structure of trees, and researchers such as William et al, who found in their 2004 study on microscopic lattice structures that: "organized microstructures like those found in seashells, e.g. nacre and conch shells, result in a dramatic increase (100x to 1000x) in fracture resistance compared to the base material" (2004, p. 2). They found that the localized damage of a microscopic lattice stayed true to the nature of the fracture resistance functions and that stress curves and failure of shear bonds to significant proportions still did not cause overall structure failure (William et al, 2004). Following this logic, designs that mimic the biological in a morphogenetic evolution of latticed structures are far more resistant to failure than conventional counterparts. This means that while the structural damage to conventional modes of architectural building systems can have dire repercussions, the way in which biometric lattice structures react to damage is more efficient. Maintaining the damage to one localized region and then distributing the weight bearing functions throughout the composite allows for adaptability, which is more in tune with a biological organism than with an

Fig. 9 Peter Testra Carbon Tower.

inanimate object. While some non-sustainable methods can arguably perform the same task, the way in which it is accomplished is far less efficient than one that has a lattice structure.

This is an approach that has been applied to the generation of Peter Testa's Carbon Tower. (Fig. 9) This high-rise building was designed to use a fully integrated woven carbon fibre structure impregnated with a resin matrix and surrounding a more conventionally constructed core of steel reinforced concrete columns. The towers basket-like lattice structural components have inbuilt redundancies, while the helixical bands give the building torsional flexibility. "The resulting hybrid structure combines a flexible building envelop with a rigid core, yielding a structure that is earthquake resistant." (Testra 2002, p16) The tower also incorporates other innovations in its manufacture. Its structural skin is self-assembled from 24 helical bands of carbon fibres, which are protruded and braided into bands on site by two portable robots. As the carbon bands rise up the tower, some fibres are diverted to form cables that run across the structure. These cables are then woven into laminated resin floor slabs. According to Beesley and Hanna (2005), the carbon fibre composite building system proposed for this design has advantages over more traditional steel reinforced building systems, as not only is the structure light and strong, but the materials are easy to transport, and when combined with a resin matrix require half the energy of steel to manufacture. Another advantage of this building system is that unlike a steel assembly process it can be easily manufactured on site.

Another example of a building system that is generated through a biological process is a project that rather than replicating biological processes artificially, literally uses the same processes as sea shells to generate structure. Seashells and coral structures are built using materials absorbed from salt water. Studies of the accretisation of seashells have lead German architect Wolf H Hilbertz to propose the development of lime-based structures (seacrete) for buildings, which replicate the same biological processes that occur in making coral and shell. This process precipitates the natural lime and magnesium found in salt water through electrolysis onto a metallic mesh, which acts as a negatively charged cathode. A Carbon or graphite anode is then placed close by so that magnesium and calcium become attached onto the mesh. Hilbertz (2006) has successfully used this process to build artificial reefs and stabilise under sea structures and has also proposed that this method could also be used to build habitable structures.

Alongside the structural impact of biological influences in the generation of building structures has been the development of intelligent or smart systems. Intelligent systems are directly connected to biomimesis but applied quite differently in terms of emphasis and integration. There are many interpretations as to what constitutes intelligence, from systems that use the latest technologies through to systems that act more responsively to variable conditions – thereby requiring intelligence in order to respond. Intelligent materials and structures are generally defined as animated systems, which mimic natural biological systems to produce prototypes, which alter and adapt. The biological systems, which they mimic, are considered intelligent, in terms of their low energy consumption, frugal use of resources, self-organising potential and ability to respond to different environmental conditions. These systems usually depend on sensors, actuators and processors in order to be responsive.

To create a responsive adaptable environment, future buildings need to become more fluid, programmed to move in response to external stimuli. This dynamic quality is the main feature that differentiates physical materials that are defined as "intelligent" from conventional static materials (Wallace et al 2002). To become dynamic, the structural components and skin of future built structures will need to be adaptable, embedded with sensor systems either at a bulk material level or at a macromolecular level depending on how the component is manufactured. Using these technologies building systems will behave like a living organism, their sensors will be able to pick up data in response to varying conditions and respond. In this respect, Oosterhuis writes:

> The sensory skin is the mediator between environmental conditions (both external and internal) and the synthetic entity of the body itself. The sensory skin is an intelligent

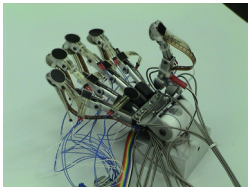


Fig. 10 A robotic hand which uses intelligent systems to operate.

> membrane enveloping and protecting the building body as a cell. The sensory skin is the interface between body and environment and hence between the body and its users. (Kas Oosterhuis, 2006)

Hight and Perry define intelligent systems as:

> Examples in which intelligence is embedded in a given technological or material system range from genetic and nanoengineering, to the development of new and increasingly adaptive organic LED display systems and amorphous alloys, as well as the burgeoning field of programmable matter material systems in which the fundamental properties of that material – for example, its rigidity or flexibility – can be altered via information. (Hight and Perry, 2006, p7)

According to Wallace et al (2002), intelligent systems are based on the principle that all living systems use sensors (nerves), actuators (muscles), a control centre (the brain), and a host structure (a body, with or without bones) to sense changes in the environment (refer table below). Consideration of these attributes has lead to the development of "smart" systems that similarly use sensors and actuators and processing control centre to mimic natural systems. The sensors used within these systems are usually visual/optical, acoustic/ultrasonic, electrical, chemical, or thermal/ magnetic. These sensors relay electrical signals to a control unit, which is able to process this input and respond to it in some way. The response is relayed by actuators, which are usually piezoelectric materials, shape memory alloys and electro-rheological fluids. Piezoelectric materials have an ability to develop an electric charge when subjected to a mechanical strain. This means they can also act either as sensors or actuators by creating a mechanical strain in response to an electric charge. Common piezoelectric materials include lead zirconate titanate (PZT) ceramic and polyvinylidene fluoride (PVDF) polymers. Shape memory alloys are metals that "remember" their geometry such as nickel-titanium alloys, while electro-rheological fluids are suspensions of extremely fine conducting particles within a non-conducting fluid. These fluids have the unique ability to quickly go from a solid state to a fluid state. The responses carried out by actuators are triggered by a control system. Control systems allow for the provision of conditioning or learnt behaviour to lead to responsiveness to adjust to existing conditions.

In intelligent applications they include microprocessors, and controlling systems, which mimic biological systems such as neural networks, the application of fuzzy logic and non-linear adaptive controller.

INTELLIGENT SYSTEMS		
SENSORS (Nerves)	ACTUATORS (Muscles)	CONTROLLERS (Brains)
Optical Chemical Acoustic/Ultrasonic Electrical/Magnetic	Piezoelectric Shape memory Alloys Electrorheological Fluids	Microprocessors Neural Networks Fuzzy Logic

Table 2. Intelligent systems.

Many prototypes of fluid dynamic systems have been built in the materials and engineering fields, especially with the development of smart materials which use the interdisciplinary technologies of materials and structures, sensor and actuator systems, and information processing and control systems to produce models that are able to respond to variable conditions. These systems have been mainly applied to specialised applications such as the aeronautics industry, for instance in the development of wings on aeroplanes that change shape depending on whether the plane is flying or taking off. These wings are made from composites, which have piezoelectric properties, which can bend and shape the wings when an electrical voltage is applied.

Although developments using this technology in the building industry are still emergent, eventually smart material structures will be developed which won't be reliant on passive systems, but will be active in their response to environmental stimuli. These systems will use advances in the development of actuators, piezoelectrics, shape memory alloys, electro-rheological fluids or electrochromic glasses, to transform their form or adapt to different environmental conditions by absorbing vibration or controlling light transmissions. Fernandez (2005) and Addington (2005) both suggest that future new composites using smart technologies will be constructed with

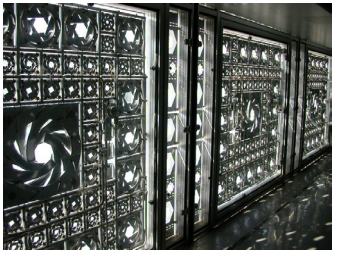


Fig. 11 Jean Nouvel's Institute du Monde d''Arabe has an intricate facade that modulates light to the interior using shutters that open and close like a camera lens.

Fig. 12 Tristan d'Estree Sterk's tensegrity structure, has been used for a proposal for shape shifting buildings, from the Office for Robotic Architectural Media and Bureau for responsive Architecture.

thin polymeric smart skins embedded with multifunctional abilities which will control physical conditions such as acoustic noise, vibration, drag, and skin friction and degradation from external contaminants caused by pollutants and erosion.

It could be argued that the Institute du Monde d'Arabe designed and built in 1998 by Jean Nouvel (Fig. 11), can be considered an early example of a building using an intelligent system, with its interactive animated façade. Reminiscent of the intricate screens found in Islamic mosques, the façade was constructed with a series of high-tech photosensitive ocular devices, which operated like camera lenses to open and shut, controlling light levels and transparency to the interior. Unfortunately the sensitive mechanised system controlling the façade has gradually failed; undermining the efficacy of the design, and reinforcing the vulnerability such systems have. Other examples of responsive façades include Saurbach Hutton's GSW Headquarters Berlin (1999), which controls sunlight, and heat absorption, using computer controlled perforated panels, which tilt in response to heat and light levels. More sophisticated versions of flexible programmable building surfaces and structures include Mark Goulthorpes' Aegis Hyposurface (2001) an elastic architectural surface made up of small metal plates that are controlled pneumatically and reactive in real time to electronic stimuli from the environment (movement, sound, light, etc) and Tristan d'Estree Sterk and Robert Skelton's "tensegrity" (Fig. 12), a moveable structural surface, composed of a complex skeletal building system of sensors and actuators to control rods and wires using pneumatic "muscles" to change the shape of the building. D'Estree Sterk's intention in creating this structure was to imitate the ways in which natural systems made of many interconnected elements could be manipulated to change shape without losing structural integrity. He has argued that flexible structural systems have advantages over fixed structures and that the net effect of using adaptable systems will result in an ability to build much taller and lighter structures that flex in response to wind direction, a strategy being researched by d'Estree Sterk to design tall lightweight buildings.

Other materials that are interactive to environmental conditions include electrochromic glass, a product developed as an energy-saving component for buildings. This glass has the ability to change colour on command. It works by passing low-voltage electrical charges across a microscopically thin coating on the glass surface, to activate an electrochromic layer which changes

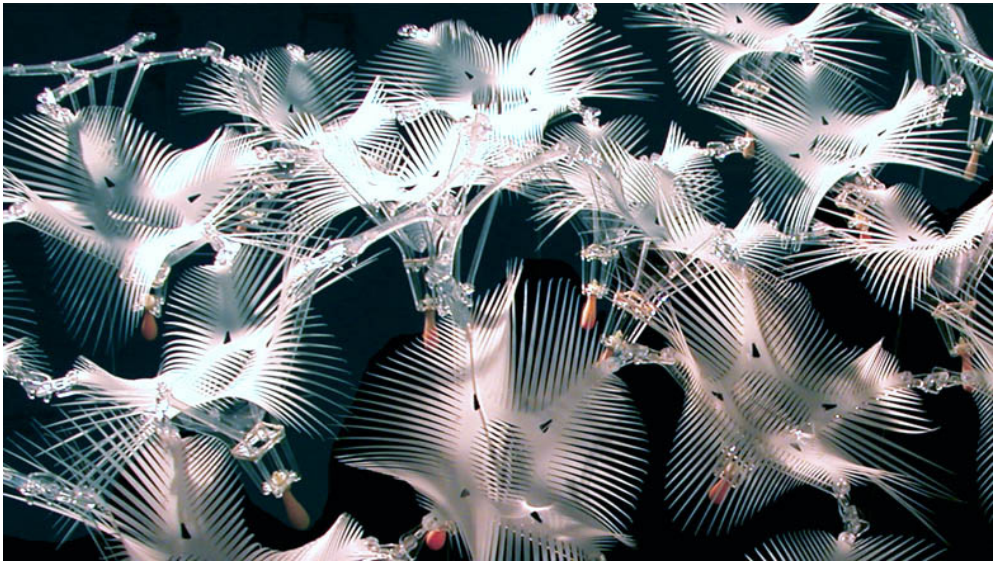


Fig. 13 Philip Beesley's Orgone reef is a proposal for the fabrication of a geotextile that supports its own eco system like an artificial reef. it comprises of undulating surface of laser cut components, which are activated by sensors and actuators that respond to varying stimuli such as movement.

colour from clear to dark. This electric current can either be activated manually or by sensors which react to light intensity. This ability to darken the glass effectively reduces solar transmission into the building. When there is little sunlight, the glass brightens, so that the need for the artificial light is minimized. It has also been used as a privacy device to screen windows.

Philip Beesley's living surfaces (Fig. 13), which respond to external stimuli, are more extreme examples of how these responsive systems are being experimentally applied.

When Le Corbusier (1923) stated that "A house is a machine for living in," little did he know that in an effort to create more biological self-sustaining structures, future houses would evolve and be crafted as intelligent machines or forms of artificial intelligence, capable of integrating predictive outcomes with " the sophisticated computational and operational assemblies of a technical apparatus." (Hight, Perry 2006, p7) These machines would have sensors to record stimuli and initiate reactions to those stimuli through interactive systems that work together to allow the building to respond and adapt to changing circumstances. Interaction would come from stimulus and response, so that if a building needed to adjust a temperature function, the stimulus would be changing weather conditions. This would be measured by a series of sensors that carried the message to other components of the system to create a response. Temperature change is just one example in a large series of potential implications in interactive intelligent structures. Other dynamics that interactive systems delve into include: automated temperature adjustments, lighting, sun control, energy generation, security, human recognition, fire prevention and response, repair, maintenance, analysing occupancy, resistance to wind/snow load and earthquakes.

