Exploring the Emerging Design Territory of Construction 3D Printing – Project Led Architectural Research

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Exploring the Emerging Design Territory of Construction 3D Printing – Project Led Architectural Research

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Declaration.

I certify that except where due acknowledgement has been made, the work is that of the author alone; the work has not been submitted previously, in whole or in part, to qualify for any other academic award; the content of the thesis is the result of work which has been carried out since the official commencement date of the approved research program; and, any editorial work, paid or unpaid, carried out by a third party is acknowledged; and ethics procedures and guidelines have been followed.

James Gardiner

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Abstract

3D printing techniques (also known as additive fabrication) are maturing and increasingly being used as an alternative means for niche product manufacturing. These fabrication techniques are now being scaled up and adapted for full-scale fabrication within the construction industry. While it has been suggested that construction 3D printing (fabrication of construction elements using scaled up 3D printing machines) could lead to significant advances within the construction industry, there are currently few examples of how such advances could be achieved at a building scale.

Although there has been significant effort invested in the development of construction 3D printing techniques, little detailed architectural design exploration has been published to establish methods for its application within the construction industry. My central proposition is that further detailed architectural exploration, focused on design for construction 3D printing combined with off-site fabrication methods and digital design tools, is necessary to tease out the potentials and limitations of construction 3D printing techniques.

This exegesis is split into two parts; the first part presents background research based on interviews, site visits and literature review, focused on the topics; design, off-site fabrication, digital design tools and 3D printing within construction and parallel industries (aerospace, automotive, manufacturing and shipbuilding). The second part of the exegesis presents case studies of three architectural projects, which I designed, focused on design for fabrication using construction 3D printing. These case studies include: Freefab, a visionary design for a high-rise apartment building on Sydney harbour, designed in 2004. And two new architectural projects: Villa Roccia, a rock inspired house to be built in Sardinia and (in)human habitat a speculative design for an artificial reef in the Red Sea.

The original contribution of this research is in the primary field survey of practices and emerging trends within the construction and parallel industries.

Original contributions are also made in the synthesis of selected practices identified from literature review and the field surveys to form novel design and construction methodologies. These methodologies have been tested through the design of unique architectural projects focused on fabrication using construction 3D printing.

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KEYWORDS

Rapid Manufacturing, Rapid Prototyping, Solid Freeform fabrication, Additive Manufacturing, Additive Fabrication, Automated, Freeform Fabrication, Construction 3D printing, Off-site fabrication, Prefabrication, Design, Architecture, Parametric, Scripting, Optimisation, Contour Crafting, Freeform Construction, D-Shape, CAM, CAD, Optimization, Digital Design, Digital Definition, Construction, Sustainability, Deep Scaffold.

1. Introduction - Exploring the Emerging Design Territory of Construction 3D Printing

1.1. Introducing the field and research

Additive Fabrication is emerging as an important new field within product manufacturing and is revolutionising the way objects are designed and fabricated in niche markets within aerospace, medical, toys and jewellery (Wohlers, 2010). Having originally emerged from the field of Rapid Prototyping, Additive Fabrication differs principally through the production of end use parts rather than prototypes. Developments in Additive Fabrication have an application within the construction industry, with the scaling up of Additive Fabrication techniques to create ‘Additive Fabrication for Construction’: a number of Construction 3D printing[1] machines have been in development since 1996 (Dini et al., 2008, Khoshnevis, 1996)

Significant resources have been invested over the last two decades in the development of construction 3D printing techniques such as Contour Crafting™, D-Shape™, Concrete Printing™ and Mineraljet™. Efforts, predominantly by engineers, have also been made to identify potential applications for these techniques within the construction industry (Pasquire et al., 2006, Buswell et al., 2007b, Soar, 2006a, Buswell et al., 2005, Pendlebury et al., 2006). Strangely despite sustained high profile media attention focused on Construction 3D printing (Abrahams, 2010, Werthheim, 2004, Discovery_Channel, 2006) there has to date been little focused architectural attention on how to design and detail buildings for construction 3D printing techniques. This has not substantially changed since this PhD research commenced with only two authors Roche and

[1] The term Construction 3D printing will also be used within this exegesis and has the same meaning as Additive Manufacturing for Construction. A discussion of terminology is included within the index of terms.

Gardiner (Roche et al., 2007, Gardiner, 2004b, Gardiner, 2011) having published material on their detailed architectural projects.

This exegesis is primarily concerned with filling this gap of detailed architectural exploration, focused on design for construction 3D printing fabrication with the aim to tease out potentials and limitations of particular construction 3D printing techniques. The theoretical aims of this research are to explore the potentials and limitations of emerging Construction 3D Printing techniques through action research, analysis and critical reflection on the results in the form of case study projects. With the aim to increase our understanding of the future opportunities and limitations of these techniques within the architecture and construction.

Different characteristics and approaches underpin each of the three case study projects that form the foundation upon which this exegesis is based, which has resulted in three very different projects. These different characteristics and approaches include; speculative and commissioned design, development of new constructions systems and hybridizations of old ones, design for specific individuals and design for undefined groups, building models, testing and prototyping at full scale, design for humans and design for aquatic animals and plants.

These projects are very different from each other, although they all share the same thread, digital design for fabrication with construction 3D printing techniques. There is also a common thread between the projects which include; exploration, invention and the teasing out of the potentials and limitations of construction 3D printing. Although the subject matter of the projects is novel, the approaches that I have taken as an architect in these projects is not new and has precedents in the work of other architects such as Gaudí, Otto, Hensel and Menges.

Construction industry and architecture

The original motivation for this body of research came through a frustration with practice in the Australian architecture and construction industries. I graduated from interior design in 1997 and have worked primarily in Architecture since. I graduated from Architecture at UTS Sydney in 2004[2], the University degree at that time, required students to work in the field of architecture and study simultaneously. This practice of work/study gave me an unusual opportunity of working within the industry and thus understanding the problems of the field first hand and having the opportunity to creatively investigate potential solutions to the problems of the industry through university design projects, a form of 'Action Research' (Bradbury and Reason, 2001). Since completing the architecture degree I started my own architectural practice Faan Studio[3] in Sydney in 2005 and became a registered architect in 2006.

The problems that I experienced during this period (1997-2007) were caused within both the design[4] and the building professions and included: problematic communication between stakeholders and inaccuracies in documentation, material and energy waste, building mistakes and the need for re-work and resistance to change by builders, tradesmen and design professionals. These and many other issues were well documented by 2002, when I first began to seek solutions to these issue, in the United Kingdom (Egan, 1998) and in the USA (NAHB, 2001).

"*There is a deep sense that the* (construction) *industry as a whole is under achieving. It has low profitability and invests too little in capital, research and development and training. Too many of the* (construction) *industries clients are dissatisfied with its overall performance*" (Egan, 1998)

The Egan report identifies many major problems within the construction industry and clearly identifies the construction industry to be in need of urgent improvement. By 2004 similar issues were also clearly in focus for other architects, with publications documenting issues and suggesting alternative working methodologies, such as off-site fabrication (Kieran and Timberlake,

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[2] The UTS Architecture degree until 2005 required students to work in architecture throughout the course after 1st year.

[3] Faan Studio was formerly known as jamesgardinerdesign

[4] Architecture and engineering

2004, Woudhuysen and Abley, 2004) as a potential solution. The question and many others were trying to answer at the time can be defined as primarily: how can design and construction improve? This question became a key motivation for of this research, although answering this question is outside of the scope of the exegesis.

Construction sustainability

Within the building industry *construction sustainability*[5] is increasing in importance and urgency: as the developing world strives toward western living standards (Zhu and Lin, 2004) and the world is faced with human induced global warming[6] (Garnaut, 2011, Solomon et al., 2007) and diminishing natural resources (Holling and Meffe, 1996). Governments and international agencies are increasingly calling for change within the construction industry (United_Nations, 2006, Constructing_Excellence, 2009) or legislating change (Demaid and Quintas, 2006) within the construction industry to meet the challenges presented in meeting sustainability targets, legislated controls such as LEED (U.S._Green_Building_Council, 2011) and Australian BASIX (NSW_Department_of_Planning, 2011) rating systems).

The issues that I experienced from within the construction industry first hand as well as an awareness of the issues of sustainability led me, like others (Woudhuysen and Abley, 2004, Kieran and Timberlake, 2004) to look for alternative practices, tools, techniques and methods that could be adopted to mitigate some or all of the issues faced. Potential for the construction industry has

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[5] Defined in the index of terms

[6] Human induced global warming is considered for the purposes of this research to be a proven based on the current scientific published reports (refer references above) and the status that it is given by Australian and world scientific groups (IPCC, CSIRO climate change, Climate Scientists Australia) and government/non-government related bodies (UNFCC, USGCRP, climate commission (Australia). It is however acknowledging that this phenomenon is still being actively debated and there are detractors of the theory.

long been identified with the implementation of off-site fabrication (Corbusier, 1931, Gibb, 1999a, Davies, 2005, Woudhuysen and Abley, 2004).