However, as evidenced in Nouvel's façade for the Institute du Monde d'Arabe, the technological advances surrounding intelligent systems are not fail proof solutions. In nature, those organisms that adapt the most readily and easily are the ones that do not become extinct. The same wisdom can be applied to the architectural components surrounding intelligent design that allow the building structure to adapt. Hight and Perry argue, "such hybrid assemblages are more profound than wholly artificial intelligence" because as an extension of the social body, they "cannot differentiate practice from product, or a notion of the human or social from the technical." (Hight, Perry 2006, p9) This means that learning, gathering information and responding to that

information will be the pattern of future building systems capable of adapting to surrounding conditions. But, in order to survive and remain functional, these environments will require an ongoing relationship to "manage their evolution over a much-extended period of time." (Burke, 2006, p.95) That is, they will need to be constantly monitored and tweaked and have updates installed to ensure their ongoing functionality. As a result, rather than a certain endpoint/product, in order to allow for a continual evolution these intelligent systems will never be complete, but will "always be in a state of evolution". (Burke, 2006, p.95) In this respect following Dollens argument, architecture will no longer be separated from its biological connection but will become part of an ecosystem "a symbiotic growth dependant on human intelligence and muscle (or its mechanical replacement)." (Dollens p. 13)

As we search for more ways to develop better examples of efficiency in buildings and structures, the pinnacle of self-regulation and efficiency is the biological organism. Using evolutionary design processes, future buildings will incorporate many of the physical characteristics of biological structures in the generation of their form. In crafting structures using self generative processes, buildings will become not only structurally efficient, but the system that goes into making the building will also be efficient and environmentally sound. The biometric model of building will be as much a part of the natural environment as possible while also being crafted through a methodology that limits its broader impact. This would compliment a building's low energy consumption and self-organizing potential and also in the application of more intelligent systems allow buildings to become more responsive to differing environmental conditions.

1.4 STRATEGIES TOWARDS DEMATERIALISATION AND LIGHTNESS

The last section examined recent studies of generative processes used by biological systems that have inspired the adoption of similar strategies for designing and manufacturing more intelligent, efficient and sustainable building systems that behave like biological structures. The concepts raised by the analysis of natural systems emphasise the notion of an architecture that is not a uniform and static entity which is imposed on the environment, but is an assemblage of a complex series of material and energy systems that become more sustainable with the implementation of smart technologies or adaptive systems which allow buildings to generate or conserve energy and transform over time in response to external forces. Drawing on the fundamental principles of biological systems, this section discusses strategies that have been applied to design and manufacturing processes that exploit qualities of lightness and self-organisation in relation to dematerialisation.

In architecture "lightness" can be defined in terms of transparency and luminescence, or as "lightness" in relation to weightlessness and dematerialisation. Lightness has many articulations, from an intricacy of detailing, that can be visually liberated from its physical weightiness (such as Gothic cathedrals), through to construction methods that optimise the load bearing capacity of a material by reducing its weight through substitution with either lighter or thinner materials, through to architectures that rely on temporal ephemeral nomadic construction systems, or building systems which engage with qualities of transparency. In this chapter the focus is on lightness in terms of dematerialisation and reducing weight as a sustainable strategy to minimise the use of resources and improve energy efficiency.

The dematerialisation of the physicality of architecture to create an effect of lightness using composite construction initially occurred in the construction of gothic architecture. According to Western (2003) examples such as Salisbury cathedral incorporated marble stiffened by brass rings to create a physical structure capable of transcending the gravitational and physical limits of its materiality, to create a delicate tracery of stone, which soared upward to appear almost weightless. Described by Ruskin as like "a cobweb lifted by the wind," this effect was further enhanced by windows strategically placed to permeate light and shadow over the structure to

create an effect which (in spite of its weighty construction)"defied any acknowledgement of its gravitational pull, transcending its physical limits into an awe inspiring spiritual realm" (Weston 2003). Since then, the impulse to remove weight from matter in buildings has become a recurrent theme with massive materials like stone and concrete subjected to hybrid recombinations to create miraculous feats of gravity defying lightness, thinness and dematerialisation. While medieval architects were more concerned with a spiritual transcendence against the physicality of a material world, the modern emphasis on dematerialisation has been mainly driven by either: technical advances in materials, or processes that significantly reduce the amount of material required, (for instance with steel reinforced concrete), or by the scarcity of the material available, or by economic factors.

Dematerialisation refers to an approach to meet the performance requirements of a building using less material, which in turn causes a reduction in cost of resources and effort required to produce a building. (Fernandez, 2005) This approach has over the last century lead to an overall reduction of building components through the development of more thin-skinned building systems. These material reductions have been driven more by economic concerns rather than environmental considerations. But with global warming a new focus, there is a shift in relation to how materials can be used more efficiently. To avoid excess consumption and conserve resources buildings will be constructed to optimise efficiency through using less material. Western notes that the heightened awareness of issues relating to sustainability will lead to the development of thin-skinned facades, stretched over the surface of buildings capable of satisfying a complex array of requirements. They will have in-built intelligent systems that alter or open and close with changes to temperature, light and other environmental factors. This adjustable quality means that these facades will act more like biological systems, acting like a multilayered skin mediating the body's relation to its environment. (Weston 2003) These intelligent skins will achieve this by combining various types of devices such as high performance glass to control daylight by shading or excluding light, and skins which repel or retain thermal energy (Weston 2003) While many thin layered skins and multifunctional fabrics have already been developed, both Weston (2003) and Fernandez (2005) argue that the real potential of layered thin-skinned assemblies has yet to be fully exploited in the development of new sustainable building prototypes.

Fig. 14 Lightweight concrete parabolic roof structure designed by Felix Candella.

Alongside the development of intelligent, thin skinned surfaces and structures has been the development of aerated materials using foams and honeycombs, and lightweight pneumatic and lattice structures, both for enhanced thermal insulation (energy efficiency) and structural effect. Air, in its material capacity, has advantages over all other materials in that it is cheap, readily available, lightweight, and when used in combination with other materials has structural and insulating capabilities. In the building industry air has been used to develop lightweight composite foam and honeycomb panels for insulation, and also larger scale pneumatic and tensile structures.

In the 1950s German architect, Otto Frei, began studying cobwebs and soap bubbles to create lightweight tensile structures (Frei 2004). He observed that soap bubbles use a minimal surface material subject to the constraints on the location of their boundaries. Frei used these observations to design lightweight tensile structures using double curvatures (hyperbolic paraboloids) to resist external forces. Frei wasn't the first person to use the structural effect of a hyperbolic parabola in an architectural building. In 1896, the Russian Engineer Vladimir Shukov designed a tower that used a hyperbolic paraboloid to optimise its strength, enabling the tower to become taller than one built using more conventionally built systems. Buckminster Fuller was another pioneer who researched the efficacy of hyperbolic paraboloids in the generation of his geodesic structures and tensegrity structures. As well, architects such as Felix Candella also used minimal surfaces to design lightweight parabolic roof structures (Fig. 14).

In mathematics a minimal surface is defined as a surface with a mean curvature of zero. Soap bubbles are minimal surface structures in that they use the least material in relation to a given volume without compromising their structural properties. As well as soap bubbles other examples of minimal surface structures include honeycombs, zeolites, gyroids, Weaire-Phelan structures and foams. In building applications minimal surfaces have been used both for individual building components in the development of foamed/honeycomb sandwich panels as well as for designing larger parabolic and tensile structures, most notably for developing complex structural systems such as PTW's Water Cube designed for the Beijing Olympics. This building mimics water bubble forms to create both the structure and cladding system. In the example of the Water Cube, the structure was made from a limited series of steel sections specially fabricated to allow for variable angles while the cladding system was made from thin cushions of lightweight transparent Teflon

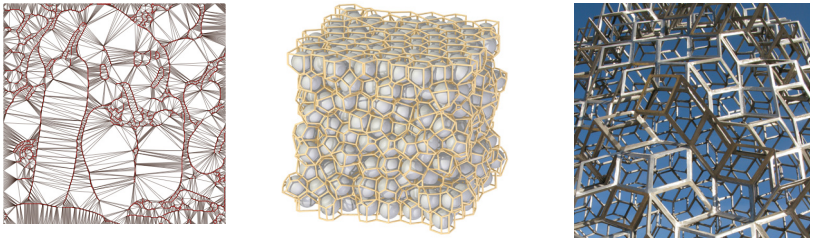


Fig. 15 From left to right, Delauney triangles and 3D models of a Voronoi diagram and Penrose tile pattern.

"PTFE", making the building exceptionally energy efficient. (Weinstock 2006).

In 1917 Darcy Thompson described the mathematical structure of close packed cells, foams and bubble structures in terms of their optimisation of ideal geometries and minimal materiality and deformation. Although Thompson's studies weren't focused on architectural applications, his observations have become relevant to contemporary designers interested in generating optimal structures. In an article entitled "Self- Organisation and Material Constructions," Michael Weinstock discussed the development of self-organised foamed structures that are prevalent in natural systems in terms of how they could be applied to artificially make better building materials. He writes that "design and construction strategies based on space filling polyhedra and foam geometries offer open structural systems that are robust and ductile" (Weinstock, 2006 p. 40), and suggests that this approach could be used not only in development of lightweight cellular materials that self-organise such as honeycomb/foamed metals, ceramics, polymers and glass, but also could be used to design larger scale cellular structures such as the Water Cube. While numerous foamed and honeycomb products have already been designed for the aerospace and building industry such as foamed aluminium, ceramic, carbon, concrete, polyurethane and glass, and composite panels made with honeycomb cores, constructed out of paper or aluminium, Weinstock argues that most of these systems were designed without enough knowledge of the cellular properties of the material, which would if manipulated (through using digital fabrication techniques and nanotechnologies) lead to superior products. This point is also reinforced by research carried out by Salvatore Torquato, an expert in the development of nanotechnologies whose interest is primarily in the design of multiple functional optimal structures for composites. Using mathematical modelling techniques, his studies have lead to conclusive evidence that triply periodic minimal surface structures have the capability of producing superior composites mainly because of their ability to perform more than one function. While Torquato's research is primarily directed towards small scale (nanoscale) structural composites, his observations also have implications on applications at larger scales.

Linked to the study of minimal surface structures are biomorphic cellular structures. Many researchers have written about the ability of social insects such as bees, paper wasps or termites to develop efficient and complex material systems from simple cellular units. These material

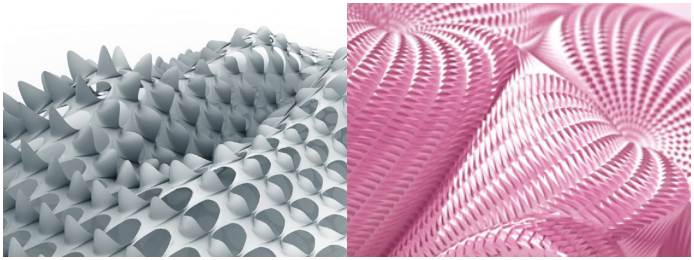


Fig. 16 Marc Fornes (left) and Alisa Andresek (right) generated structures.

constructions involve the instrumentalisation of the self-organising properties of a material. A key to the success of these systems is an understanding of the material used and a subjugation of individuality, such that individual units are assembled to varying intensities influenced by invisible environmental factors to organise them. Based on this principle, it is not the individual unit that creates diversity. Rather, the intensity of a collective combination creates diversity. This is a process that can operate from a microscopic to macroscopic scale. Such processes allow the material "to become" synthesised by a collective community to produce a form. Mark Fornes is another one of a series of contemporary designers interested in the generation of biomorphic cellular structures. He has developed this concept in a series of projects entitled "Theverymany", using tessellations of simple units such as those found in honeycombs, Delauney triangles, Voronoi diagrams and Penrose tiling patterns (Fig. 15), as generators of form which are determined algorithmically through a variety of boundary conditions of different faces, edges and vertices. These cellular patterns have enabled Fornes to generate robust yet extremely intricate and beautiful 3D structures using minimal materials. He is currently using these strategies to develop a large-scale self-supporting carbon fibre roof structure.

This interest in the generation of heterogeneous structures developed through the organisation of smaller cellular units using algorithmic scripts has lead another prominent designer, Alisa Andrasek, to create what has been described as a "gene library of behaviourally defined 'cells' (localised components) and environments (global components)." (Ednie-Brown, 2006, p. 20). This library of components have been organised by Andresek into the Continuum Collective as an ever-evolving archive of source material for researchers working in this area. Like other designers working on the development of parametrically generated networks she has observed that these, "behavioural fields are set up through discrete agents – generative components, which are constrained into internally cohering relations across various hierarchies – host environments." (Andrasek, 2006) Using a similar approach to Fornes, Andresek has used scripts to generate complex 3D cellular structures (Fig 16).

Most architectural advances in research into minimal surface structures using self generative applications of cellular biometric lattice structures have been generated through Columbia University's Materials Potency Lab, The Architectural Association's Design Research Lab and the

Emergence Design Group at MIT. These universities have all set up collaborative experimental laboratories to combine technologies using parametric software to generate a programmatic approach to generating form that is not based on a unified system of parts but instead is more of a shared collective of mobile relations. Initial experiments carried out by these collaborative laboratories began with simple curved and folded structures, but advances in digital programming coupled with rapid prototyping manufacturing techniques have enabled the development of more complex 3D lattice structures. These structures are no longer simply drawn or physically modelled but are generated through scripts, allowing for variations within each unit, and for these structures to be more easily fabricated and exponentially altered in response to varying conditions in spite of their complexity.

As generators of form, cellular, foam, lattice and bubble structures all offer a similar function in their capacity to reduce and minimize surface area occupied by a structure. In terms of their environmental impact, not only do airy cellular structures reduce the amount of finite resources necessary to construct them, they can be more energy efficient, more structurally stable and they also generate less waste thus allowing more efficiency to exist within the given parameters of the structure. Essentially, minimal surface structures can be summed up as maximizing the strength of structure while minimizing the amount of surface area and material necessary to accomplish the same task. Digital technologies have been opportunistically used to successfully create complex minimal surface structural systems, especially using rapid prototyping techniques, but their application into designing sustainable large scale building prototypes also requires developing systems that can cope with coordinating their intricate structural parts, multiple functionality and inevitable transformation over time. This transforms the role of the designer into a collaborator within a constantly evolving system, and undermines conventional approaches to generating uniform building systems. The effect of digital technology in the generation of sustainable prototypes is discussed more fully in the next section.

1.5 THE IMPACT OF THE DIGITAL ON SUSTAINABLE DESIGN PROCESSES

The last section considered the impact of biomimetic studies in the production of thin-skinned lightweight building systems that are more flexible and adaptable, and also the development of lattice like cellular structures largely based on the self-organising principles and enhanced structural capabilities of minimal surface structures. This section considers how digital technologies in relation to algorithmic processes have significantly altered the role of designer to a role based on collective intelligence rather than individual genius. It also outlines the link between rapid prototyping manufacturing techniques and the design process.

Advances in computer generative techniques to process and organize knowledge flows through genetic algorithms have lead to processes, which like Darwinian theories of evolution, rely on natural selection to quickly generate optimal solutions for complex problems. Based on a principle of survival of the fittest, genetic algorithms begin with a population that becomes modified through recombination or mutation. With each successive generation, preference is given to better resolutions based on either a particular criteria that determines what is best, or through the input of human judgement. Mutation is one of the key aspects of generative algorithms as it inserts a random element of diversity into the generative process, so some outcomes within each generation are unpredictable. If they are successfully selected, these mutations prevent each successive generation from simply replicating themselves, thereby introducing robustness to the overall process. Engineers use genetic algorithms to solve various structural problems through finite element analysis in the development of particular composites, and also in the development of nanomaterials that replicate biological structures through self-organisation, molecule by molecule. They have also been extensively used by architects to visualise complex networks/skins and to generate morphogenetic forms and self organising structures which like nanomaterials, mimic biological models but at a larger scale to create responsive environments.

The issue of scale in relation to the replication of biological systems which self organise into a cellular structure or network that can be applied to a building system is complex, as a direct translation of the relations between miniscule particles and cellular structure does not necessarily

lead to optimization at a larger scale. Scale is dependant on many collaborative factors. Critical to the success of using digital technologies in this way is the notion of a collective intelligence that encompasses knowledge about the ways in which biological and social systems operate, alongside the logic of mathematical methods used to programme and compute data into scripted codes, and also knowledge of materials science and other emergent technologies. In other words, this requires the consideration of how material forms become co-evolved with the input of multiple collaborators rather than generated by a singular creator. This point is emphasised by Manuel DeLanda:

> To return to the genetic algorithm, if evolved architectural structures are to enjoy the same degree of combinatorial productivity as biological ones they must also begin with an adequate diagram, an "abstract building" corresponding to the "abstract vertebrate". And it is at this point that design goes beyond mere breeding, with different artists designing different topological diagrams bearing their signature. The design process, however, will be quite different from the traditional one, which operates within metric spaces. It is indeed too early to say just what kind of design methodologies will be necessary when one cannot use fixed lengths or even fixed proportions as aesthetic elements and must instead rely on pure connectivities (and other topological invariants). But what is clear is that without this the space of possibilities which virtual evolution blindly searches will be too impoverished to be of any use. Thus, architects wishing to use this new tool must not only become hackers (so that they can create the code needed to bring extensive and intensive aspects together) but also be able "to hack" biology, thermodynamics, mathematics, and other areas of science to tap into the necessary resources. As fascinating as the idea of breeding buildings inside a computer may be, it is clear that mere digital technology without populational, intensive and topological thinking will never be enough. Deleuze and the Use of the Genetic Algorithm in Architecture. (DeLanda, 2002, p12)

DeLanda identifies a fundamental concern encountered with digitally generated processes based on biomorphic evolution. In order to generate multiple functional systems, one has to harness the expertise of multiple disciplines or at least collaborate between these disciplines. The specialisations of architecture and engineering on their own are far too limited to fully

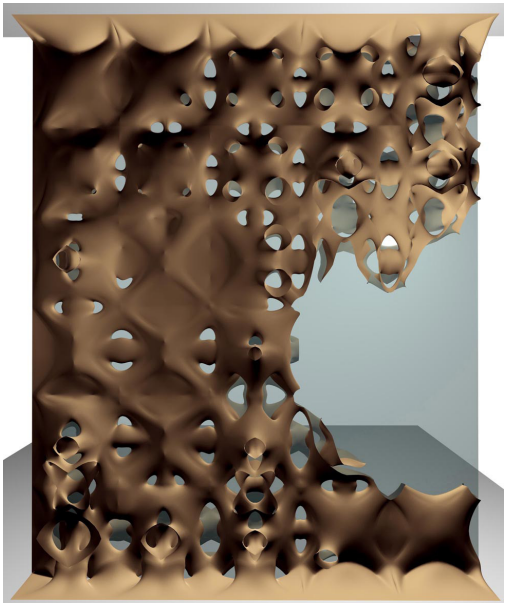
Fig. 17 Evans Douglas Flora_Flex slip cast ceramic surface.

take advantage of the full potential of this technology. An in-depth awareness of the many different elements and materials affecting the design at every scale leads to a more sensitive consideration of their interdependence, and successful integration based on a multidisciplinary approach. Without this approach, computers simply become beguiling tools capable of processing data and creating complex forms and digitally generated systems without any comprehension of the implications of the impact of what is being produced. How sustainable is it to use rapid prototyping and digital technologies to generate derivative biomorphic forms, which are structurally independent of any inherent material capabilities? A purely digitally focused approach to generating form risks being as presumptive and unsustainable as methodologies that resist diversity in favour of uniformity. Instead, DeLanda and others have argued that instead they should be used to explore the intrinsic and self-organising characteristics of material systems that are a result of many varied relations.

The sheer versatility and visual complexity of what can be physically produced through the linking of morphogenetic digital technologies and rapid prototyping techniques is clearly evident in the work of designers such as Evan Douglis, who has used genetic algorithms to breed beautifully complex surfaces such as his Helioscopes or Flora_flex project (Fig. 17). But in terms of their sustainability these projects demonstrate the risk in how these technologies are applied. Projects such as Helioscope or Flora_flex remain in the realm of conventional form making albeit a much more seductive and virtuoso type of form making due to the application of digital technologies, While the forms are bred like a biological system, they are produced without a consideration of a wider environmental impact beyond their idealised generation.

The emphasis on harnessing collaborative intelligence and having an in-depth understanding of scientific principles for the generation of material systems and organisating of data, leads to the concept of a mechanical self generative process which is no longer strictly bound to the designer's control. This point is emphasised by Burke who writes: "An architecture which is mired in the cult of the object is unable to utilise the advantages of collective organisation and interconnection, preferring tidy distinctions and clear boundaries over protocols of exchange within deep networks." (Burke 2006 p.91) The use of digital processes which create forms that

Fig. 18 INVERSAbrane designed by Sulan Kolatan and William Mac Donald, generates a microclimate within buildings by collecting and recycling water and light.



are dependant on the organisation of the relation between things has led to a fundamental shift in relation to the role of the creator and what is created. A system that evolves in relation to long-term investment and involvement with multiple collaborators and the generation of what Verbes has described as " increasingly malleable forms of spatial and material intelligence with increased capacities to adapt to contingencies of use and interaction" (Verbes 2006 p.69), can no longer be simply owned by one creator, or linked to a singular product. Brett Steele elaborates this argument further by suggesting that any approach to the generation of architectural form that does not take into account the profound changes that are occurring with the way in which seemingly stable architectural forms are organised and generated, risks being threatened by its own "outright irrelevance" (Steele, 2006 p.58) Building systems, argues Burke, in his commentary on the significance of collective intelligence, "in this context can be seen not as the production of built products , but the development of ideas and methods that result in vectors of research marked by built moments. In this sense, practice itself becomes a locus of design where formal inclusions or delay are not a temporary moment before reaching some ideal architecture or final form, but rather an ideal state in and of itself. It is the goal to remain open, responsive and fluid, to negotiate and renegotiate as new contextual pressures become apparent; to imagine practice as a project within which projects may be built but are never complete, but are always in a state of evolution". (Burke 2006, p. 95)

In a collaborative approach, once something has been generated it always undergoes change influenced by contextual, internal and material forces. As a consequence, once it has been generated it is then also free to " develop more complex informational ecologies". Burke has described this quality as "going native", a feral quality which means that the designer's role becomes redirected towards managing the cultivation of a building system much as one would manage biological ecosystems rather than focusing on a singular fixed outcome.

Rapid prototyping has also profoundly changed design production as it enables a direct connection between design and manufacturing processes, which hitherto has been separated. This has meant that computers are no longer used by architects to simply document buildings, but through script and code, computers can generate and fabricate complex morphogenetic structures and a more varied repertoire of material applications using rapid prototyping techniques which are no longer separated from modes of production and consumption. As

Erdman writes, "it was not until the emergence of the computer that an active relationship between technologies of production and cycles of use began to affect one another in substantial ways and reconfigure the very architecture of the technology." (Erdman et al 2006, p. 87) Over the last decade, digital technologies have begun to slowly bridge the gap between design and manufacturing processes. Traditional manufacturing processes have always denigrated complexity in favour of uniformity of the object. Rapid prototyping techniques encourage a production of surfaces/structures, which express emergence and diversity. By opportunistically using existing manufacturing processes alongside, rapid prototype machines and CNC fabricators it is possible for designers to efficiently manufacture moulds to produce unique and complex structural systems. An example of how this technology is beginning to be applied is INVERSAbrane (Fig 18), a product developed by Architects Sulan Kolatan and William Mac Donald through Dupont Industries. INVERSAbrane is a strangely formed complex multifunctional three dimensional building membrane. The designers claim that this membrane is designed to generate a microclimate within buildings due to its ability to collect and recycle air, water and light, although how this is actually achieved is not explicitly explained.

While existing manufacturing techniques have limitations in terms of their ability to produce multiple and variable components, rapid prototyping technologies have the potential to produce multiple and variable options. At the moment, these technologies have not been developed to a level that has been profitably or sustainable be applied to large scale building operations, although David Clemento has argued that the ability to apply this technology at a large scale is almost achievable. He writes "Architects using rapid fabrication technology at a building scale could economically create complex singular designs as well as customisable multiples. First these will appear as building components and later as full scale structures" (Clemento 2007, p. 72) He argues that the initial movement in this direction is already evident in the development of a 3D printer designed by Behrokh Khoshnevis. Khoahnevis's creation is capable of printing concrete forms using a specially formulated fast setting concrete. Clemento states that structures generated using these technologies will not be limited to "adobe-esque load- bearing" architectures but will reflect structural complexity and innovation and will also integrate multiple materials, and incorporate a "nerve like web" of features such as plumbing and electricity. Another potential advantage of rapid prototyping he argues is that structures would be able to be manufactured

with greater certainty, and minimal waste.

One of the main challenges for designers using digital technologies is to understand the ways in which existing technological manufacturing processes can be advantageously combined with digital or emergent technologies to profitably, and in a sustained way generate more complex building structures. There is also a limitation in scale in relation to how these technologies can be applied effectively. Most rapid prototyping techniques can only cope with small-scale production. For emergent manufacturing processes to be effective and sustainable, a design team rather than a singular designer, has more potential to harness the potential of digital technologies through engaging in a more thorough understanding of material properties, data systems, the mathematical and biological systems involved in the generation of their complex structures and also an in-depth understanding of the different types of existing manufacturing processes which can be applied to the generation of material structures. The use of digital technology challenges traditional top down approaches to manufacturing building systems by encouraging a multidisciplinary collaborative approach that can generate diverse and sustainable building systems which are multifunctional, self organising and evolutionary in terms of their ability to adapt to ongoing changes.

These first sections have briefly outlined areas of emergent technologies used in relation to the generation of building systems which are influenced by the study of biomimetics and research into nanotechnology and which have the potential to become more sustainable in terms of their manufacture, energy efficiency, flexibility, adaptability, improved structural capabilities, materiality and consideration of a more in depth collaborative approach to initiating their generation based on digital technologies. The following section considers traditional processes used to make material selections, classifying materials and describes the main manufacturing processes used by the construction industry.

2.1 MATERIAL SELECTION STRATEGIES

With the development of new composites one is immediately faced with the avalanche of endless possibilities of material choice and applications. It has been estimated that there are "40 000 – 50 000 materials and at least 1000 different ways to process them". (Ashby, 2004) When presented with such an overwhelming quagmire of possibilities, the process for making selections between materials and their different applications to develop new prototypes becomes acutely critical. How are such decisions made when the management of knowledge in relation to material properties is a challenge in itself? How do materials become classified into some sort of hierarchy, which enables the designer to navigate the different possibilities and come to a decision in relation to how they can be applied and comparatively evaluated? What is the process for determining a comparative analysis between mechanical, physical or thermal elements, and characteristics such as cost, or availability, or sustainability that is often unsubstantiated? And how are manufacturing processes factored in? How sustainable are these processes? Because of the variable nature of each intrinsic element, any classification to determine and comparatively analyse each of these factors is inherently complex. Moreover, the task becomes further complicated by other non-quantifiable extrinsic considerations, such as the experiential effect of a material or cultural considerations, which seem to randomly and precociously assert themselves across all other quantifiable criteria undermining any mechanical analysis.

Alongside these considerations in relation to material selection has been the historical and uneasy separation between manufacturing processes, material science and the designer's intention, which has affected material selection processes and the products being manufactured. Each sector has traditionally approached the design, use and application of materials from quite diverse positions. While this separation has often hindered the development of new solutions, because of the gap in knowledge of manufacturing or design processes, or lack of understanding of a material's basic properties or how it is used, this disjunction has sometimes revealed innovative solutions unburdened by the obstacles of expectation. (Fernandez, 2005)

The development of emergent manufacturing processes has begun to play a key role in the type

of new products being developed. Most existing manufacturing processes were initially developed through extracting materials from non-renewable resources and using fossil fuels to process them. While there is complacency by the industry to change these profitable but unsustainable practices, these processes are gradually being surpassed by processes, which are more environmentally considerate. This has become apparent with the development of digitally driven manufacturing processes which are capable of producing building systems which are more structurally efficient and which incorporate "micro electro-mechanical systems" into their infrastructure (Ashby 2005) or which manufacture materials with micron level capabilities utilising "smart" and nano technologies. Rather than creating passive prototypes, emergent manufacturing processes can incorporate (at a microscopic level), interactive interfaces into the development of the material allowing it to respond to different stimuli or external conditions (Addington, 2005). This has lead to a vanguard of designers, who are working at directly linking the design process to digital manufacturing processes, inextricably binding the design process with manufacturing outcomes. But, as previously indicated, fully taking advantage of the potential of these emergent processes requires the collaboration and merger of an extensive skills base from designers, biologists, physicists, artificial intelligence experts, materials scientists and engineers etc.