Off-site fabrication

The potential to implement off-site fabrication within the construction industry to me, on a superficial level, seemed illusively easy until I started to intensively research the area for a series of design projects in my final years studying architecture. At this time I realised that there was no single way to design or detail for off-site fabrication but instead a myriad: of which surprisingly little documentation providing detail could be located and less again had been proven to be viable through commercial success (Davies, 2005). It also became apparent that many of the most famous architects of the 20th century had designed or developed a system for prefabricated buildings. Particularly famous examples of these included; Buckminster Fuller 'Witchita House', Jean Prouvé 'Maison Tropicale', Frank Lloyd Wright 'Jacobs House', Walter Gropius[7] 'General Panel System', Charles and Ray Eames 'Case study house no. 8', Richard Rogers 'Zip-Up Enclosures', Paul Rudolph 'Oriental Masonic Gardens', Moshe Safdie 'Habitat '67' and Kisho Kurokawa 'Nakagin Capsule Tower' (Bergdoll et al., 2008, Davies, 2005). I asked myself the question, with such a variety of systems developed by such prestigious architects, 'why is off-site fabrication not more prevalent today?'

Answering this question and others that arose during this explorative research period became the primary motivation for extensive global and local field research (including site/factory visits, interviews and questionnaires) within the construction and parallel industries between 2006 and 2009; focussed on off-site fabrication, the implementation of automated fabrication and digital design tools.

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[7] Including Konrad Wachsmann

Digital design tools

Potential for the construction industry has, like off-site fabrication, also been identified to exist with the use of digital design tools[8]. The main benefits of such 3D CAD tools today identified by Nicholas can be briefly summarised as: improved co-ordination of documentation and consultants, the ability to interface with CAM (computer aided manufacturing) equipment, the use of analysis and optimisation software to aid the design process and the increased ability to deal with complexity (Nicholas, 2008).

I had learnt how to use CAD programs in 3D before I had learnt how to use CAD in 2D[9]. Following on from this I continued to lean toward 3D CAD within my office work and all of my university projects. Hence drawing and documenting buildings in 3D seemed the logical path to follow, although at the time (1997-2004) from my experience such documentation in Sydney architectural practices was not widespread and only a few architectural CAD programs (Archicad™, Autodesk™, Architectural Desktop™ (ADT) and Revit™) were at the time designed specifically for coordinated 3D documentation (Garba and Hassanain, 2004), as they are today with the significant advances of Building Information Modelling (BIM).

On further investigation into the use of digital design tools for design and documentation, a number of leading architects and offices at that time including Gehry Partners, Burry, Future Systems and Foster and Partners were actively tapping into the potential of 3D Digital design tool beyond its use as a design and visualisation tools with the use of scripting, analysis and parametric modelling (Lindsey, 2001, Kolarevic, 2003, Burry, 2002, Shelden, 2002). This innovative

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[8] Refer to definition of digital design tools in the index of terms (chapter 1.5)

[9] The CAD course at Enmore Design Centre, SIT Sydney focused specifically on the use of 3D CAD instead of 2D CAD, it was explained to me at the time that if you learn 3D CAD you will be able to teach yourself 2D and that the opposite way of learning is more difficult. Discussion with Albert Chia, CAD tutor Enmore SIT 1995.

use of digital design tools in many cases followed in the path of developments and/or pioneering practices of the parallel industries[10] (Kolarevic, 2003).

CAM and Additive Fabrication

After significant research in the field of off-site fabrication and 3D digital design tools it seemed, to me, that there must be a 'silver bullet'[11] automated fabrication computer aided manufacturing (CAM) technique that could unlock the potential of off-site fabrication and the emerging capabilities of 3D digital design tools. Although the use of CAD/CAM have been used for some time within the parallel industries, implementation within the construction industry has taken hold more recently (Burry, 2002, Mitchell, 1999, Kolarevic, 2003).

"*While the CAD/CAM technological advances and the resulting changes in design and production techniques had an enormous impact on other industries, there has yet to be a similarly significant industry-wide impact in the world of building design and construction. The opportunities for the architecture, engineering and construction (AEC) industries are beckoning, and the benefits are already manifested in related fields"(Kolarevic, 2003) p15*

The predominant CAM techniques, used for architectural projects, being laser/plasma cutting, punching and CNC milling/cutting. Although there are significant benefits with the implementation and exploitation of these techniques, my imagination was captured by another group of techniques: Additive Fabrication. Additive Fabrication, also commonly called '3D printing', emerged from Rapid Prototyping techniques developed for the manufacturing in the 1980's (Wohlers, 2007).

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[10] Aerospace, Automotive, Shipbuilding and manufacturing

[11] Silver Bullet definition "*something that acts as a magical weapon; especially : one that instantly solves a long-standing problem*" Merriam Webster Online - http://www.merriam-webster.com/dictionary/silver%20bullet Access date 21st August 2011

It seemed certain, when I first came into contact with these machines at UTS, that such techniques would be scaled up sooner or later for the fabrication of buildings or construction elements. On discussing such thoughts with the workshop manager at UTS[12], it was mentioned to me the existence of a concrete printer, but no leads could be given. After an exhaustive search I came across an article on Contour Crafting and subsequently found the, at the time, obscure Contour Crafting Website. On discovering the construction 3D printing technique it became apparent that this could be potentially game changing 'silver bullet' fabrication method for the construction industry that I was searching for.

For my final architecture studio at UTS I decided to test the combination of Contour Crafting fabrication technique, off-site fabrication methods and 3D digital design tools as the starting point for the design of an apartment building named 'Freefab Tower' which is presented in this exegesis as a case study (Chapter 4.1). This project formed the starting point from which this PhD research followed with considerably more rigour.

[12] Discussion with John Dennison in the UTS Industrial Design Workshop April 2004

1.2. Hypothesis and themes

Through the attempt to answer the questions: ‘how can design and construction improve’ a hypothesis has emerged focused on what I call ‘the silver bullet’ construction innovation, that will enable the benefits of off-site fabrication to be realised, with construction 3D printing. Although my personal motivation for this PhD remains focused on the question ‘how can design and construction improve’ and the eventual transformation of the construction industry; the focus of the PhD is much more modest. There are still too few detailed architectural projects designed or fabricated to be able to quantify these improvements or to be able to definitively state that construction 3D printing will unlock the potential of off-site fabrication, digital design tools or transform the construction industry.

The hypothesis is therefore as follows:

A hybridisation of new and existing design practices, digital design tools, off-site fabrication methods combined with construction 3D printing techniques could lead to significant advances for architecture and construction. To better understand the potentials and limitations of construction 3D printing combined with off-site fabrication methods and digital design tools, further detailed architectural exploration is required.

The Hypothesis has two specific components: the first is to further explore design for construction 3D printing techniques through the combination of new and existing design practices, digital design tools and off-site fabrication methods. The second is to glean from these projects the potentials and limitations that exist for specific construction 3D printing techniques in order to better understand how construction 3D printing might be implemented to advance architecture and construction.

The hypothesis raises a series of questions, as follows:

- If an architectural project is to be fabricated using a particular construction 3D printing technique
    1. What are the implications for the way it will be **architecturally designed**
    2. What are the implications for **documentation** - the way the project will be designed/documented using 3D digital design tools
    3. What are the implications for the way the project will be designed and assembled for **off-site fabrication**
    and
    4. What are the opportunities for **construction sustainability**?

These four questions related to design, documentation, construction and sustainability will be used is the primary subjects of scrutiny in the analysis of the three case study projects presented in this exegesis.

The three case study projects: Freefab Tower, Villa Roccia and (in)human habitat were all conceived quite differently. The first Freefab Tower was completed prior to the commencement of this PhD and was completed as an entirely speculative project, the second Villa Roccia is a commissioned project, which has had three distinct design stages and included prototyping. The third project (in)human habitat was conceived as a speculative project and has since transformed into a live project which should move into prototyping later in 2011. It is therefore considered that this explorative project led research can lead to tangible outcomes and add not only to theory but also to practical knowledge (Downton, 2003) in the field of construction 3D printing.

The format of this exegesis varies from standard exegesis format; in this exegesis the Hypothesis and the Methodology have been moved to the beginning, before the background chapter in order to clarify the questions that are being addressed and to clearly state the methods used to address these questions. By stating these items up front it should be easier to understand the content from the outset.

1.3. Defining the research outline

This exegesis is constituted in two main parts; the first part introduces the subjects under study, terminology used, the motivations and position that underpin this research, the hypothesis that guides the focus of study, the methods that have been used to generate the research as well as the body of background research.

The subjects that constitute the background research include the following

- Architectural **design**
- Construction **Sustainability**
- Digital design **tools**
- Off-site fabrication **methods**
- Additive Fabrication **techniques**

This background research is built on broad based literature review of the above-mentioned topics as well as primary qualitative and quantitative data and information obtained through construction and parallel industry[13] interviews and questionnaires.

The second part of this exegesis includes three architectural case studies that have been generated through applied research and are presented and analysed in reference to the background research and hypothesis. The three architectural case studies include both speculative and commissioned architectural projects designed by me between 2004 and 2011. Each of the three projects was designed for fabrication using construction 3D printing and have been designed with the focus on exploring the potentials and limitations of this type of fabrication technique.

---

[13] Parallel industries – Aerospace, Automotive, Shipbuilding and manufacturing.

The analysis of case studies focuses on responding to the questions that emerged in response to the hypothesis (chapter 1.2) and differs slightly from the background research topics listed above.

This analysis of the case study projects will concentrate on the question

How have potentials and limitations of a particular construction 3D printing technique been manifested and what does this mean?

With focus on the following subjects

- Architectural design
- Digital definition (using 3D digital design tools)
- Off-site fabrication
- Construction sustainability

Each of the case studies will be analysed separately in reference to the relevant background research. A discussion of the findings from the case studies will then be presented in the conclusion, which will focus on important findings and trends.

To finalise the exegesis the significance of the research will be discussed, further research opportunities will be described including how this work can be used as a platform for further research.

1.4. Index of abbreviations

2D – Two-dimensional

3D – Three-dimensional

BIM – Building information modelling

CAD – Computer aided design

CAM – Computer aided Manufacturing

DDAA – Delivering Digital Architecture in Australia

GC™- Generative Components (parametric Digital design tool from Bentley)

RMIT – Royal Melbourne Institute of technology

SIAL – Spatial Information Architecture Laboratory (RMIT)

.stl – Stereolithography file format for 3D printing

US – United States of America

UTS – University of technology Sydney

1.5. Index of terms

Additive Fabrication

The term rapid manufacturing has been the most widely used by industry; defined as "*a technique for manufacturing solid objects by the sequential delivery of energy and/or material to specified points in space.*" (Asiabanpour et al., 2008) and "*the use of a computer aided design (CAD)-based automated Additive manufacturing process to construct parts that are used directly as finished products or components*". (Hopkinson et al., 2006a) Together these two definitions give an indication of both the how the technique creates objects and what these objects are used for; *finished objects or components*.

Many terms have been coined by academia and industry over the last two decades including: Rapid prototyping, Rapid Tooling, Rapid Manufacturing, Solid Freeform Fabrication, 3D Printing, Direct Manufacturing, Layered Manufacturing and Additive Manufacturing[14]. Wohlers has proposed alternative terms 'Additive Fabrication' and '3D printing' (Wohlers, 2007) after consultation with leaders in the industry, both terms will be used within this exegesis. 'Additive fabrication' will be used for small-scale professional fabrication and 'construction 3D printing' used for large scale construction applications. The term '3D printing' will also used in place of additive fabrication in some cases where additive fabrication occurs at home or on inexpensive additive fabrication machines developed for the consumer market, as suggested by Wohlers (Wohlers, 2007). It is acknowledged that neither terms are perfect but they are the best of a problematic bunch.

There is a problem with many of the terms coined by industry and academia; Rapid prototyping, Rapid Manufacturing, Solid Freeform Fabrication, Direct

[14] There are many more terms that have been coined for this field of fabrication techniques, which will not be discussed here. These terms are the most commonly used to describe prototyping, tool building (tooling) and fabrication processes.

Manufacturing, Layered Manufacturing. The problem with these terms can be described as having one or both of the following attributes; first they do not accurately or clearly describe the technique. For example the term 'manufacturing' is a process defined by The Concise Oxford Dictionary "*Manufacture (v). 1. make (something) on a large scale using machinery.*"[15] or by the Australian Oxford Dictionary "*Manufacture (n) 1. (a) the making of articles especially in a factory etc."*[16] Additive Fabrication can and usually does occur without 'fabrication on a large scale (i.e. making many) and outside of a 'factory'. The Second problem with the terms listed above is that they often contain words that are no longer particularly relevant to the technique. For example the term 'Rapid' was originally associated with the rapid production of prototypes over traditional means.

Construction 3D printing

As stated above within the definition of Additive Fabrication the term 'Construction 3D Printing' will be used instead of other alternative terms such as 'Freeform Construction', 'Construction Scale Additive Manufacturing' and 'Additive Manufacturing for Construction'.

The term 3D Printing is considered by Wohlers as being a term which will be enduring and that is also easy understand (which is helpful in the construction industry).

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[15] The Concise Oxford Dictionary accessed through The Oxford Reference online premium. http://www.oxfordreference.com.ezproxy.lib.rmit.edu.au/views/SEARCH_RESULTS.html?y=7&q=manufacture&category=s7&x=20&ssid=11352459&scope=subject&time=0.12405618691837. Accessed date 4th August 2011

[16] The Australian Oxford Dictionary accessed through The Oxford Reference online premium. http://www.oxfordreference.com.ezproxy.lib.rmit.edu.au/views/SEARCH_RESULTS.html?y=7&q=manufacture&category=s7&x=20&ssid=11352459&scope=subject&time=0.12405618691837. Access date 4th August 2011

“I truly believe that 3D printer will become the term of choice in the future to describe systems that fabricate parts additively. The term is easy to say and understand, given that most people understand the basics of three dimensions and printing. Combined, it communicates exactly what is happening technically in these machines. I believe that few people won't get it.” (Wohlers, 2007)

The term ‘Construction Scale’ is also not preferred, as in ‘construction scale 3d printing’, as the term scale is often understood to mean ‘scaled’, as in the term ‘scale model’ and can therefore be confusing on first exposure to the term. Scale can, in the alternative sense also be understood to mean that a construction scale 3D printer can only produce construction size objects such as buildings and large panels etc, whereas the three machines developed to date can all operate at different scales and produce different size products. They have however been developed for the construction industry, which has its own technical challenges to overcome, so it is considered shrewd to include the term to be clear that the techniques are appropriate to use for construction.

The second reason for steering away from the term ‘scale’ is that once the concept is understood for example ‘Construction Scale 3D printing’ the term scale (as in size) is no longer relevant and is a cumbersome add-on for a term that will be used frequently in conversation and written material. Again I don’t propose the term ‘Construction 3D Printing’ to be the perfect term, I do however believe it to be the best term available today.

Potential

The Oxford Dictionary online defines Potential as “*1 [mass noun] latent qualities or abilities that may be developed and lead to future success or usefulness….*"[17]

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[17] Oxford dictionaries Online. http://oxforddictionaries.com/definition/potential Access date 5th August 2011

This research is focused on identification of potential rather than quantification of what that potential will result in, quantification of such potential is beyond the scope of this PhD research and resulting exegesis.

Parallel Industries

The term Parallel Industries is used to refer to the group of industries that are considered to have practices in parallel to the construction industry, such as digital CAD design, off-site fabrication and the use of CAM automation for fabrication of their product. These industries include Aerospace, Automotive, Shipbuilding and Manufacturing.

Design

The word Design is "given quite specific and different meanings by particular groups of people." "design is both a noun and a verb and can refer either to the end product or to the process" (Lawson, 2005). The Oxford Dictionary[18] definition can be distilled down to the following 1. production of a "*plan or drawing*" (or 3D model[19]) 2. "*the art or action of conceiving…something before it is made*" 3. "*The arrangement of features*" 4. "*A decorative pattern*" 5. the "*purpose or planning that exists behind an action, fact or object*". Benton further defines design as "*a process of conscious decision-making*" (Benton, 2008), although it can be argued that many aspects of the design decision making process may be made based on unconscious preferences.

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[18] Oxford Dictionaries (online) http://oxforddictionaries.com/definition/design Access date 8th July 2011

[19] 3D model is added to this dictionary definition as this primary means of communicating design intent for production using CAM fabrication technique. This means of production and use of 3D data directly for fabrication instead of 'plans or drawings' is still relatively unusual within architecture and manufacturing fields generally and thus is probably the reason why 3D models are not included in this dictionary definition.

The definition of design in the context of this exegesis, is generally related to architectural design and in this instance is largely concerned with items: (1) production of a 3D model (2) The art or action of conceiving something and (5) The purpose or planning that exists behind an…object.

Parametric

Holzer (cited Burry 1999, 79) describes a parametric design/model as *"set up on the basis of rules and references that govern geometry and thereby provide the designer with syntax for creating an unlimited number of morphologically different versions of the same design-template"*

Scripting

"Scripting is a text based method for using design tools…..Scripting allows the designer direct access to an applications commands…as well as to general control structures such as loops, logical and mathematical operators and conditionals which dictate the sequential progression through the methods when the script executes." (Nicholas, 2008) There are two main types of scripting in common usage by designers; text based scripting and visual scripting. Both types rely on text scripts, but the second (visual scripting) uses modules of pre-defined scripts within a visual interface to allow for scripts to be assembled with little knowledge of grammatical scripting language (e.g. VBA, c+, python).

Optimisation

This term in this exegesis refers to a group of software used to find a single or multiple 'optimal' solution(s) to single or multiple performance criteria. The Oxford Dictionary[20] defines optimize as to "*make the best or most effective use of (a situation or resource)*". In most cases optimization software generates multiple

[20] Oxford Dictionaries (online). http://oxforddictionaries.com/definition/optimize#m_en_gb0583750.005. Accessed 15 july 2011

‘acceptable’ ‘compromise’ solutions or designs, which can be selected by the designer. (Fonseca and Fleming, 1995)

Tools

The term ‘tools’ in this exegesis refers mainly to digital design CAD software. This term is used as a heading and general term to refer to a broad range of CAD software in use by architects and engineers as well as within the parallel industries.

Digital Design Tool

The term digital design tool in this exegesis refers to the use of CAD tools that have as their focus a core design capability (Rhino™, Generative Components ™, CATIA™, Maya™) rather than a core focus on the production of 2D documentation (Autocad™, Revit™, Archicad™, Vectorworks™).