The selection of materials in the designing of composites also relies on the analysis of performance requirements prior to the combination of the constituent elements to create an integrated design. This means that the performance criteria and manufacturing processes need to be clearly defined. This can happen intuitively, based on the amalgamation of data and information of past experience, or systematically through selective analysis. Performance criteria usually come from a diverse set of intrinsic values such as the insulating capability, stiffness, elasticity, ductility, durability, light emitting qualities, mechanical strength and cost. The evaluation of these different criteria, in turn, relies on the collation of huge amounts of material property data for each component, and consideration of fabrication technology. In a systematic analysis, this data is formally ranked and assessed to allow for comparative evaluation in relation to the combinations of sets of particular intrinsic values. These are quantified in relation to a consideration of cost, or insulating properties and so on, or compared in relation to more variable extrinsic evaluations such as aesthetic consideration, historical relevance, cultural significance, and so on. Extrinsic values are the more difficult to quantify as, like fashion, they are ephemeral, dependant on

innumerable contingencies. Often it all boils down to intuitive/cultural or historical preference - which makes it difficult to be objectively evaluated, as it can capriciously change over time. (Fernandez. 2005)

Apart from the more esoteric considerations, such as aesthetic quality, or cultural or contextual significance which is not easily resolved through a deterministic design processes, the ability to select materials for the development of composite panels has traditionally involved a translation of the design requirements into specific materials and processes. This initially requires a classification system to select and rank the most apt solutions, and then a further analysis of these solutions to focus in on the best outcomes. Four main approaches have typically been used for selection processes of materials (Ashby, Lenz et al,):

- The analysis of historical experience based on inductive reasoning from previous experimental design processes to draw out a resolution to a particular requirements – this is a strategy most commonly used by architects.
- A free search analysis of performance criteria, objectives and constraints, and design requirements using material indices and software to support decision making - a strategy more commonly used by engineers
- Questionnaires, based on expertise to determine specific preferences. This involves a selection process, which guides the user through a structured set of questions.
- Weighted properties method which ranks certain materials based on their performance criteria.

The first and second strategies have the strongest capability of efficiently revealing innovative solutions: the first through its experimental nature based on previous experience and the second through random scoping of select criteria. The questionnaire-based approach is more time consuming and tends to rely on already known expertise and definitive answers. As such it is less likely to scope unknown potentials (Ashby 2004). Free search analysis has certain advantages over historical analysis as it is more systematic and has the capability of drawing out unexpected potentials that aren't obviously apparent, although its more mechanised approach has weaknesses in terms of the application of extrinsic values. The advantages of the weighted method are that

it allows the designer to factor in extrinsic values such as contextual relevance so long it can be given a numerical value (Dehghan-Manshadi et al 2007).

Using Material Indices and computational data

To make this selection process more efficient Material Indices have been developed to collate variable data values to optimise material selection (Ashby 2005). Using this method, sustainable alternatives can be easily identified. These graphically visualised indices have also been effectively applied to the development of a number of software programmes, which use simple screening algorithms to collate databases and optimise material selection processes using a series of selectors, which is supported by information on processes and manufacturing data and links to manufacturers. These software programmes are extremely effective databases for material selection resolution.

But while the application of computational tools provides a powerful method to quickly evaluate selection processes for the intrinsic quality of materials in a "quantitative, rational, and systematic way" (Granta 2006), these tools are generally reliant on analysis of clusters of materials that have either already been developed and applied, usually as traditionally constructed monolithic components using unsustainable manufacturing processes. The limitations of these data bases has disadvantages, as new or distinct geometrical configurations, or applications to newly developing and more sustainable manufacturing processes, or data on new materials such as woven, or multi layered composites are absent and still need to be entered and considered separately, along with any other variables, which in spite of such rational evaluative processes aren't easily determined. The risk in applying a deterministic approach to making selections is a tendency to default towards existing practices, which aren't sustainable, and disregard emergent practices.

SOFTWARE USED FOR MATERIAL SELECTION (Ashby 2004)	
Name of software	Objective of software and evaluation method
CES (Granta Design, 2004)	A number of specialised databases on materials and processes and the possibility to create new ones. Utilises free search strategies and screening of the database.
Fuzzy Mat (Bassetti, 1997)	Uses the same database as CES, multi-criteria selection using fuzzy logic.
CAMD (Landrau)	Uses the same database as CES, expert guide for developing the set of requirements implementation of coupled equation and value analysis. Strategy uses free searching and questionnaire and screening of the database by recursive algorithm.
Fuzzy Composite (Pechambert Durratti)	Optimization of composite materials selection and dimensioning of structural sandwiches. Uses genetic algorithms, screening and mechanics modelling of possible solutions to evaluate selection.
Sandwich selector (Lemoine)	Optimization of materials selection and dimensioning for structural sandwiches. Uses genetic algorithms, screening and mechanics selection.
Fuzzy Glass (Bassetti)	Optimization of glass composition for properties and processability. Database for correlation. Uses simple algorithms coupled with fuzzy logic to evaluate selection.
Fuzzy extrude (Heiberg)	Optimization of aluminium extruded alloys selection including extrudability and shape via expert rules, using questionnaires and screening to evaluate selection.
Fuzzy Cast (Bassetti)	Optimization of aluminium cast alloys selection including hot tearing and mould filling via expert rules, using questionnaires and screening to evaluate selection.
STS (Landru)	Selection of surface treatments according to compatibility with base material and required function, using questionnaires and screening to evaluate selection.
VCE (Landru)	Identification of value coefficients in design procedure from existing solutions based on analogy.

SOFTWARE USED FOR MATERIAL SELECTION (Ashby 2004)	
Name of software	Objective of software and evaluation method
MAPS (Landru)	Identification of possible applications for a material from the properties/performance profile. Uses free search and screening of the data to evaluate selection. (Landrau et al 2002).
Astek Expert Lae	Selection of optimal joining methods from existing solutions, using analogy and case based reasoning.
CES Aesthetics (Johnson)	Suggestion for industrial design from a database of objects using analogy, and case based reasoning.
Failure Expert (Bouget)	A guide to failure analysis and possible solutions from a database of cases, using analogy and case based reasoning.

Table 3, Software used to select materials.

Genetic algorithms have advantages over other strategies, as their evolutionary capacity means that rather than revealing singular solutions, they offer many and novel alternatives beyond the scope of any human driven research capacity. While genetic algorithms have been used to optimise solutions for composite panels which have a discrete set of materials and geometry, (see table above) using traditional manufacturing processes, they have not been specifically applied to resolving a more generalised design strategy for developing sustainable structural composites.

Any tool that scopes the potential development of sustainable structural composites needs to be generative, self-organising and responsive to user participation and changing variables. In order to generate useful information, it also needs to be restricted to clearly defined and relevant performance criteria, such as sustainability (of materials and manufacturing processes), structural ability, durability, energy efficiency and lightness. Geometrical complexity and existing sustainable and emerging technological and manufacturing processes also need to be factored in.

While it isn't the intension of this research project to use algorithms to generate a plan, it is useful to consider how they could be applied to efficiently locate strategic areas for the development of structural composites and what criteria might be used. This would require a selection of

the best structural composite prototypes based on clearly defined criteria and identification of the specific constituent elements that make up each component such as bonding elements, structural components, cladding, application of emerging technologies, insulating elements and so on. Software programmes such as CES, the NZIA sustainability index and Greenbuild data could be applied in part to optimise this initial selection process. Once these solutions are selected, the fitness functions need to be defined in terms of performance criteria, for instance: sustainability, structural ability, lightness, energy efficiency and durability. This fitness function determines the quality of a given solution and which elements should be passed on to successive generations. This aspect of the selection process requires an in-depth awareness of the potential of each fitness function so as not to limit its on-going generation. If the awareness is too limited, the outcome is predictable. If it is broad enough to be compatible with multiple combinations, the potential variations are limitless. Once the fitness function and selection of solutions is identified, the genetic algorithm can be used to randomly breed a generation of solutions. With each generation, a series of solutions is selected based on fitness, which would ultimately result in the fitness improving with each successive generation.

2.2 CLASSIFICATION SYSTEMS

This section presents a synopsis of the generic classification systems used to determine the performance of different materials used in the building industry and also an outline of the different matrix and fibre configurations of materials used for composite construction.

Materials are classified for buildings in terms of a series of complex systems of performance criteria that invariably alter in relation to particular given applications. The most important consideration in material selection is sustainability in relation to energy efficiency and environmental impact and the ability to moderate extreme contrasts between an external and internal environment and withstand structural loads. These factors in turn are considered against aesthetic values and cost. For architectural applications, building materials have traditionally been classified primarily in terms of the ways in which they are applied as cladding systems. This leads to five main categories: glass, concrete, timber, metal and plastic. Linked to cladding systems, which control air, water vapour, humidity, and temperature are structural elements which support them, such as materials which are capable of carrying loads, e.g. columns, beams, trusses, cables, shells. While cladding and structural systems can be integrated as one system, it is more usual for cladding and structural systems to be built as separate entities – with the structural components enclosed by lightweight cladding elements, which act like skins over the whole structure to moderate the internal environment. Integral to these two main components is a third category which relates to energy efficiency, insulating materials and building services that are also used to control the internal environment.

An alternative approach to classifying materials is one that has been established by Harvard University Graduate School of Design for its Material Collection (Schroepfer and Margolis 2006). This Material Collection is classified according to inherent properties and the separation from conventional contexts in terms of application. Thus qualities such as texture, elasticity, transparency, fluidity and fragility form the initial criteria that are in turn cross-referenced to operations of fabrication (perforated), or properties (reflective) or form (honeycomb). Schroepfer and Margolis argue that the advantages this classification system has in relation to the traditional architectural version above or the conventions of the engineering model that follows, is

that it encourages a serendipitous encounter with unexpected possibilities.

Engineers and material scientists classify materials quite differently in relation to six broad family groups: metals, polymers, elastomers, ceramics, glasses, and naturals. Unlike architectural classification systems which are determined by how the materials are applied, each of these groupings is determined by certain properties that are common, such as chemical composition, ductility, elasticity, yield strength, tensile strength, compressive strength and toughness. The list and tables below outline these main groupings and also outline their specific application in relation to the architectural applications and also consideration of sustainable alternatives. (Typically, hybrids also form another separate group, but in this outline, hybrids have not been separated into their own group, but included within the other groups).

METALS

Metals are not generally used in a pure state for building construction, but rather as alloys or mixtures of other elements to optimise their performance (Ashby, Fernandez and Ballard Bell et al). The most common metals traditionally used in architectural applications include iron, aluminium, copper, zinc, lead and titanium. Metals have a high strength to weight ratio, are malleable and easily shaped. They are used in architectural applications as structural elements, as reinforcement in concrete and as cladding and joinery components. Since the industrial revolution metal products have been used ubiquitously in building construction, but as a sustainable material, metal has distinct disadvantages in comparison with other materials. The processes used to manufacture steel products produce high carbon emissions, and some metals currently used for cladding applications have limited durability in relation to weathering. The one advantage metals have in terms of their sustainability is their ability to be recycled, although even this process creates relatively high carbon emissions. Developments to improve the sustainability of steel products have involved developing more energy efficient manufacturing processes and improving its strength and durability using nanotechnologies to repel corrosive elements and make it stronger and sometimes more ductile. These measures in themselves aren't enough to compete against the development of more sustainable alternatives, less reliant on oil consumption, such as carbon fibre that is used as an environmentally friendly metal substitute in structural

applications.

METALS AND THEIR APPLICATION (After Ashby 2005, Fernandez 2005 and Ballard Bell et al 2006)		
	Type	**Application**
Ferrous These metals contain iron. In the building industry mild steel is used as a structural component for metal framing and as reinforcing in composites.	**Cast irons**	Automobile parts
	High carbon steels	Cutting tools
	Medium carbon steels	Engineering tools
	Low carbon steels	Mild steel structures
	Low alloy steels	Springs, gears
	Stainless steels	Transport, food, surgical, curtain walls, flashings
Non ferrous These metals are used primarily as external claddings, metal panels, tiles, sheets, radiant barriers, or as non-structural components such as window and door frames, insulation, ducting or as metal coatings on glass.	**Aluminium alloys**	Window joinery
	Copper alloys	Electrical conductors, roof and wall cladding
	Lead alloys	Roof and wall cladding, sound insulation
	Magnesium alloys	Automotive castings
	Nickel alloys	Gas turbines, jet engines
	Tin alloys	Wall cladding
	Titanium alloys	Structural, aerospace, medical, wall cladding
	Tungsten alloys	
	Zinc alloys	Roof and wall claddings

Table 4. Metals and their application. (After Ashby 2005, Fernandez 2005 and Ballard Bell et al 2006)

POLYMERS

The construction industry is one of the highest consumers of polymers, due to their lightness,

ability to be shaped easily, their low cost, durability, and corrosion resistance, plus their ability to achieve different colour variations and levels of transparency. (Bell/Rand, 2006) On their own they are primarily used in plumbing, cladding, flooring, insulation, lighting, glazing and other applications. They are also used as either a lightweight or more durable substitute for traditional materials or as a way of modifying the performance of traditional materials - and also as sandwich composites. In terms of sustainability the development of polymers has been historically problematic due to toxic manufacturing processes and their toxic emissions, and limitations in terms of how they are recycled after their usefulness leading to the creation of monstrous hybrids that end up in landfills (McDonough et al. 2002). While non-sustainable polymers such as insulation made from polystyrene are still heavily used in building applications, greater consumer awareness has meant that sustainable alternatives are replacing existing non-sustainable products. More sustainable developments in polymers have been focused on reducing toxicity both in manufacture and in the products themselves, and in developing recyclable and biodegradable alternatives, and also in developing lightweight building fabrics such as metal, glass or carbon fibre reinforced polymers, biopolymers using natural materials and products such as ETFE ethylene-tetrafluoroethylene - the material used to clad the Watercube building in Beijing. With recent advances in non-toxic manufacturing processes and developments of recyclable or biodegradable versions, combined with intelligent technologies, as a durable and lightweight building product, polymers show great promise – for generating alternative sustainable building materials.