Digital Definition

The oxford dictionary of English defines definition (n) as “*1. a statement of the exact meaning of a word, especially in a dictionary. an exact statement or description of the nature, scope, or meaning of something: our definition of what constitutes poetry. [mass noun] the action or process of defining something.*”[21]

The second part of the above definition is used here “*an exact … description of the nature, scope*” of a building or design element. The term ‘Definition’ was used quite regularly within interviews with the parallel industry companies (refer Appendix C) interviewed and referred to the 3D documentation model used for design, analysis and manufacture. The term ‘digital definition’ is expansion of the term definition used by DDAA interview participants. Here the term refers to a

[21] The Oxford Dictionary of English. Accessed online through Oxford Reference Online Premium. http://www.oxfordreference.com.ezproxy.lib.rmit.edu.au/views/ENTRY.html?entry=t140.e0212430&filter_out=long&srn=1&ssid=588473131#FIRSTHIT Access date 5th August 2011

detailed and information rich 3D digital design model that is used as the central definition and documentation for a project, negating the need for paper and 2D documentation. This term has been adopted in place of other terms such as 3D documentation and digital file. A digital definition file that is an '*exact … description of the nature, scope'* of a an object, assembly or project is required for CAM fabrication and other activities related to procurement of buildings and building elements. This term becomes particularly important with the construction 3D printing of buildings and elements, due to the need for accurate and coordinated digital data for the fabrication of a project.

Generative design tools

First it is important to define generative design; Nicholas states "*The key feature of Generative Design process is that, from the application of a series of basic rules for variation to an initial state, new and perhaps unpredictable information is produced. Generative design processes typically consist of a design representation, a generation mechanism (commonly either grammar-based or evolutionary), and a means for evaluation and acceptance of the new generation.*" (Nicholas, 2008) These processes today tend to be CAD based software tools and in this exegesis generative design tools are considered to include three types of digital design tool: parametric, script based and optimisation tools. The term Generative CAD tools will be referred to in some cases generally and in others the specific type of Generative CAD tools will be identified i.e. BESO™ an optimisation tool, Grasshopper™ a visual scripting tool.

Boolean (operation)

This term refers to a number of operations available within digital design tools such as Rhino™ and Netfabb™. These operations involve the interaction between two objects that overlap in space. For example; the addition of one to another, the subtraction of one from another or the subtraction of the non-overlapping elements of both to create an object made from the intersection of both.

Methods

The Concise Oxford Dictionary defines method as *"Method n. 1. a particular procedure for accomplishing or approaching something."*[22]

The term 'methods' is used in this exegesis to refer to groups of methods, especially construction methods, including off-site fabrication. This term is used as a heading and general term to refer to a broad range of construction and assembly methods and practices used within the construction and parallel industries.

Techniques

The Australian Oxford Dictionary defines Technique as "*1. Technical skill in an art. 2. a means of achieving one's purpose, especially skilfully.*" [23] The meaning of the word here is taken to be the technical means of achieving one's purpose. The term 'techniques' is used in this exegesis to refer mainly to automated fabrication techniques, including Additive Fabrication and computer aided manufacturing (CAM). This term is used as a heading and general term to refer to a Additive Fabrication techniques, especially Construction 3D printing.

Construction Sustainability

For the purposes of this exegesis the terminology 'construction sustainability' will be used and will include the following (further explanation regarding the use of the term can be found in chapter 3.4):

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[22] Concise Oxford Dictionary accessed through The Oxford Reference online premium. http://www.oxfordreference.com.ezproxy.lib.rmit.edu.au/views/SEARCH_RESULTS.html?y=12&q=method&category=s7&x=20&ssid=997352754&scope=global&time=0.294992489168941. Accessed online 4th August 2011

[23] The Australian Oxford Dictionary accessed through The Oxford Reference online premium. http://www.oxfordreference.com.ezproxy.lib.rmit.edu.au/views/ENTRY.html?entry=t157.e55343&srn=3&ssid=50108468#FIRSTHIT Accessed online 4 August 2011

Material use – raw and processed material inputs throughout the life of the building, sustainability of the resource, waste, recyclability.

Energy use – embodied energy of raw and processed materials, sustainability of the resource, fabrication of the building, operation of the building, decommissioning, capture of energy from the environment.

Air – pollution, recycling

Water – use, collection, waste and recycling

Bio-diversity – support and improvement of flora and fauna

Human factors – functional, thermal, acoustic, sunlight access and ventilation.

Refer to the following chapter for further definition (3.4) of construction sustainability.

Off-site fabrication

The term 'off-site fabrication' will be used within this exegesis instead of alternative terms such as 'Prefabrication', 'Pre-assembly', 'off-site construction', 'system building', 'construction industrialization' and the plethora of other terms used. These terms are regularly used interchangeably, have ambiguous definitions and are loaded with associations. For example Gibb cites Whites' definition of prefabrication as "*a useful but imprecise word to signify a trend in building technology*" that "*could be stretched so wide as to lose all meaning*" (Gibb, 1999a) p7.

The terms Prefabrication and Pre-assembly are both used within this exegesis but their definitions are limited to the following:

'*Prefabrication is a manufacturing process, generally taking place at a specialised facility, in which various materials are joined to form a component part of the final installation*' (Gibb, 1999a) p1.

and

"*Pre-assembly is a process by which various materials, prefabricated components and/or equipment are joined together at a remote location for subsequent installation as a sub-unit. It is generally focused on a system*" (Gibb, 1999a) p1.

The term 'off-site fabrication' is used within this exegesis to describe a broader practice, as defined here again by Gibb: "*Off-site fabrication is a process which incorporates prefabrication and preassembly. The process involves the design and manufacture of units or modules, usually remote from the work site, and their installation to form the permanent works at the work site.………off-site fabrication requires a project strategy that will change the orientation of the project process from construction to manufacture and installation.*" (Gibb, 1999a) p2

What is important here to note, is that the definition of the term includes three specific items:

- Location: *'prefabrication and preassembly'* being in a different location from the '*work site*' or intended object location. This may however not necessarily be a 'permanent' location.
- Object: manufacture using *'prefabrication and preassembly'* of *'units or modules'*, to create an object
- Methodology: '*project strategy*' influences 'design and manufacture' and the '*process from construction to manufacture and installation'*. i.e. Development of a specific methodology relating to development of the object including; design, fabrication, assembly and installation.

The definitions above by Gibb are particularly clear and concise, cut through the ambiguity associated with these terms and are not equalled by alternative definitions identified to date.

2.5D

This term is used in this thesis to refer to shapes that are a vertical extrusion of a profile. i.e. the top profile of a 2.5D geometry object is the same as the bottom profile, an extrusion of the object.

Topology

Topology – “6. the anatomy of any specific bodily area, structure, or part”. This word is used instead of topography - “3. the land forms or surface configuration of a region” both definitions sourced from the Collins English Dictionary – Complete and unabridged 10th edition 2009. William Collins and Sons. Accessed through - http://dictionary.reference.com/browse/topology   March 24 2011.

2. Research Methodology

2.1. Position

My position as a researcher is primarily that of an architect and designer, which can be considered quite different from either an academic or an inventor, who's roles are at the two extreme roles of the research presented in the exegesis. The term architect is defined to have two broad meanings; firstly "*1. A person who designs buildings and superintends their construction.*"[24] and "*2. a person who originates or comprehensively plans a system, project, etc: Lord Beveridge, architect of the Welfare State.*"[25]

My intention for this project is to contribute to both roles, as creative designer of buildings and the second the designer of a system for building. It is the second definition that is particularly important to define the scope of this project: in designing a system or defining a novel approach, it is important to have a broad overview of the industry and sector for which the system is being designed and a thorough understanding of each of the subjects that will comprise the system. It is not however necessary to be an expert in each of the subjects or fields, for this expertise I have and will continue to refer to others.

As a researcher I approach the exegesis and the information analysed as a participant rather than as a dispassionate observer. I am a practicing architect who is seeking and developing a solution to a specific problem; therefore my stance is not dispassionate, as I have a vested interest in finding or developing a solution.

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[24] Definition 'architect' The penguin English Dictionary. Accessed online through credo reference. http://www.credoreference.com.ezproxy.lib.rmit.edu.au/entry/1120497/ Date accessed 25th September 2008.

[25] Definition 'architect' Academic Press Dictionary of Technology and Science. Accessed online through credo reference. http://www.credoreference.com/entry/3073135) Date accessed 1st October 2007

My motivation has been to identify or develop *methods of design and construction for the use of Construction 3D printing techniques*, with the long term aim to transform design and construction. Whether this transformation is at a micro level; transforming my practice and the way my architectural projects are designed and constructed, or at a macro level; transforming the way that the construction industry (globally or nationally) designs and builds does not matter in this case. In both situations I have a vested interest, wanting my practice to change and hoping to see major industry transformation.

Impartiality, if this can in fact be achieved, is achieved by assessing how projects were realised and the emergent possibilities that result, rather than by assessing effectiveness.

2.2. Shifts in approach

One of the original intentions of the PhD was to demonstrate how the implementation of Construction 3D printing could be cheaper, more effective and efficient than current construction methods in the western world. It has since become clear that quantification of cost, effectiveness and efficiency are beyond the scope of this early explorative stage of Construction 3D printing research. The focus of this exegesis and supporting projects is instead on exploring the capabilities of Construction 3D printing techniques.

At the time of writing (2007-2011) there are no finished projects that have been constructed using Construction 3D printing techniques anywhere in the world and therefore comparison between this technique and existing construction techniques is impossible. Improvement of design and construction, which is a focus of this research, is considered to be an aspirational medium term goal, which others will be in a better position to test.

Instead this exegesis demonstrates a testing of the hypothesis in unique architectural projects. Through discussion and analysis of these case study projects and the methods used to design and fabricate them, initial conclusions can be drawn relating to the potentials and limitations of construction 3D printing both specifically and generally. In summary of my current approach, **A** combined with **B** produces a result. In some cases the result could be largely anticipated, what could not be anticipated, in many cases, were the specific tools, methods or techniques that would be required to achieve that result.

2.3. Research Methods

The difficulties in answering the questions that have initiated this research and others that subsequently emerged, were the primary reason for adopting a range of different research methods for this course of research. For example there was a difficulty answering the question 'why is off-site fabrication not more prevalent today?' because very little literature, at the time, critically evaluated and answered this question. Therefore to answer this question an alternative field research method was adopted to attempt to understand what these reasons were. The research methods listed below have become the dominant means for answering questions and developing projects within the research presented here:

- Literature review
- Industry and field research
  - Qualitative
  - Quantitative
- Embedded research
- Action research – (project-based)
- Synthesis – development of emergent original theories, systems and methods based on synthesis of research findings and resulting inspiration.

2.3.1. Literature review

This method of research was used for background research for all research topics addressed within this exegesis. As far as possible I have attempted to be thoroughly conversant in all of the topics studied. For the primary topics of Additive Fabrication and off-site fabrication, this literature review has been exhaustive, although it has not been physically possible to exhaustively research every topic due to the number of areas addressed.

For example the mechanisms that promote growth within coral polyps are a subject that is the primary concern of many marine biologists, it is not possible for me to become an expert in such a topic that is on the periphery of this research focus[26]. Where such limitations existed a reasonable level of literature review has been undertaken to understand the key concepts that need to be addressed. In some cases experts, such as Marine Biologists, have been consulted to discuss my research direction and thoughts to ensure that the conclusions on which I am basing my projects are consistent with current thinking in the field.

A broad range of media has been consulted, wherever possible including scholarly journal articles, thesis, reports, books, periodical articles, newspapers, websites and audio visual material to establish the historical background and the current state thinking on the subjects being reviewed. This literature review has been extremely broad, due to the number of topics that had to be studied and synthesised to develop the hypothesis, create the projects in detail and to remain current as the PhD progressed.

2.3.2. Industry and Field Research

In 2004 after a first round of exhaustive literature review, answers to questions could still not be answered, within a number of topic areas; such as off-site fabrication and digital CAD design. Therefore it was deemed appropriate to undertake primary field research to develop a clearer understanding of industry practices in order to gain a clearer perspective of standard industry and exceptional industry practice. This first instance of primary research, the international research component was funded by both the Jack Greenland and Byera Hadley Travelling Scholarships with the scholarships awarded in 2004 and 2005 respectively after completing my studies at UTS. The field research was

[26] This subject is relevant to Case Study 3 (chapter 6)

undertaken both in the year prior (2006) and just after commencement of the PhD research (2007). This international context was regarded as vital for the research, as it was considered, after preliminary research, that Australian industries could not provide an adequate survey of current leading off-site fabrication practices within the construction and *parallel industries*[27]: due to Australia's small size and level of competitiveness, in the industries in question, in comparison to other countries.

Figure 1 (a) DSME shipyard South Korea - Image (b) Skanska precast paenl factory, Stragnas, Sweden. Images James Gardiner

This first phase of field research focussed primarily on prefabrication and digital design practices within the construction and the parallel industries (aerospace, shipbuilding, automotive and manufacturing). The inclusion of the parallel industries was in recognised the fact that these industries have grappled with many of the same issues that were of primary concern in this research (Kolarevic, 2003, Egan, 1998, Kieran and Timberlake, 2004). Furthermore in many cases some of these industries are decades ahead in implementing solutions to issues

[27] Refer to Chapter (1.5) for definition of Parallel Industries.

currently being faced in construction[28]. The industries studied are in some aspects fundamentally different to the construction industry but in other ways very similar, as described in the research report (Gardiner, 2010) (refer images Figure 1 a & Figure 2).

Figure 2 - Boeing factory Seattle. Image source - http://www.petergreenberg.com/2010/07/19/boeing-787-dreamliner-debuts-at-farnborough-airshow/ Image accessed 7th August 2011

The first round of interviews and site visits, can only be considered in this exegesis through reference to material that I have published due to ethics approval issues[29]. This research included field and site visits and interviews with 33 companies in 10 countries; such as NASA, Boeing, Toyota, IKEA homes, Misawa Homes and Hyundai Heavy (Gardiner, 2010). This research focussed on assessing current capabilities and practices with the industries, which could be

[28] This was confirmed based on discussions and observations from both national and international field research.

[29] Although the majority of the field visits and interviews occurred after the commencement of this PhD I was not made aware of the RMIT requirements of ethics approval, thus none of my interview transcriptions and data could be used as a primary resource within this research. Retrospective ethics approval is not possible.

transferable to the construction industry, and also included visits to two of the three groups developing of Construction 3D printing[30].

A second round of industry surveys were conducted in 2008 within Australia, including over 44 companies, as the field res"earch component of the 'Delivering Digital Architecture in Australia'. This field research examined Australian industries, whereas the previous international field research had excluded Australia, thus filling a gap in the previous research that I had completed. The intention of the DDAA field research was to assess barriers and opportunities for implementing digital design and automated fabrication in Australia. This research concentrated predominantly on the use of digital design tools, their link to automated fabrication techniques, the way information was shared within teams. My research interests were overlaid onto this agenda, namely in the area prefabrication within construction and parallel industries. The new round of field interviews and site visits assessed the parallel industries, and the construction industry and sub sectors in more depth than the previous study.

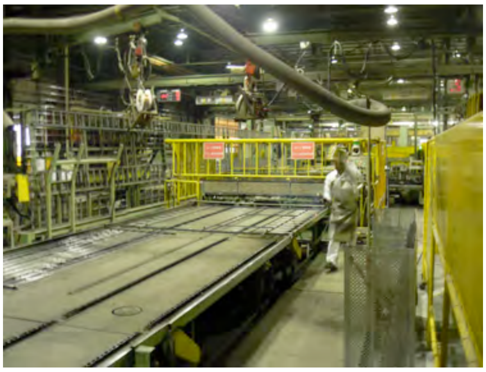

Figure 3 (a) Misawa Factory, Japan (b) Taalman Koch house near Joshua Tree, California. Images James Gardiner

In most cases this primary industry research focussed on leading companies within each industry and sector. This second round of field research was conducted across industries and sectors, with a minimum of three companies

[30] Contour Crafting, university of Southern California and Concrete Printing Additive Manufacturing Research Group, Loughborough.

visited within each sector in order to identify trends and comparisons between them. In a number of critical areas, such as the off-site fabrication sector, a larger number of companies were visited to gain a more in-depth understanding of the sub-sector and the practices implemented.

Overall this industry and field research effort encompassed visits, and in many cases interviews[31] and questionnaires, with over 77 companies in 11 different countries. To make full use of the interviews and questionnaires that were conducted in 2008, two methods of analysis were used, qualitative and quantitative analysis, discussed below. Dominik Holzer assisted with the formulation of the interview questions and questionnaires and participated in a sample round of interviews, which resulted in minor revisions to interview questions and questionnaires.

Qualitative analysis

Qualitative analysis (Dey, 1993) was used to analyse and interpret transcriptions of my face to face and telephone interviews[32], these interviews were either recorded or thorough notes were taken during the interview. The interviews were used to ask questions that could not be easily answered within the format of a questionnaire and were also useful to identify attitudes, terminology and issues that were not anticipated. As far as possible, within the interviews and questionnaires, exactly the same questions were asked of each group or sub-sector being interviewed to ensure that the answers could be compared.

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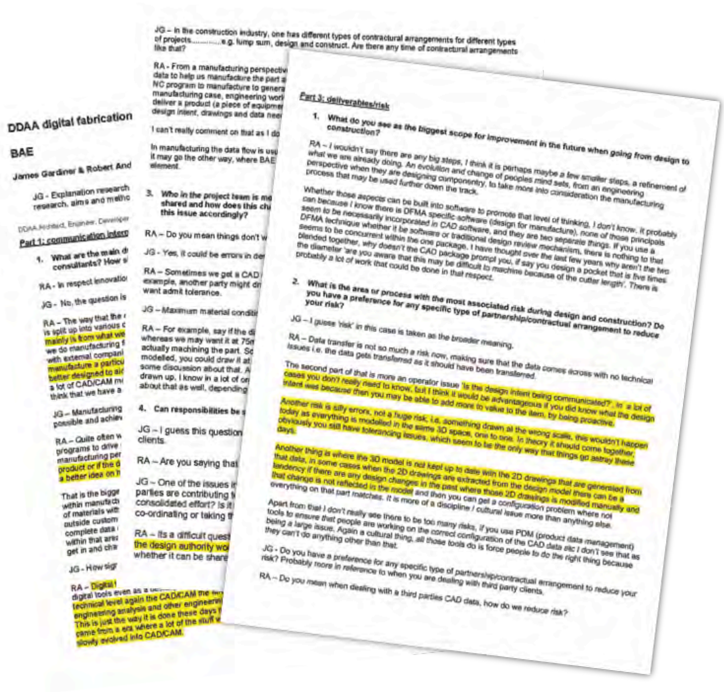
[31] Due to RMIT ethics rules interviews from the first round of interviews in 2006 could not be used, The interviews were conducted prior to being informed of Universities ethics rules and receiving ethics approval. Retrospective ethics approval is not granted at RMIT.

[32] The majority of interviews were face to face.



As questions were being asked across industries, the questions needed to be broad enough to be reasonably understood by respondents from each of the sectors, some clarification to the meaning or aim of the question had to be made to account for differing to industry focus, respondent job role and personality types. Questions were amended slightly after the first four interviews in response to difficulties found with the wording of the questions.