POLYMERS AND THEIR APPLICATION (After Ashby 2005, Fernandez 2005 and Ballard Bell et al 2006)		
	Type	**Application**
Elastomers These can be either thermosetting or thermoplastic polymers that are soft and deformable. In buildings, they are used as sealants, adhesives or for flexible moulded components. They are also used as vapour barriers, and for seismic padding as a viscous damping system (tall buildings).	**Butyl rubber**	Seals, anti vibration, insulation, tubing
	EVA	Insulation
	Isoprene (IR)	Tubes, insulation
	Natural rubber (NR)	Electrical insulation, tubing
	Neoprene (CR)	Wet suit seals
	Polyurethane elastomers (elPU)	Packaging adhesives
	Silicon elastomers	Electrical insulation

POLYMERS AND THEIR APPLICATION (After Ashby 2005, Fernandez 2005 and Ballard Bell et al 2006)		
	Type	**Application**
Thermo plastic These are plastics which deform under heat. Unlike thermoset polymers, they can be endlessly recycled. In the building industry they are primarily used as glazing, pipes, vapour barriers, flooring, light fixtures and as foam insulation	**Acrylonitrile butadiene styrene**	Car interiors, furniture, boats
	Cellulose polymers	Tool handles, decorative trim
	Acrylonitrile butadiene styrene	Packaging, blister packs, bottles
	Cellulose polymers	Plumbing, packaging, bottles, fabrics, textiles, ropes
	Ionomers	Used as a substitute for glass, light fittings
	Polyamides (nylons)	Packaging, squeeze tubes
	Polycarbonate	Electrical connectors, racing car parts, fibre composites
	Polyethelene	Blow moulded bottles, film, sails
	Polyetheretherkeytone	Used as a substitute for glass
	Polyethelene terephalate	Zips, appliance parts, handles
	Polymethylmethacrylate (acrylic)	Rope, furniture, pipes
		Insulation, toys, packaging
	Polytetrafluoroethylene	Nonstick coatings, electrical insulation, tape
	Polyvinylchloride PVC	Plumbing pipes, gutters, window frames, tiles and wall panels

POLYMERS AND THEIR APPLICATION (After Ashby 2005, Fernandez 2005 and Ballard Bell et al 2006)		
	Type	**Application**
Thermoset These are harder and stronger than thermoplastics. They can only be formed once, making them difficult to recycle. They are most commonly used for creating composite panels, laminates, adhesives,	**Epoxies**	Adhesives, resin and fibre composites, lightweight structural parts,(aerospace, bike frames, boat hulls) using carbon fibre matrix Boat hulls and automotive parts using glass fibre matrix Epoxies are also used in combination with concretes and plasters to create more durable composites
	Phenolics	Electrical plugs, sockets, adhesives
	Polyurethane	Finishes
	Polyesters	Furniture, boats
Foams These are mainly used as insulation and for sandwich composites	**Flexible polymer foam**	Cushioning foam
	Rigid polymer foam	Thermal insulation, sandwich panels

Table 5. Polymers and their application. (After Ashby 2005, Fernandez 2005 and Ballard Bell et al 2006)

CERAMICS

According to Ashby, ceramics are generally described as being non-ductile, brittle yet strong materials that can be easily formed. Ceramics such as concrete and glass ceramics have been

extensively used in the building industry as load bearing structural elements (reinforced concrete), insulation (fibre glass batts), cladding elements (brick and tiles), and to transmit light (glass). Ceramics are very durable, but their manufacturing processes create relatively high carbon emissions. As a result, most of the recent innovations in material developments have been focused on enhancing their energy efficiency to make them more sustainable. In the concrete industry this has been directed towards developing ultra high performance ductile concretes (to compete with less sustainable steel products) (Struble et al, 2007) and smart concretes, such as concretes embedded with sensors which self heal, or embedded with photovoltaic cells to collect and store energy (Ballard Bell et al 2006) and also the so called "green concretes". According to Meyer, a professor of Engineering from Columbia University, for every ton of concrete produced, one ton of CO2 is released into the atmosphere. The strategy behind the development of green concretes is to reduce the amount of Portland cement required in their manufacture, through using recycled toxic by-products from other industries such as fly ash and silica fume. Both fly ash and silica fume additives become non-toxic when combined with concrete and have added advantages in dramatically improving its mechanical properties and durability (Meyer, 2002). But while green concretes reduce the amount of Portland cement required, the fact that green concrete relies on toxic by products of existing non-sustainable industries makes long-term sustainability seem dubious. Other strategies to improve the sustainability of concrete have included developing composites, which use alternative fibrous additives such as carbon fibres, waste wood, straw, paper and recycled aggregates such as ground glass powder.

Glass is another area that has seen significant developments aimed at improving its energy efficiency by controlling heat loss or gain mainly through applying coatings which create low emissivity, or through the development of products such as electrochromatic glass which transform glass from opaque to transparent to control light and heat, or through the development of glass products embedded with photovoltaic cells to collect energy. While it is durable and can be used as a passive solar heating system, even with improvements in energy efficiency, it is questionable whether glass can really be defined as a sustainable building product in spite of claims to the contrary by industry. When compared with other materials that have transparent qualities, such as some of the transparent polymers, glass requires energy to be produced.

More generally, consideration of sustainability has lead to developments in ceramic materials, which have improved energy efficiency and reduced dependency on virgin resources. The development of sustainable prototypes has lead to innovations such as, ceramic foams, and foamed silicate (aerogels).

CERAMICS AND THEIR APPLICATION (After Ashby 2005, Fernandez 2005 and Ballard Bell et al 2006)		
	Type	**Application**
Technical Ceramics These are fine ceramics capable of load bearing applications, but because of their expense (apart from silicon based products) they are not used extensively in building applications. They are mainly used in the aerospace industry.	**Alumina**	Cutting tools, spark plugs
	Aluminium nitride	Microcircuit substrates and heat sinks
	Boron carbide	Lightweight armour, precision tools
	Silicon	Microcircuits, semiconductors, IR windows
	Silicon carbide	High temperature equipment
	Silicon nitride	Bearings, cutting tools
	Tungsten carbide	Cutting tools, drills
Porous Ceramics Porous ceramics include load bearing brick, stone, tile and reinforced concrete, earthen materials, non load bearing brick, stone, tile veneers, exterior plaster systems, interior concrete/brick, thermal mass, clay piping, storm water conduits and ceramic electrical insulators.		

CERAMICS AND THEIR APPLICATION (After Ashby 2005, Fernandez 2005 and Ballard Bell et al 2006)		
	Type	Application
	GLASSES	
Architectural applications for glasses include non load bearing glass ceramic systems, mineral insulation, optical glass for data and lighting, glass fibre and recycled glass aggregate for reinforced concrete, structural glass, glass brick, soda-lime glass for glazing, float glass and block, glass fibre insulation, and silica glass for high performance windows and aerogel insulating systems. Of all these materials, Aerogel (invented by NASA) represents one of the most advanced developments in lightweight materials, being lighter than air, strong and with excellent insulating properties. Aerogel is typically 50-99.5% air and can hold 500 - 4,000 times its weight in applied force. Aerogel can have surface areas ranging from 250 - 3,000 square meters per gram (Steiner, 2002). Flattened out, this "would have more surface area than an entire football field.....[and] its super low density makes it useful as a lightweight structural material, and its super-high internal surface area makes it a super-insulating material". (Steiner, 2001, p1) Blue in appearance and Styrofoam-like to the touch, the substance has many implications as a future building material, having "the lowest thermo conductivity of any solid material and being so light, aerogel has tremendous potential for dozens of applications". (Steiner, 2001, p1) In building applications aerogel has already been successfully applied as a light emitting insulating material for transparent composites, but its unique qualities give it many other potential applications.		

Table 6. Ceramics and their application. (After Ashby 2005, Fernandez 2005 and Ballard Bell et al 2006)

MATERIALS DRAWN FROM NATURAL RESOURCES

In terms of sustainable development materials drawn from natural resources represent the strongest growth area for future development. The category of naturals includes all materials that are sourced from renewable resources. In the building industry this includes products manufactured from wood (timber framing, flooring and panelling), and natural fibres (wall and floor panel systems), which are used as alternatives to non-natural fibres (carbon, glass or steel). These natural fibres include wood, flax, sisal, straw, cotton, hemp and kenaf and also microscopic cellulose fibres. In buildings the applications of natural materials include: wall systems (timber, adobe, straw bale), insulation, (wood, cellulose), fabric roof structures and joinery. Historically composites made from natural materials have often been bound with thermo plastic polymers or glues that increase their durability, but also make these products less sustainable, as the combinations with glues and polymers often create toxic emissions. Another concern is that these composites are no longer biodegradable and cannot be recycled. This has meant that new developments have been focused on generating more environmentally friendly composites, using biopolymers, and non toxic glues and clays, using nanotechnologies to enhance the performance capabilities of natural fibres, and in developing high tech fabrics as lightweight cladding systems.

Material considerations for designing composites

Composite design for structural panels involves the combination of materials to optimise the material properties of each component. This requires a thorough understanding of material properties when they become combined in terms of the several criteria that need to be considered to reach optimal solutions (Fernandez, Ashby). These are as follows:

1. Mechanical ability such as ductility, elasticity, yield strength, tensile strength, compressive strength and toughness.
2. Density
3. Thermal performance in relation to thermal conductivity, thermal diffusion, melting temperature, combustibility, and thermal expansion.
4. Optical quality in terms of translucency and colour.

5. Durability in relation to corrosion and mechanical wear.
6. Economic considerations in relation to cost to construct, and life cycle costs.
7. Environmental considerations in relation to embodied energy consumption, pollution and toxicity. This is highlighted in terms of sustainability.
8. Social considerations in terms of alleviation of poverty, health and safety, and social equity.
9. Cultural considerations in relation to historical significance, and character.
10. Toxicity

The traditional design of composites also takes into consideration the composition of the individual components from which it is constructed (refer to table below). Composites made from laminates, are either composed of flat sheets which are sometimes sandwiched together with lightweight insulating core components made from balsa, foam or honeycombs, or constructed from the combination of a matrix material (which usually originates as a liquid which solidifies through heat or a chemical process) and a reinforcing agent which is most commonly a fibre. The different elements (matrix and fibre) inextricably affect the way in which the composite behaves. The matrix material acts as the host to the fibrous material, with each element, the matrix and fibre enhancing the mechanical performance of each part. The arrangement of the elements within the matrix material also significantly affects its performance. There are several typical types of compositions for fibrous elements including particulate, flake, random fibre or whiskers, as well as different compositions of woven fibres such as braided or three dimensional woven fibres, lattice structures and segmented composites. In terms of creating sustainable composites, the focus will be on developing flexible, multifunctional, strong, lightweight, energy efficient, woven, latticed, sandwiched or matrix fibre composites using materials sourced from renewable or recyclable resources. Using nanotechnologies, these composites will also be able to incorporate intelligent systems, and optimise molecular bonding and self-organising structural efficacies based on biological principles.

DIFFERENT TYPES OF FIBRES USED TO MANUFACTURE COMPOSITES (From Ashby 2005)			
Manufactured fibres	Natural polymers	Cellulose and cellulose derivatives, acetate, ardil, protein, rubber and viscose rayon	
	Synthetic polymers	Organic	Aramid, elastomers, nylon 6, polyamides, polyacrylics, polyacrylonitrile, polyesters, polyethylene terephthalate, polyethelene, polyproylene, polyolefins
		Inorganic	Aluminium, carbon, boron, silicon and others
Natural fibres	Vegetable	Flax, sisal, jute, straw, cotton, coir and others	
	Mineral	Asbestos, gypsum and glass	
	Animal	Silk, hair, fur, wool	

Table 7. Different types of fibres used to manufacture composites.

Fig. 19 Flax fibres left, have been used by the SHAC team from the Engineering School at Auckland University to reinforce a prototype or a sustainable thin walled composite panel system made with a matrix of 90% rammed earth and 10% concrete.

2.3 MANUFACTURING TECHNIQUES

This section briefly outlines a general background synopsis of the manufacturing processes and techniques used in the construction of composites. Composite structural assemblies can be defined as panels, which are composed of a combination of various materials. It is in the combining of different elements, that their effect becomes optimised in relation to how they are used. Composite panels are traditionally constructed from a lightweight core sandwiched between thin facings to produce an exceptionally stiff panel, although the previous sections suggest variations to this formula.

Because of the complexity of their performance criteria, all buildings from the most basic adobe hut to a multi storied skyscraper are constructed using composites of structural elements, cladding, insulating and joining materials. These are layered to optimise the combined effect of different elements. Although they act like composites, many of these systems aren't defined as composites as each element is assembled individually on site piece by piece in sequential layers to result in a final product. Composites are usually composed of an amalgamation of two or more materials, and they generally rely either on the impregnation of a fibrous material into a liquid matrix which hardens through a chemical reaction or the application of heat, or on the layering of different materials to form a discrete panel. Many thousands of composite products have been developed for the building industry. Each composite has specific properties relative to the materials used, the manufacturing process and the specific requirements it has been designed for.