The types of interview questions, which could not be easily answered using a questionnaire, were those that fell into the following categories:

Interview questions that

- May be difficult to describe or needed clarification
- Could not be answered simply. Such as with a yes or no or by scoring numerically.
- Were sensitive and may get a different initial response than a response received after further questioning.

Answers that

- Required elaboration

- Could have a broad range of responses
- Could lead to further insights

The questions were divided into topic groupings that dealt with a number of specific issues that could be compared across industries, such as tools, communication and risk.

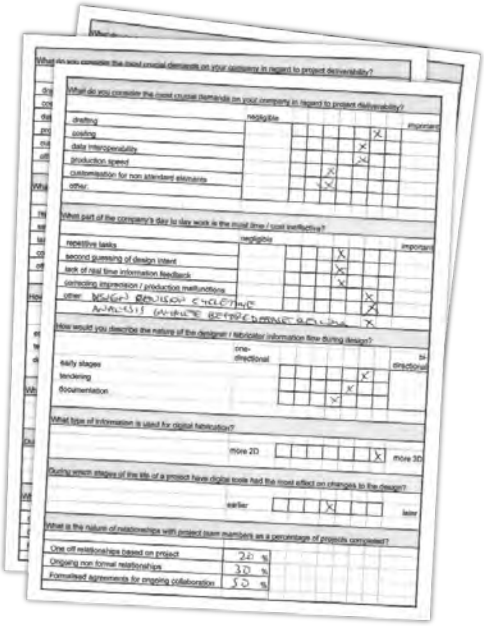
The analysis of the interviews was conducted manually by first transcribing all of the recorded interviews[33] and then collating the responses to each of the questions into groups categorised by sector and subsector (i.e. sector – construction subsector - precast concrete). After this categorisation occurred under each of the questions, analysis of these responses was made to establish trends within sectors and subsectors, broad trends were also analysed across topics.

There was an intention to use database analysis tools to further analyse the large amounts of data collected, however this could not be achieved within the time constraints of the PhD.

Quantitative analysis

As mentioned above some topics were more easily dealt with using questionnaires than others, the topics that leant themselves to answer within a questionnaire style as mentioned above were questions that could be answered with a yes or no, answering by ticking boxes that indicated degrees between one thing and another. Another response elicited through the questionnaires was listings of items; such equipment or software used by the respondents company.

[33] Approximately 50% of the interviews were transcribed by myself, the remainder transcribed by Melissa Rinovassi 40% and Dominik Holzer 10%



The data collected through this form of quantitative analysis can be easily consolidating into a database and therefore could be used to generate numerical data that could be used to generate graphs, bar charts and other useful representational material. This material is very useful for representing broad similarities and differences with the minimum requirement for explanation. As much as this data is useful for comparison between industries and groups, without field visits and interviews the reasons for differences could easily be lost. Holzer stated in reference to his own quantitative analysis “

“*As much as this method illustrates differences between distinct disciplines, it does not say why these differences are in place and what actions could help to bridge between them.*” (Holzer, 2009) p124

This data presented in graphs, diagrams and other formats was largely useful for indicating or highlighting differences between industries and groups, which could be understood through reference to prior literature review, field visits to production facilities and through reference to the extended interviews and transcriptions of these.

The first round of international field research assisted in the creation of a foundation from which to understand the Australian context of the construction and parallel industries, in the formulation of interview questions and answering questions that had not been answered through background research and literature review.

2.3.3. Action research and embedded practice

This PhD research follows a similar methodology of research employed by others at SIAL, RMIT; namely in the adoption of the methods of Action Research and Embedded Practice (Benton, 2008, Holzer, 2009, Nicholas, 2008). Holzer writes of the value of embedded practice:

"*practice requires input from academia to advance working-methods as much as academia depends on intervention from practice to advance discourse and critical investigation.*" (Holzer, 2009)

Embedded practice enables the qualities of both *"theoretical investigation of an academic body of knowledge and empirical methods through observation, interrogation and participation in practice*" (Holzer, 2009) to produce new knowledge, working methods and project based outcomes.

The way embedded research was employed in my research differs slightly from that of Benton, Holzer and Nicholas in that I was effectively embedded within my own architectural practice Faan Studio in Sydney Australia rather than within an external organisation such as Arup an engineering office or Terroir an architectural practice. The mode of embedded practice practiced by Benton, Holzer and Nicholas, shifts only slightly from my practice; from being observer and participant in a team to observer and sole participant. In explanation of this difference, much of the time that I spent creating the two new case study projects, Villa Roccia and (in)human habitat, I worked alone and was therefore the only participant.

For a brief period, between July to September 2009, the role adopted by Benton, Holzer and Nicholas was adopted by me when I was embedded with D-Shape (a construction 3D printing company). During this time I was a participant in a small team charged with prototyping the test column that I designed for the Villa Roccia project.

Figure 4 - (a) Embedded with D-Shape team (b) Prototype column design (c) Prototype column being printed in sections

This form of embedded research had two distinct benefits; the first was observational, gaining an in depth understanding of the D-Shape construction 3D printing technique through observation and use. The second benefit was through action research; testing my hypothesis at construction scale through fabrication of an object that had not been fabricated using Construction 3D printing techniques before.

Action research, which is at the core of this embedded practice, was used within this research context to build knowledge (through projects) where the information could not be obtained through literature review or industry field research. Action research, as discussed by Pasmore, has largely been used within this research as an exploratory technique to create new knowledge through '*testing hypotheses in action*' (Pasmore, 2001). Pasmore citing (Dewey, 1933) stated

"*A solution to a problem could only be regarded as viable when it was demonstrated to produce desired outcomes in practice.*" (Pasmore, 2001) p38

Prof. Peter Downton describes design research (which is a form of action research) in reference to traditional methods of academic research

"*Research as understood in sciences is not the only source of reliable knowledge. Design processes both use knowledge and also produce personal knowing and collective knowledge. Such knowledge is different, not inferior. It has characteristics in common with other knowledges and the distinct character of* *being embodied in the process of designing itself. This renders it hard to examine other than via the self-interrogation of designers. The knowledge produced in design is stored, transmitted and learnt through works in this manner such that design knowledge leads creatively to more design knowledge.”* (Downton, 2003) p124

The case study projects themselves have been used to *test the hypothesis in action* and have been used to *demonstrate desired outcomes* through embedded practice and action research. The analysis of these case studies has created new *design knowledge* through *self-interrogation* of the designs and reflection against background research and field study. Such analysis is inherently a form of ongoing and cyclic self critical evaluation that is evolved and built on during the testing of ideas, both physically and digitally, in the formation of the project. Not only is *knowledge produced in design stored, transmitted and learnt through the works produced; the* projects are also critically evaluated in the case studies here to assess their contribution to knowledge.

2.3.4. Conception

Conception, the last research method, can be considered the result of periods using combinations of the research methods discussed above. This method can be considered to be a creative consequence emerging from: literature review, industry field research, qualitative and quantitative research, action research and embedded practice. Without these other methods novel solutions and revelations would have been unlikely to have arisen. Conception is inextricably linked to these other research methods, though differs significantly by being an inherently creative and generative process.

Figure 5 (a) Freefab factory production line (b) Villa Roccia column concept (c) (in)human habitat reef deep scaffold, Images by James Gardiner

For example the Freefab case study project (chapter 4.1) and construction method emerged from the study of current world off-site fabrication methods, precast concrete construction, the contour crafting Construction 3D printing technique, direct experience with 3D computer aided design, combined with the core question: 'how can design and construction improve?'. By reflecting on the research, observations and direct experience framed by this question, an emergent hypothesis arose which was later demonstrated through project work. This cycle of literature review, industry field research, action research combined with new methods such as embedded practice, qualitative and qualitative analysis has been repeated on the case study projects 2 (chapter 5) & 3 (chapter 6), resulting in the conception of novel designs and methods.

2.4. Methodology Summary

The questions that this exegesis set out to explore could not be addressed by the application of one or even a few methods, therefore a broad range of research methods were employed to address specific questions. Literature in some fields, such as off-site fabrication, was either inadequate or did not address the issues researched in enough depth to be used as a primary resource, therefore methods such as industry field research (including interviews and questionnaires) were required to gain the data and insight required to address such questions.

In other fields such as Construction 3D printing, paper[34] projects were inadequate to understand the implications of the construction 3D printing techniques and built projects did not yet exist for analysis. Therefore a series of projects were generated that could be used to test the hypothesis, for such projects the research methods of action research and embedded practice was used.

The Conception method was integral to the formation of the hypothesis that resulted from the literature review and industry research, this method also was also integral to the process of project development. Each of the methods discussed above were indispensible in contributing to the formation of the hypothesis and case study projects.

The hypothesis and case study projects emerged from a clear and concise motivation and central question; ‘how can design and construction improve?’ From this central question new questions emerged as the research developed through literature review and field research. A hypothesis was developed from this background research, from which a new set of refined questions arose. These questions are used to define the scope of attention for the case study projects and to assess them. In essence the core question that underpins this research has not changed ‘how can construction improve’, the scope of the research has however been refined to a manageable level within the physical, resource and time constraints of a PhD.

As stated, my position within the project is both; designer of buildings and as an originator or developer of systems. This project is focused on exploring the territory of design and construction with construction 3D printing techniques and generating projects that can be used to tease out potentials and limitations of this emerging field of construction techniques.

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[34] ‘Paper’ project – An architectural term referring to unbuilt or theoretical projects that exist only on paper.

3. Background; Techniques, Methods, Design and Tools.

This section introduces the four major background subject elements, which together have been synthesised to define much of the thinking behind the work presented in this exegesis. The classifications are not perfect as all of these areas overlap and are not mutually exclusive. The classification does however help to distinguish the elements discussed, which assists description of the macro issues that are at play.

The subjects that constitute the background research include the following

- Architectural **design**
- Construction **Sustainability**
- Digital design **tools**
- Off-site fabrication **methods**
- Additive Fabrication **techniques**

Each of these categories is discussed to cover the following topics:

- Definition – beyond definition of terms covered in (chapter 1.5)
- Background
- Current state

The focus of this chapter is to not only analyse and discuss the topics above in the format described but also to identify potential, which can be explored and tested through the case study projects that follow.

Potential in the following main areas will be identified and described:

- Architectural design

- Digital definition (using 3D digital design tools)
- Off-site fabrication
- Construction sustainability

As noted above (sub-chapter 2.3.2) the construction and parallel industries have been studied globally through a series of site visits, interview and questionnaires. Within this chapter, where possible, comparative analysis is made between current trends within the construction industry and the parallel industries, based on literature review, field research and professional experience. The parallel industries have steadily improved the quality and efficiency of their design and manufacturing processes during recent decades, with dramatic improvements achieved in the quality of products produced, added value and efficiency. The construction industry has failed to keep pace with the significant improvements realised by these industries (Egan, 1998). Therefore potential for improvement in construction can lie in the practices of these parallel industries, where possible these practices are identified within this section.

Practices within industries and sub-sectors are often unique to geographic locations as well as specific industries and sectors, where possible reasons for geographic or idiosyncratically unique practices have been identified in order to understand reasons for their existence and possible barriers to their implementation elsewhere. Findings from this research as well as extensive literature review will be discussed within this chapter to illustrate and compare current practices within these industries and to discuss opportunities for design and construction using Construction 3D printing techniques.

3.1. Techniques

This section focuses on the historical context of both additive fabrication techniques and emerging construction 3D printing techniques. A description of the range of techniques is given and a categorisation of them is made. The potentials and limitations of particular techniques are identified, as well as current trends and applications in reference to the focus topics discussed above.

3.1.1. Introduction Additive Fabrication

Additive Fabrication techniques were first developed in the late 1980’s in Japan and the USA. Their primary function during the first decade after development was to produce prototyped objects quickly, hence their original name ‘Rapid Prototyping’.

“*In 1988, 3D Systems and CMET, a Japanese company, sold a total of 34 Stereolithography systems. These machines were among the first in a new class of technology that produced physical objects by joining thin layers of material, one on top of the next. The shipment and use of these machines marked the beginning of a new industry.”(Wohlers, 2007)*

These machines were at first, like most new products, very expensive ranging in cost between $75,000 to $750,000 (Aubin, 1994), today a student can afford to purchase a fully assembled open source kit machine for $1299 (Makerbot, 2011). This shift in cost indicates the growing maturity of the industry, with machines at first accessible only to a select few within large corporations, today schools and university students have access to these machines around the world and the hobbyist can build one at home based on open source 3D printer projects.

3.1.2. Rapid Prototyping to Additive Fabrication

As the quality of the output of the Rapid Prototyping machines increased, groups around the world started to use the output of these machines for end use products, hence the adaptation of the term from rapid prototyping to ‘rapid manufacturing’. Organizations such as NASA, Boeing and the FBI began using rapid prototyping devices in the 1990's for unique or small orders of parts (Hopkinson and Dickens, 2001, Ayers, 2009), this occurred for a number of reasons; strength of materials and dimensional accuracy/stability increased as rapid prototyping techniques were refined and rapid prototyping of end use products became cost/time competitive with fabrication by other means.

Additional benefits have been realized since the early adaptation of 'Rapid Prototyping' techniques that can be considered as value adding significant value for manufacturing. These benefits can be summarized as the following (Wooten, 2006, Hopkinson et al., 2006b):

- **Small fabrication runs** - fabrication runs of one with no penalty, allowing for customization and individualization of products (such as individual form fitting).
- **Highly complex geometries** - including interlocking but physically disconnected assemblies (e.g. textiles)
- **Reduction of fabrication constraints** - reduction in design for fabrication items such as draft angles.
- **Part consolidation –** through reduction in fabrication constraints
- **Fabrication for assembly** (prefabrication) – increased ability to incorporate joints for interlocking assemblies (especially where fabrication size constraints exist)
- Potential for **customisation of material properties** through functionally graded materials

As discussed in (chapter 1.5) the terms used since these early days of development have varied significantly between groups and authors. The term rapid manufacturing replaced the term rapid prototyping, this term itself has since been replaced by additive fabrication although there is still little consensus on terminology as the sector continues to develop.

Additive Fabrication techniques build up objects in sequential layers based on a digital three-dimensional model. There are a large variety of techniques used by the different additive fabrication machines; although these techniques can be broadly classified into two groups. Others have made classifications of additive fabrication techniques such as (Bourell and Beaman, 2004) and (Hopkinson and Dickens, 2006). The categorization by Hopkinson et al. defines categories for emerging additive fabrication systems as: solid, liquid and powder. This categorization is not particularly useful, for discussion within this exegesis, because it focuses on the starting state of the materials rather than active process that create the final objects. As a consequence a new categorization has been made. This classification is made based on listings and descriptions of additive fabrication techniques and description from the State of the industry report by (Wohlers, 2010). The categories and subcategories of techniques are listed in bold type, followed by a brief description as required. Representative companies who produce systems in these categories are listed in brackets.

Deposition of material to build up an object

- **Paste deposition** of premixed materials – (Fabber)
- **Melted Deposition** - Fused Deposition Modelling (Polymer – Stratasys, HP & Makerbot)
- **Inkjet deposition –** Inkjet deposition of photopolymer and light curing **(**objet**)**

Selective state change of materials in a chamber or on a platform (in some cases using catalysis), state change may be temporary (e.g. temporary melting to liquid) or permanent (e.g. solidification).

- **Melting** - Selective sintering using laser, electron beam etc (Metal – MTT, ARCAM & EOS, Stratasys, EOS)
- Light **Curing** – Stereolithography (CMET, 3D systems, & DWS)

- **Bonding** - Selectively adding a bonding material to a powdered material - Inkjet - jets binder onto powder (Z-corp & Ex One)
- **Chemical** reaction **–** Selectively adding a material to another to create a chemical transformation - D-Shape

This categorisation/classification is useful for the purposes of this thesis as it differentiates two primary methods of creating objects. This categorisation works for almost all of the processes listed in the Wohlers report Appendix C & D (Wohlers, 2010). This classification excludes Lamination as this technique relies on subtracting large amount of material relative to the object built, hence it can be considered a subtractive fabrication technique with additive processes. Extensive testing of this categorisation has yet to be undertaken to assess the usefulness/accuracy of the categorisation. Additional classifications will likely need to distinguish techniques that utilise multiple operations such as additive and subtractive finishing processes.

3.1.3. The desktop 3D printer

The Additive Fabrication industry is now maturing, an excellent signal of this is that Additive Fabrication devices are now becoming available as desktop devices, and at a price point that enfranchises small companies and even students[35]. Self-assembly Additive Fabrication '3D printer' kits have been developed by a number of organisations and companies including: the 'Fabber'[36] by fabathome[37], the 'Darwin' and 'Mendel' machines by Reprap[38].

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[35] I was able to purchase Reprap kits for both a UTS architecture studio and for myself (a student).

[36] The 'fabber' has now been uninspiringly renamed to Model 1 & 2.

[37] Fabber machine developed since 2007 - http://fabathome.org/ - Accessed 10th February 2011

[38] Reprap 1: Darwin machine developed since 2005 - http://reprap.org - Accessed 10th February 2011

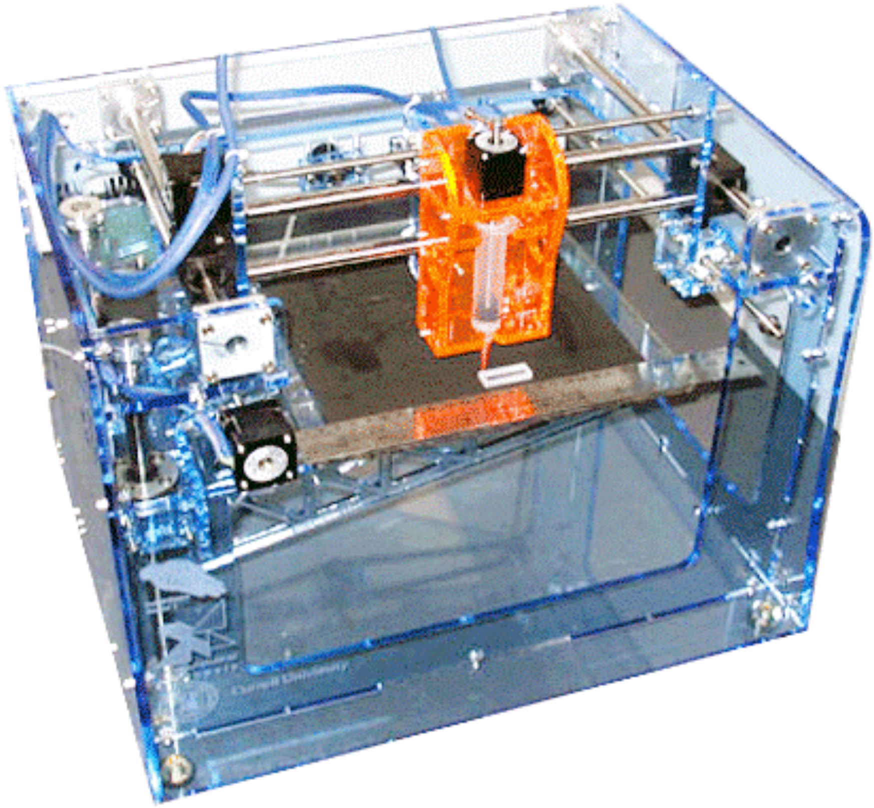

Figure 6 - Fabber Machine developed by Cornell University - Image source http://www.fabathome.org/wiki/index.php/Fab%40Home:Choose_Your_Fabber - Accessed 5th July 2010

These organisations have open source as a key operating principle (Bowyer, 2011) (Fab@home.org, 2011) which is enables 3rd party companies to sell kits and machines based on these open source developments. The cupcake CNC machine by Makerbot industries[39] is based on the Reprap Darwin and the Botmill Glider 3 is a fully assembled version of the Reprap Mendel[40]. There are also a plethora of companies selling standard or specialised kits and parts.