In the past, traditional approaches to designing composite components developed largely on an ad-hoc basis with new materials developed from a wide variety of possible processes and materials available. This approach did not explicitly consider the molecular bonding structures or manufacturing processes employed to fabricate composite elements. Each manufacturing process has a unique influence on the mechanical properties of the component due to the "unique macro mechanical properties" of the manufacturing process. (Mukesh et al, 1992) The bonds produced between atoms in the manufacturing processes determine many of the properties of the final product and also affect the choice of manufacturing process utilised. More recently the importance of material research has entered a new realm of relevance with the application of

nanotechnologies. In-depth research funded by global corporations using nanotechnologies has lead to the creation of new products that have enhanced performance attributes such as for the development of high strength timbers, concrete, and energy efficient glass.

Like materials, the manufacturing processes used to manufacture composites are classified according to different methods used to shape, join and finish each element. Each process can be used only for certain types of materials, and affects not only the potential shape of a product but mass, thinness/thickness and tolerances. Not all processes are compatible with different materials. The compatibility of a process against a material matrix is illustrated in the following table after Ashby (2005).

On the following pages, the tables show the main types of manufacturing processes used in the production of different material elements for the building industry.

		Metals, ferrous	Metals, non ferrous	Ceramics	Glasses	Elastomers	Thermoplastics	Thermosets	Polymer foams	Composites
Shaping	Sand casting	•								
	Die casting	•								
	Investment casting	•	•							
	Low pressure casting		•							
	Forging	•	•							
	Extrusion		•							
	Sheet forming	•	•							
	Powder methods	•	•	•						
	Electro-machining	•	•	•						
	Conventional machining	•	•	•	•	•	•	•	•	
	Injection moulding			•	•	•	•	•	•	
	Blow moulding				•		•			
	Compression moulding				•	•	•	•		

		Metals, ferrous	Metals, non ferrous	Ceramics	Glasses	Elastomers	Thermoplastics	Thermosets	Polymer foams	Composites
Shaping	Rotational moulding					•	•	•	•	
	Thermo-forming					•	•	•		
	Polymer casting					•	•	•	•	
	Resin-transfer moulding						•	•	•	•
	Filament winding									•
	Lay-up methods									•
	Vacuum bag									•
Joining	Adhesives	•	•	•	•	•	•	•	•	•
	Welding, metals	•	•							
	Welding polymers					•	•	•	•	
	Fasteners	•	•	•	•	•	•	•	•	
Finishing	Precision machining	•	•				•	•		•
	Grinding	•	•	•	•					•
	Lapping	•	•	•	•					•
	Polishing	•	•	•	•		•	•		•

		Metals, ferrous	Metals, non ferrous	Ceramics	Glasses	Elastomers	Thermoplastics	Thermosets	Polymer foams	Composites
Rapid Proto-typing	Ballistic Particle manufac-ture	•	•	•	•	•	•	•	•	•
	Stereo Lithography	•	•	•	•	•	•	•	•	•
	Laminated object	•	•	•	•	•	•	•	•	•
Nanotechnologies	Self assembly	•	•	•	•	•	•	•	•	•

Table 8 The compatibility of different types of manufacturing processes.

Fig. 20 BioWall, a hand made self supporting woven fibreglass structure based on soap bubbles, designed by Loop as a flexible wall system that supports living plants.

The second part of this research outlined the traditional processes used to make material selections, classifying materials and describing the main manufacturing processes used by the construction industry. The following section documents a design that draws on some of the research on emergent and existing technologies discussed in the previous parts.

3.1 DOCUMENTATION.

The research in the previous sections of this thesis has highlighted several areas of interest using emergent technologies for potential sustainable development, such as using nanotechnologies for manufacturing durable energy efficient biocomposites, or the development of structurally efficient lightweight responsive intelligent systems which adapt to changing environmental requirements to reduce energy consumption, materiality or stuctural loading, or the development of complex cellular structural systems using digital technologies and minimal surface structures to reduce materiality and also improve structural efficacy. Most of the strategies for developing sustainable prototypes using emergent technologies rely on a bottom up approach, which considers relations between things and the material properties of individual components rather than a traditional top down approach, which determines an overall structure and then considers how it is made. However the question was how could emergent technologies be exploited in a sustainable way within a New Zealand context, especially given the fact that most of these technologies in other countries are limited to small scale or highly specialized applications, as they are still in the process of being developed. In this respect, while it was very tempting to consider developing a flexible yet strong, lightweight system using nanoenhanced timber manufactured cellullose fibrils, and combined with an intelligent tensegrity structure, it seemed more relevant to look at developing a more passive structural system that use readily available manufacturing processes, while at the same time exploiting digital technologies in its generation. Another consideration was the relevance of how these technologies could be applied to develop a sustainable prototype especially in relation to existing and proven systems such as the zero energy ZALEH houses, built using low technologies, designed for passive solar gain using renewable materials such as straw bale and adobe.

In New Zealand, the majority of small scale domestic dwellings are still built using timber framed construction which is well suited to New Zealand's earthquake prone situation, and is sustainable if sourced from renewable plantations, and treated through non toxic processes. However, this profile radically changes when buildings become larger or more expensive, with concrete and steel becoming the predominant materials used in preference to timber.

Concrete blocks also maintain a high profile in residential and larger scale commercial applications largely due to their low cost in relation to durability, good thermal and acoustic performance and ease of assembly, but concrete blocks do not specifically optimise form as a contributor to their structural efficacy. According to a 2008 BRANZ report, every tonne of concrete produced emits 160 kg of carbon dioxide. If this data is considered in light of advances in performance capabilities of concrete alongside the environmental cost of carbon emissions required for cement production, traditional concrete blocks are unsustainable especially in relation to non-optimal use of material resources (concrete and steel).

It was with this in mind that this practice-based design research project began to examine a proposal for the generation of a 3 dimensional concrete block system using less material, building on research covered in the first part of this thesis especially in relation to the development of minimal surface structural systems. Minimal surface structures require minimal materials to generate form, and are structurally optimal. In his research into finding the optimum micro structure for developing composite materials, Torquato found that triply non periodic minimal surface structures have advantages over other structural systems because not only are they structurally efficient but they also have multiple performance capabilities. While this proposal does not look at the microstructure of concrete in terms of a minimal surface structure, it does look at how a minimal surface structure could be applied at a larger scale. The hypothesis of this project is based on several propositions:

- Could a triply minimal surface structure be advantageously applied to the generation of a more sustainable concrete block system, using less materials and improving structural/ performance capabilities?
- Could a minimal surface structure be replicated in the manufacture of a concrete block without requiring an over reliance on rapid processing techniques? (This recognises the fact that rapid prototyping is not well established, and is limited in terms of the scale at which the technology can be applied economically).
- How could new advances in the development of concrete be advantageously applied to the development of this prototype?
- How would a concrete block designed in this way be applied to designing a more

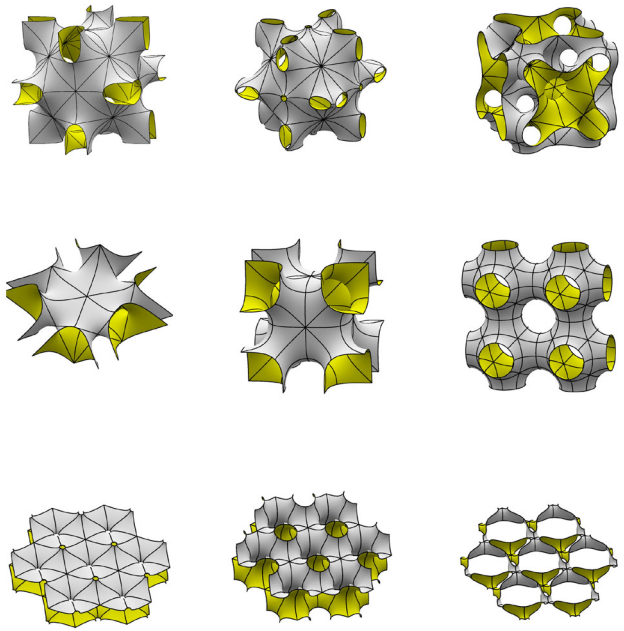


Fig. 21. Different types of minimal surface structures from left to right: Neovius' Surface, Neovius Complementary P surface, Schoen's Manta Surface of Genus 19, Schoen's Complementary D Surface, Schoen's I-WP Surface, Schwarz' P Surface, and variations of Schoen's Hybrid-I [P,F-RD] Surface.

sustainable building system?

Triply non periodic minimal surface structures are abundantly evident in naturally occurring systems, such as the curved parabolic formations of corals, petals and leaves, or on a more microscopic scale in porous structures such as sponges, radiolarian, soap bubbles, foam and gyroids. Even microscopic sections of solids such as bone and wood have airy cellular structures that mimic triply non-periodic minimal surfaces. For this investigation, the question was how this type of structure could be manipulated to generate a block work system which could be applied architecturally, and what scale or type could be used to make it, as there are versions that have already been mathematically modelled, as proposed buildings although not necessarily applied, or only built as small scale developments. Digital formulas are available for the mathematical generation of minimal surface structures (Fig 21) (refer Appendix A). The advantage of using existing mathematical models is that at some stage a more thorough analysis could be made of its performance and it also means that that the component can be scripted and evaluated through algorithmic applications if the technology became advanced enough to manufacture variable units economically.

From the many different types of minimal surface models, one particular pattern of a Manta version designed by Schoen (Fig. 22) was selected for testing. This version was selected because it was not one that I had seen previously developed architecturally and because it had a balanced juxtaposition between surface and void creating a parabolic curved form that was self-supporting. that could be moulded. This model also had the potential to generate complex forms in spite of its simplicity. From Schoen's model, physical cardboard models were constructed creating simple cells that were linked to become a more complex structure. Although the initial model was based on Schoen's model, further versions were developed to generate a continuously linking structure. This second model resembled optimal packing arrangements, as if the resulting structure was the remaining interstitial space left over from closely packed cells. This linked version was selected for further development, because it had a stronger potential to be able to be assembled into larger structural panel systems and also could be moulded using concrete composites or other substitutes (for instance, biopolymers). Initially I sought mathematical and computational support to generate the model digitally using Brakkes formula, but when the formula could not be applied,

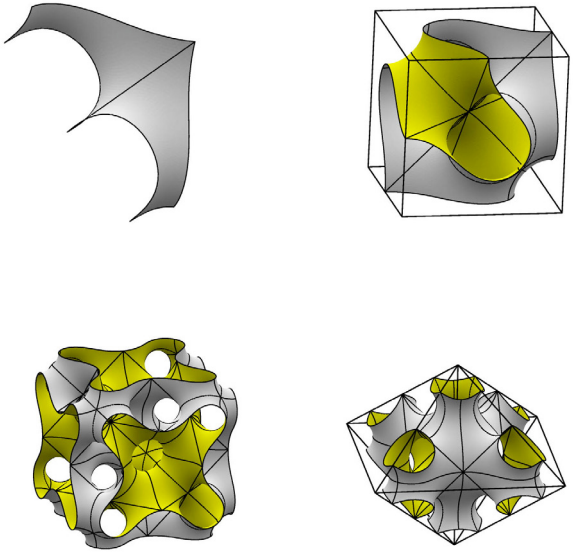


Fig. 22. Schoen's manta model and examples of its recombination based on the combination of surface curved in two directions.

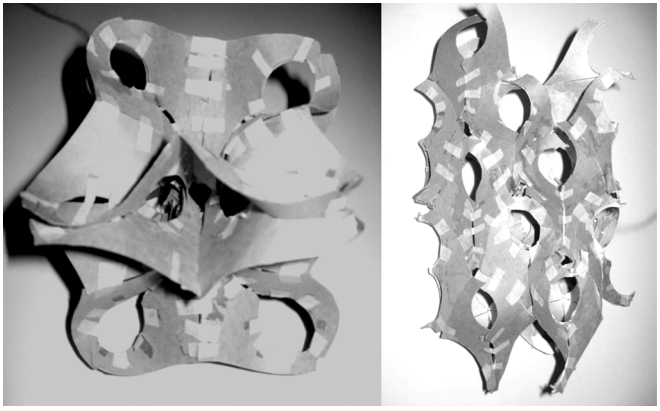


Fig. 23. Paper models of Schoen's manta surface left and its development into larger surface right.

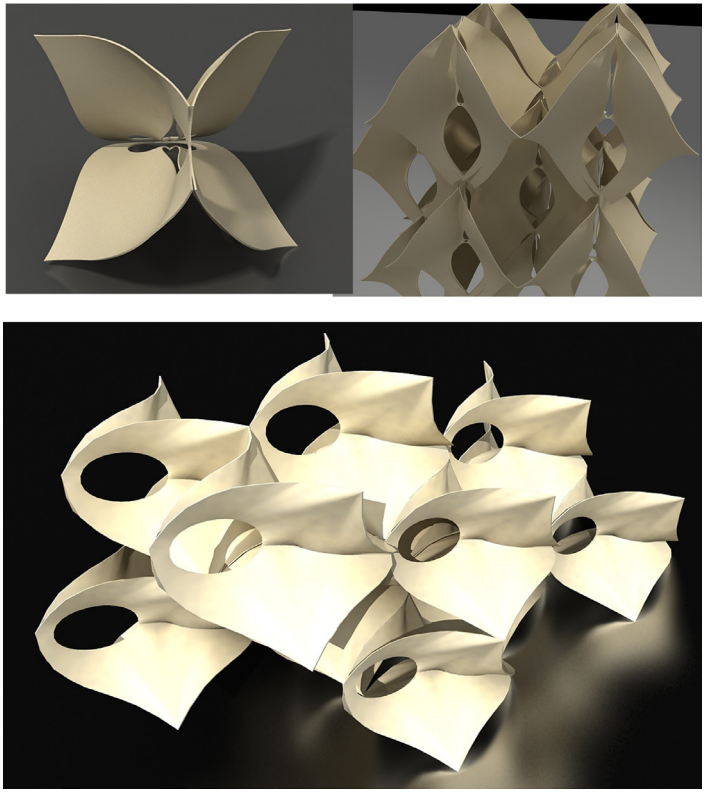


Fig. 24. Digital models based on cardboard prototype modelled by Miran Kim.

low tech physical modelling was used to generate the prototype for a model that was later transformed into digital versions (Figs. 23 and 24).

In the physical models, the initial component was formed from a single strip with dual curvature. While the form was simple, it became complex and had greater structural resistance as it became combined with additional units. In its construction, the relationship of the singular component had to be considered in relation to neighbouring elements, which in turn needed to consider multiple organisation and density in such a way that the individual components were moderated against the multiple assemblies. In the physical models the structure was self-supporting due to the combination of each component and its dual curvature.

Critical to the success of the application of a minimal surface structure to the production of a concrete block was determining its scale and thickness which would enable the proposed block to be replicated as a substitute within a similar module to a concrete block. In order to be economically viable it also had to be able to be manufactured in a mould using existing technologies. In New Zealand, concrete blocks are normally constructed with 20mm walls using a dry concrete mix consisting of Portland cement and aggregate to create a concrete shell with compressive strength of 12 MPa. On the inside of these walls is the addition of steel reinforcing and infill concrete to give a combined structural strength of 15 MPa and thermal mass.

Unlike a traditional concrete block, which is reinforced by steel, the proposed design was going to be reliant on its curved surfaces and the use of a high performance concrete for strength. This required an analysis of existing curved concrete structures to determine wall thickness. Many beautiful thin walled curved reinforced concrete parabolic shell structures have been developed as curved roof systems although, none from my research, had been developed as a concrete block wall system. Older versions of parabolic roofs relied on steel reinforcing encased by a layer of Ferro cement, and they also often needed reinforced ribs to stabilise them. More contemporary curved roofs using High Performance Fibre Reinforced Concrete UHPFRC has lead to an overall reduction in the thickness, with some (depending on span) being only 20mm thick. (Lafarge, 2008)

Ideally finite element analysis would optimise the thickness of the shell and size of the openings

Fig. 25. Kazuya Morita's concrete pod.

prior to its manufacture. But in this case the prototype was tested manually, as the intention was not just to consider its strength in comparison to traditional reinforced concrete block work, but also how it could be made. Inevitably, the proposed design would be refined and improved as part of an ongoing process in relation to input from different environmental criteria and its application. For instance the thickness of the shell could vary according to different criteria, such as differing wall heights, roof/floor loads, wind loading and bracing requirements for earthquake. A single block would not be able to cover all variables, and would be limited to mainly residential developments. So while strength was a factor, it was assumed that the thickness could change according to application, and according to how the block system performed under test conditions.

From a search of existing curved concrete structures, the thinnest shell found belonged to a perforated egg shaped "concrete-pod" based on the thickness ratio of a hens egg (Fig. 25). This pod, designed in 2005 by Kazuya Morita had a 12mm thick shell made from cement, aggregate and glass fibre, and was strong enough to support a person within it. Based on the consideration of how the block would be fabricated, an 8 - 16mm thick shell was selected as a conservative width to use on a test prototype. This width allowed for a maximum aggregate of 8 mm, and could be easily poured as a cast mould.

Because of the dual curvature and interlinked cellular units, minimal surface structures are complex to replicate through traditional moulding processes. The proposed minimal surface concrete block required an interlocking two part mould, the size of each cell being determined by a ratio of cells to the traditional concrete block module, and their ability to be easily fabricated. A traditional block of 200 x 400 x 200 mm high has 2 x 1 cells. After evaluating possible cellular distributions, the proposed block using the same proportions as a traditional concrete block had 3 x 1.5 cells. This was the maximum number of cells achievable using rapid prototyping and moulding restrictions. With the cells evenly distributed the block ended up being narrower (120 mm) than a traditional block (190mm).

The perforations between the cells created particular problems in terms of mouldability. The perforations come from the mathematical model, and would not be required if the blocks were insulated. However, as this proposal was concerned with testing the structural effect, and reduced

Fig. 26. Models testing scale of cells and mouldability with paper and plaster versions to right.

materiality rather than thermal efficiency a perforated version was developed in favour of the insulated version.

Another consideration was to determine what concrete admixtures would create the best structural performance. Over the last decade there has been significant developments in improving the performance of concrete particularly by using admixtures such as silica flume, fly ash and super plasticisers that reduce the cement to water ratios, critical for producing stronger concretes. Sika provided expertise in recommending the best admixture. Because the concrete was of superior strength, reinforcing fibres were not required.

Unlike traditional block work that has a closed cell structure, the proposed model was open with perforations through it occurring both vertically and horizontally. This made it resemble a crenulated breezeblock wall when assembled into larger panels. Breezeblock walls or jahli screens have traditionally served several purposes in architecture, to create a modulated microclimate for interior spaces. On external walls, perforated screen walls such as those seen in Islamic mosques are used as shadow screens, reducing heat loading to interior spaces. These screen walls also encourage the flow of natural ventilation and daylight to the interior, while maintaining security and a sense of privacy. Perforations and undulating surfaces also have an additional advantage of dissipating sound waves and creating variations in airflow between sun heated surfaces and shaded surfaces, thereby reducing the overall heat gain. In addition to these attributes the perforations can also carry services such as plumbing and electrical conduits, and support other performance requirements like thermal insulation.

With end use and environmental conditions factored in, and engineering support, a full scale digital analysis can test the design in terms of structural loading, airflow, sound insulation, thermal absorption/insulation, and fluid dynamics. In this respect, while the project has mainly relied on traditional low tech modes of production, through physical and digital modelling, the evolution of more varied organic generations can be explored based on environmental data and its arrangement can be modulated to take into consideration specific environmental criteria such as air flow, light modulation and thermal efficiency. This data would create deformations of the original form, with the data leading to expansions, compressions, sheers or elongations of the

Fig. 27. Developmental models showing transformation into block. based on mouldability.

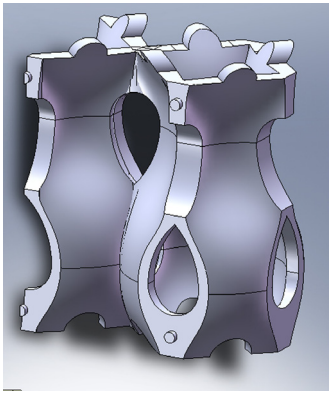
surface to optimise formation. In this respect each unit can become uniquely shaped through rapid prototyping to fit its purpose. Limitations of large-scale rapid prototyping technology make the application of creating multiply diverse units economically unfeasible at this stage.

While the proposed block conforms to the modulation of traditional concrete blocks it can either be laid horizontally or vertically to form perforated screen walls. Infilled versions of the vertical module can be insulated for external walls for improved thermal mass and sound absorption using sustainable infill materials such as fibre reinforced rammed earth, wool or straw. There is also the potential to construct the block as a single modulated cast panel that could be used in wall/floor or roofing applications.

To manufacture the block, 3mm rapid prototyped moulds strengthened with resin were initially made as moulds, although these moulds were replaced with silicon moulds for enhanced flexibility. Sika recommended that the block should be cast using Sika® MonoTop® Micro-Concrete. which has a compressive strength of 55MPa after 28 days. Time constraints lead to Sika® Grout 212 being used which has a compressive strength of 50 MPa after 7 days.

	Cubic capacity of a single block	Compressive strength	Emergy	Ratio cubic capacity/emergy
Reinforced Concrete block 190 x 190 x 390 mm	0.1407 m^3	12.5MPa (block) 17.5MPa (grout) 15MPa (combined)	1.4Mj/kg	140 x 100% = 140
Perforated minimal structure block	0.01795 m^3	26MPa	1.6Mj/kg	1.6 x 34% = 54

Table 8 Compressive strength against environmental impact.



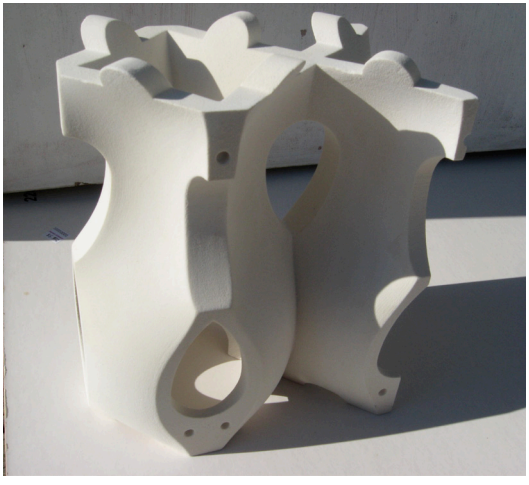


Fig. 28 Digital model and rapid prototype print. Unmouldable.

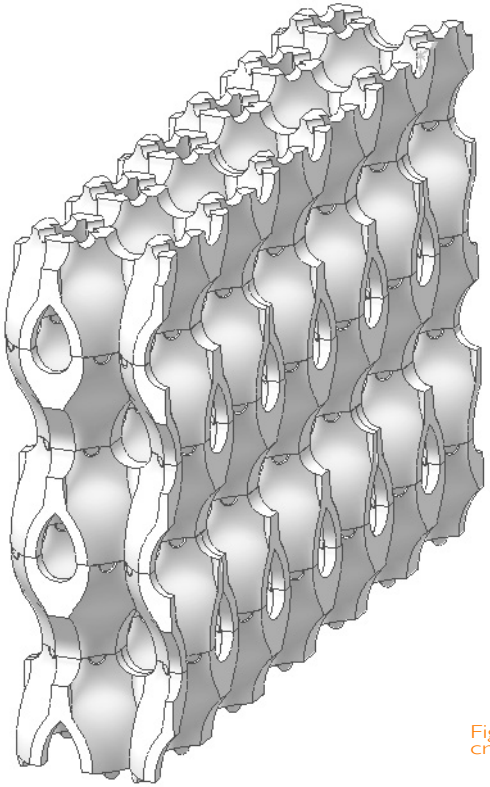
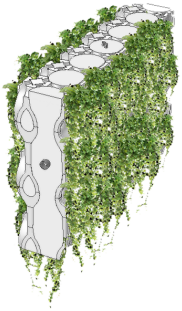
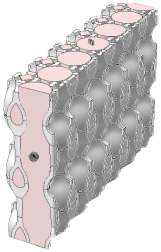


Fig 29 Digital models of concrete block assembly.



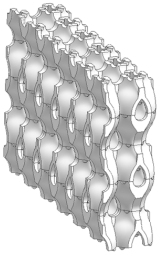
Living Wall

The Living Wall is designed to accomodate plant ecologies. This also enhances its thermal insulating properties.



Warm/Sound Wall

The Warm/Sound Wall is infiled with insulating materials such as cellulose or wool that either absorb sound or heat.



Shadow/Air Wall

While being exceptionally lightweight, the Shadow/Air Wall moderates interior environments by dispearsing heat and wind loads.

Fig. 30 The multiple performance capabilities of the block wall system. This ranges from living wall systems which are used externally, and in-filled with compost mixed with vermiculite, and drip feed watering systems to sustain living plants, through to insulated versions, which are used on external walls, and in-filled with insulation such as rammed earth, or wool fibres. Other variations include a perforated version which moderates airflow and heat gain to interior spaces and acts as a privacy screen.

Rather than testing an infilled version, perforated versions of the block were tested as it was assumed that these were likely to be the weakest version. After a 4-day cure compressive tests were undertaken. In these tests the blocks failed at a range of 45, 56 and 42 kN (refer Appendix B). When these figures were averaged and calculated against the cubic capacity of the block they gave a compressive strength of 26 MPa. This result demonstrates that the compressive strength of the proposed design is more than equivalent to a traditional reinforced concrete block which has an average strength of 15MPa. When the overall volumetric capacities of the different blocks were compared, there is a significant reduction in material by 66%. Even though high performance concrete creates more carbon emissions, the reduction in material radically reduces the overall environmental impact by 61% when compared with a traditional concrete block wall system. While concrete blocks are normally tested in relation to compressive strength, to fully test structural capabilities a shear test would prove overall structural stability.

For this proposal an attempt was made to reduce environmental impact through a design that uses less material through optimising the structural capabilities of a concrete block using a minimal surface structure. But, from an environmental perspective, there are problems with this design, as it remains reliant on concrete as its primary material. The compressive test results mean that it is possible to produce more sustainable versions by using green additives such as fly ash or silca fume used in the concrete mix. Even better, other substitutes for concrete can be considered such as bioresins made from soy or vegetable oil based resins reinforced with fax fibres or hemp. Determining alternative substitutes for the concrete forms another stage to this project.

Overall wall thicknesses and voids have also not been tested in relation to materiality. While this is dependant on how it is applied, it also offers further opportunities to optimise the design. The proposed design had a compressive strength of 26 MPa and wall thickness varying from 8 - 16 mm compared with a traditional reinforced concrete block of 15MPa. The test results mean that the wall thickness can be reduced to get a comparable compressive strength to traditional blocks. Improvements can also be made to improve ductility by using polypropylene reinforcing combined with a lower strength concrete.

Another area to optimise the design is through considering the overall scale of the void/walls. For this project, it was assumed that the proposed design could act as a substitute for a concrete block wall system using readily available existing and some emerging technologies in terms of small scale rapid prototyping in its manufacture. This lead to the design conforming to existing practice, in terms of its generation, with uniformly shaped blocks being produced rather than infinitely variable

Fig 31. Moulds used to cast concrete. Resin impregnated plaster in background and in front flexible silicon version.

Fig 32. Concrete casts fractured through compression testing.

versions. However, rather than being uniformly formed, the wall/voids within the block can vary depending on load with larger thicker wall/voids at the base of walls gradually tapering to smaller thinner walled versions as it gets higher There are drawbacks to producing deformed or non uniform versions in that they are dependent on large scale rapid protyping for their manufacture which is not an affordable option.

Fig. 33 Cast concrete blocks stacked to show assembly.

3.2 CONCLUSION

Manaaki Whenua, Manaaki Tangata, Haere whakamua
Care for the land, Care for the people, Go forward. (Maori proverb)

Buildings produce the most waste, emit the most carbon emissions and consume the most energy in the world. As our buildings become more fluid and adaptable what will we do as designers, materials scientists and researches to build better and more sustainable architecture and more life sustaining building systems? How will we reduce waste in our building and manufacturing processes? What will we do to conserve energy? How will we reduce carbon emissions? Can we rely on traditional technologies to produce sustainable buildings? Will emergent technologies lead to the development of better building systems and a healthier synergy between our natural and constructed environment? Or will these technologies in their excess compound any sustainable approach. This research project outlines the development of emergent technologies in consideration of the utilisation of nanotechnologies and replication of biological systems using digital technologies and emergent manufacturing processes to generate more sustainable building prototypes.

While some of the ideas expressed in this work at the beginning of this thesis are applicable to a distant future, some of the concepts and steps towards these methods are already feasible and should be developed to their fullest. In their book, *Understanding Sustainable Architecture,* authors Bennets, Radford and Williamson explain:

> It is clear that in seeking a sustainable architecture there is no unequivocal course of action that will suit all ethical stances, all objectives and all situations. There is no class or style of design which is unequivocally sustainable architecture, and no fixed set of rules which will guarantee success if followed. Rather, there are difficult interrelated decisions to be made that are contingent on particular circumstances. (Bennets et al, 2002, p. 127)

With so many dynamics and opinions regarding the future of sustainable architecture, the true danger lies in inaction due to the many stakeholders involved in processes that extend beyond ethical considerations. As a discipline, "we now need to focus on how we can recognize a sustainable building

design in our own, or others' work, which carries with it the implied further question of how an architect can act morally in her or his professional sphere in relation to sustainability" (Bennets et al, 2002, p. 127).

What has come out of this encounter with emergent technologies is a move away from the seduction of consumption made explicit through the technological wizardry and virtuosity of form making, that emerged with the initial development of digital technologies, through to one that considers how emergent and digital technologies can be applied to produce a more sustainable approach to generating architectural building systems which consider the relational potential of material systems. Rather than offering a definitive explanation of sustainable practices, this thesis presents a collection of ways in which sustainability can be thought about, through different types and modes of technology that will constantly evolve into collectives of new areas of knowledge and production. Underlying this approach is the shift away from top down approaches that rely on uniformity towards the generation of components that have "increasingly malleable forms of spatial and material intelligence with increased capacities to adapt to contingencies of use and interaction". (Verebes, 2006 p69).

Navigating a pathway towards a more sustainable future in the development of products for the building industry is complex. Over the last few years, the word sustainability has become a marketing catchphrase adopted by industries to promote more environmentally friendly products and manufacturing processes. In undertaking this research, identifying existing sustainable practices was difficult. While methods such as Life Cycle Analysis exist to measure the sustainability of manufacturing methods and processes, and the New Zealand Green Building Council offers ratings for sustainable buildings, there are no systems to regulate the way in which Life Cycle Analysis is applied, or regulate how products are marketed as being sustainable. Data that came from manufacturers seemed to wildly contradict independently produced sustainability indexes. Many of the existing processes used to manufacture so-called "sustainable" products are compromised by either their reliance on the exploitation of existing non-renewable resources or use of unsustainable manufacturing techniques. As a consequence, a widespread green wash, along with a limitation of alternative choices has created an illusion of a prevalence of sustainable practices in relation to existing industries. This misrepresentation is evident in industries that

manufacture and promote glass. Glass has developed significant advances in terms of its energy efficiency and reduction in carbon emissions through more efficient manufacturing processes. It also has advantages as a building material in relation to its recyclability, natural lighting, durability and its positive effect in relation to passive solar heat gain. Because of its high-embodied energy, glass as the sole external cladding system for multi-storey buildings can hardly be considered sustainable. But in industry literature, glass is regularly promoted as a sustainable building product. This is symptomatic of many industries developed since the industrial revolution that are more interested in protecting the profitable consumption of products drawn from cheaply available virgin resources, rather than addressing long-term effects or sustainability. Consumers condone the use of non-sustainable products, mainly through ignorance or lack of choice. Without regulation surrounding the marketing of sustainable materials and manufacturing processes combined with a more in depth understanding of the wider energy effects, it is difficult to make informed choices about the products we are buying. Global awareness of dwindling supplies of fossil fuels and concern over the environmental effects of carbon emissions will eventually lead to a greater awareness, regulation of industries, and a demand for more sustainable alternatives.

Addington argues that the continuation with traditional methodologies in the name of sustainability in relation to reducing energy consumption has perversely increased our total energy consumption in new buildings that have supposedly been designed with energy conserving features. She writes, "Ironically in our own desire to take a leadership role in the development of a sustainable future, we have chosen the path of least resistance, the path that allows us to continue to design buildings in old ways, with just a few high profile but more broadly ineffective alterations." (Addington, p45, 2007)

While there has been some development within the ceramic (concrete and glass) and polymer (acrylics) industries to produce more environmentally friendly materials, these industries remain reliant on the extraction of materials drawn from non-renewable resources, or are dependant on fossil fuels for their production, or produce toxins either during or post manufacture. Arguments supporting the development of more sustainable alternatives to existing building systems are persuasive. There is a huge potential for developing alternative sustainable building systems. This can be achieved through:

- Developing building systems and composites which specifically target sustainability in terms of material selection, (sourced from renewable or recycled resources) energy efficiency, durability and the application of advanced and sustainable manufacturing processes.
- Using molecular manufacturing techniques (nanotechnologies) to enhance the performance qualities, energy efficiency and durability of not only existing traditional building materials but also composites constructed using recycled materials such as glass, paper, aggregates and composites made from natural renewable materials such as wood, bamboo, straw, flax and other materials sourced from renewable resources.
- Developing more efficient and flexible structural systems, using minimum materials based on self-generative/organising principles of biological systems and morphogenetic design processes.
- Harnessing intelligent systems to optimise structural capabilities, flexibility/adaptability and enhance energy efficiency.
- Engaging in collaborative intelligence to take advantage of the intelligence of cross-disciplinary specialist fields effecting material science, form generation and manufacturing processes.
- Considering the overall material energy flows in relation to climatic variance.
- Accommodating evolutionary processes to allow for ongoing development and consideration of diversity.

Advances in digital processes and rapid processing techniques, along with developments in nanotechnology, design and manufacturing processes are radically changing the way in which buildings can be generated, directly linking design and manufacturing processes. Instead of the preoccupation with form, a shift has occurred towards a bottom up approach with a more intense focus on science, technology and material behaviour that has radically changed the way in which things can be made. Whether or not these emergent approaches are more sustainable than traditional sustainable methods largely depends on whether they can be affordably and efficiently applied at a larger scale. In this respect some of the new technologies discussed in this work such as manufacturing buildings using nanoassemblies may not eventuate for a long time,

even though a development using this technology has been realised in other ways, such as in the surface treatment of panel composites. The only real way of taking advantage of emergent technologies in a sustainable way is through a highly considered, approach which collaboratively merges different fields of intelligence drawn from quantum science, mathematics, materials science, engineering, biology, computer science, and architecture. This is an approach which encourages the opportunistic exploitation of existing and emergent technologies to generate more sustainable alternatives to the status quo.

APPENDIX A FORMULA OF SCHOEN'S BATWING SURFACE FROM KEN BRAKKE.

```
// batwingadj.fe
// Adjoint of Schoen's batwing surface.

// Programmer: Ken Brakke, brakke@susqu.edu, http://www.susqu.edu

/* Commands:
   gogo - typical evolution
   showcubelet - display 1/8 of cubic unit cell, as on web page
   showcube - display cubic unit cell
   showpair - show two fundamental regions, the "bat"
   showocto - show octahedron, as on web page
   transforms off - show just single fundamental region
   setcolor - to color one side yellow, as in my web page.

  To turn off showing all the edges in the graphics display,
     hit the "e" key in the graphics window.
*/

parameter asize = 0.45208  // shape parameter, for period killing

constraint 1 // mirror plane in adjoint
formula: x + z = 1

// Constraints for use after adjoint transformation
constraint 3 formula: x = z
constraint 4 formula: y = 0.5
constraint 5 formula: y = x
constraint 6 formula: x = 0
constraint 7 formula: y+z = 1
```

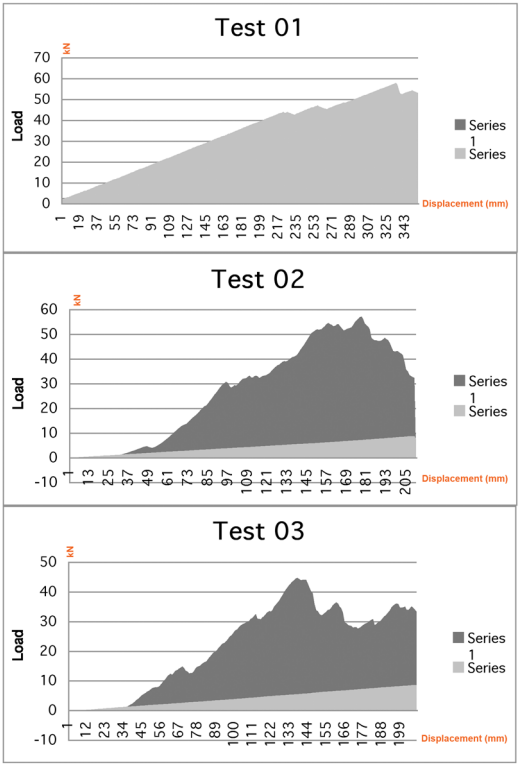
```
view_transform_generators 10
-1 0 0 0   0 1 0 0    0 0 1 0   0 0 0 1 // a: x mirror
 0 1 0 0   1 0 0 0    0 0 1 0   0 0 0 1  // b: x y swap
 1 0 0 0   0 0 -1 1   0 -1 0 1  0 0 0 1 // c: y+z=1
 swap_colors
 0 0 1 0   0 -1 0 1    1 0 0 0   0 0 0 1 // d: C2 rotation
-1 0 0 0   0 1 0 0    0 0 1 0   0 0 0 1 // e: x = 0 mirror
 1 0 0 0   0 -1 0 0   0 0 1 0   0 0 0 1 // f: y = 0 mirror
 1 0 0 0   0 1 0 0    0 0 -1 0  0 0 0 1 // g: z = 0 mirror
-1 0 0 2   0 1 0 0    0 0 1 0   0 0 0 1 // h: x = 1 mirror
 1 0 0 0   0 -1 0 2   0 0 1 0   0 0 0 1 // i: y = 1 mirror
 1 0 0 0   0 1 0 0    0 0 -1 2  0 0 0 1 // j: z = 1 mirror

vertices
1   0 0 0 fixed
2   1 0 0 fixed
3   asize (1-2*asize) (1-asize) fixed
4   asize -asize 0 fixed

edges
1  2 1 fixed
2  1 4 fixed
3  4 3 fixed
4  3 2 constraint 1

faces
1  -4 -3 -2 -1

read
hessian_normal
```

```
// good evolution, getting lots of facets near vertex 2 cusp.
gg := { refine edge where valence == 1; g 5; r; g 10; u;V;
        g5; hessian;hessian;
        g 5; hessian; hessian;
        r; g 5; u;V; u; g 5; hessian; hessian;
        g5; hessian;hessian;
        r; g 5; u;V; u; g 5; hessian; hessian;
        g 5;V; u;V; hessian; hessian;
        r; g 5; u;V; u; g 5; hessian; hessian;
        refine edge where original == 1 or original == 3;
        g 5;V; u;V; hessian; hessian;
      }

// Some distances in the adjoint
calc := {edge3dx := sum(edge ee where original==3,
          sum(ee.facet ff, (ff.y*ee.z-ff.z*ee.y)/sqrt(ff.x^2+ff.y^2+ff.z^2)));
         edge3dy := sum(edge ee where original==3,
          sum(ee.facet ff, (ff.z*ee.x-ff.x*ee.z)/sqrt(ff.x^2+ff.y^2+ff.z^2)));

         printf" edge3dx - edge3dy: %g   \n",edge3dx-edge3dy; }


read "adjoint.cmd"

// Call this to do adjoint transformation!
adj := { unset vertex constraint 1;
         unset edge constraint 1;
         adjoint;}

// Applying constraints after adjointing
```

```
frame := {unfix vertices; unfix edges;
    minx := min(vertex,x);
    set vertex x x-minx;
    miny := min(vertex,y);
    set vertex y y-miny;
    minz := min(vertex,z);
    set vertex z z-minz;

    maxyz := max(vertex,y+z);
    set vertex x x/maxyz;
    set vertex y y/maxyz;
    set vertex z z/maxyz;

    foreach edge ee where original==1 do
    { set ee.vertex constraint 6;
      set ee constraint 6;};
    foreach edge ee where original==2 do
    { set ee constraint 5; set ee.vertex constraint 5; };
    foreach edge ee where original==3 do
    { set ee constraint 7; set ee.vertex constraint 7; };
    foreach edge ee where original==4 do
    { set ee constraint 3; set ee.vertex constraint 3;
      set ee constraint 4; set ee.vertex constraint 4;
      fix ee; fix ee.vertex;  };}


// To get true asize after evolving after adjointing
true_asize := { printf "True asize: %20.15f\n",
   sum(edge where original == 2,length)/sqrt(2)/sum(edge where original==1,length); }

showpair := { transform_expr "d"; show_trans "R"; }
```

```
showcubelet := { transform_expr "dbcb"; show_trans "R"; }
showcube := { transform_expr "efjdbcb"; show_trans "R";}
showocta := { transform_expr "igcdada"; show_trans "R"; }
octa_edge := { va := new_vertex(.5,.5,.5);
               vb := new_vertex(0,0,1);
               ea := new_edge(va,vb);
               set edge[ea] fixed;
               set edge[ea] no_refine;
               vc := new_vertex(0,0,0);
               eb := new_edge(vb,vc);
               set edge[eb] fixed;
               set edge[eb] no_refine;}

setcolor := { set facet backcolor yellow }

gogo := { gg; adj; frame; show_trans "R"; hessian; hessian; }
```

APPENDIX B



Graphs showing outcome of compressive tests with failure demonstrated at moment when the graph descends. Failure occurs at a load of 45, 56 and 42 kN.

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