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[39] Cupcake CNC machine under development since 2009 - http://wiki.makerbot.com/ - Accessed 10th February 2011

[40] Botmill Glider 3 available since 2011 - www.botmill.com - Accessed 10th February 2011

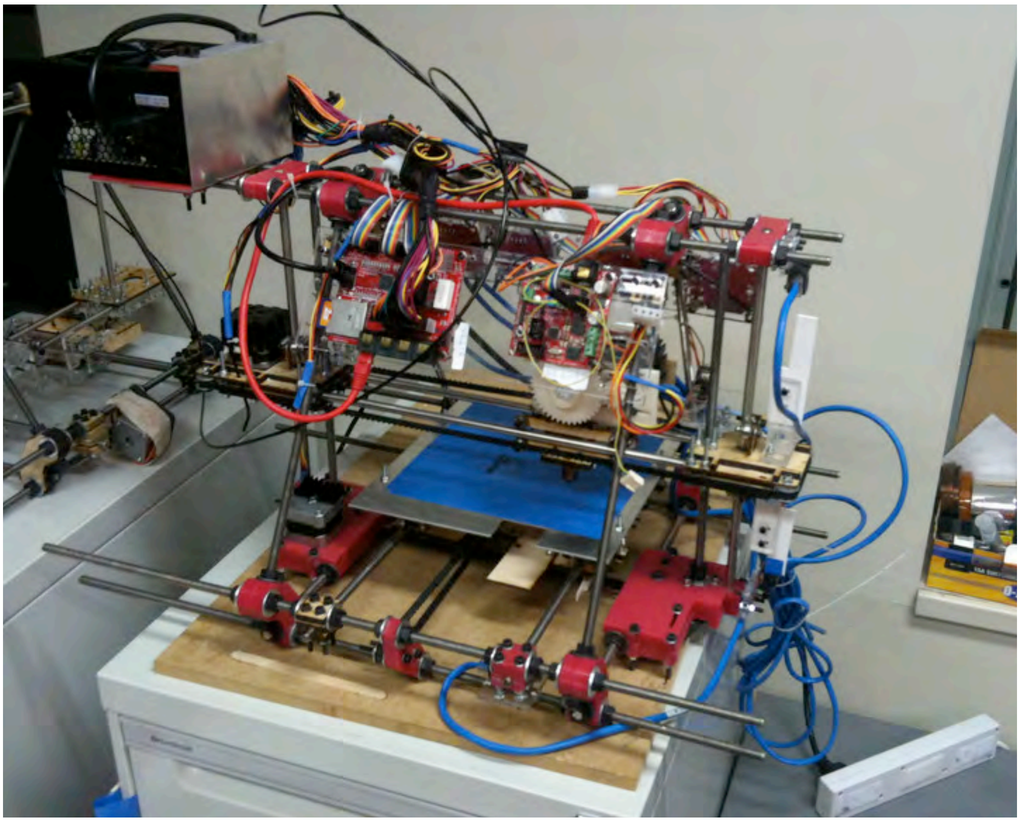

Figure 7 – Reprap Mendel made by my students and I in the Reprap studio at UTS July 2010. Image James Gardiner

The interest in the open source 3D printer has been strong, which can be evidenced by the highly active blogs, forums, and wiki's focussed predominantly on the Reprap and Makerbot machines[41]. Complimenting these primary sources of information and discussion are a second tier of projects based around building the machines or using them for student projects[42].

This shift in scale and price is very similar to the development of the personal computer, in the 1970's (Allan, 2001) in which personal computers were developed and sold as kits, by individuals and small enterprises to fill a growing demand. A similar scenario has evolved with rapid prototyping/manufacturing,

[41] Open source related blogs and wikis for additive fabrication; http://blog.reprap.org/ http://forums.reprap.org/ http://blog.makerbot.com/ - All websites accessed 20th July 2010

[42] A Wiki site for the 'fablab' architecture studio that I taught at UTS studio in July 2010 focussed on students building a Reprap machine. http://reprapstudio.wikispaces.com

where large and expensive machines were first developed for the corporate sector, the cost of these machines has slowly reduced to enable individual small businesses to participate in the market. The same pattern is now occurring with the development of open source additive fabrication machines to meet this low price point demand, as discussed under the title "*Learning from the history of the computer revolution*" (Fab@home.org, 2011).

Figure 8 - Altair 8800 the first kit form personal computer. Image source http://en.wikipedia.org/wiki/Altair_8800 - Accessed 8th August 2011

Similarly, large companies are now beginning to cater to this emerging market, with the development of moderately priced machines for the home user such as ~$10,000 3D systems "V-Flash personal 3D printer" and the recent acquisition by the same company of Bits from Bytes (Peels, 2010) which signals its interest in the low cost 3D printer market.

3.1.4. Additive Fabrication Applications

A number of industries have already found niche applications for the creation of consumer and specialty products using additive fabrication techniques such as: Dental for bridges and crowns, Orthopedics with customized bone replacements such as hips and knees, defense (for small run parts or highly complex parts such as turbine blades) (Wohlers, 2010), toys (online customized toys[43]), jewelry[44], furniture and lighting[45].

Figure 9 – (a) Gas turbine by EOS for aerospace. Image source - http://www.eos.de/en/applications/aerospace.html Accessed 9th August 2011 (b) Laser sintered dental crowns by Concept Laser. Image source - http://i.materialise.com/blog/entry/3d-printing-in-medicine-what-is-happening-right-now-in-patients Accessed 9th August 2011

Current benefits of additive fabrication techniques include: a level of design freedom unmatched by alternative fabrication technologies[46] (Hague, 2006), the fabrication of complex structures and geometries (refer image Figure 9 a & b) that would be difficult or impossible to fabricate using alternative methods (Williams et al., 2010), the design of highly customised or individual products (Wohlers, 2010) that can be fabricated cost effectively (Hopkinson, 2006) and sustainably (Diegel et al., 2010). Architects such as Neri Oxman are beginning to see the

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[43] Sculpteo custom figurines - http://www.sculpteo.com/en/ - Accessed 8th August 2011

[44] Shapeways jewellery - http://www.shapeways.com/themes/jewelry - Accessed 8th August 2011

[45] Freedom of Creation - http://www.freedomofcreation.com/collection/products - Accessed 5th August 2011

[46] Such as CNC milling (subtractive) or injection moulding (formative).

potential of functionally graded materials for fabrication at construction scale (Bullis, 2011).

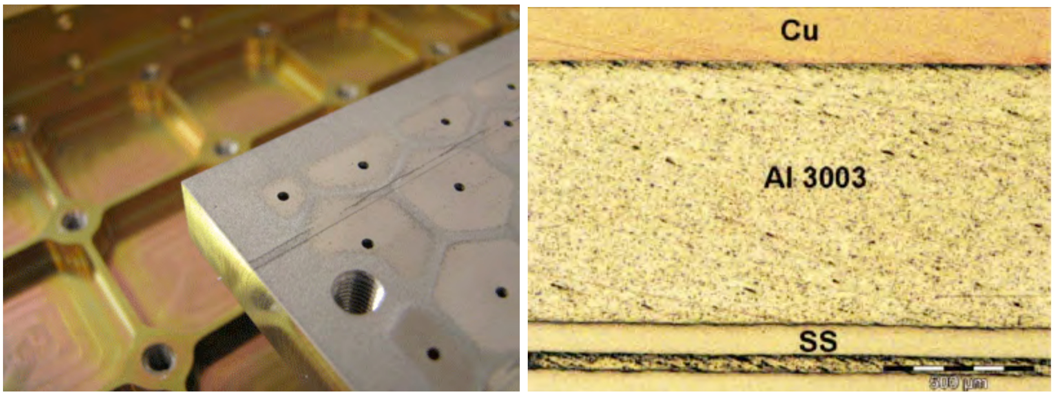

Figure 10 (a) Ultrasonic consolidation of functionally graded metals by CASM, Utah State University. Image source - http://cse.usu.edu/casm/index.html - Accessed 9th August 2011 (b) Metal Functionally graded material using ultrasonic consolidation, image annotated with chemistry abbreviations for metals. Image source from journal article (Kumar, 2010).

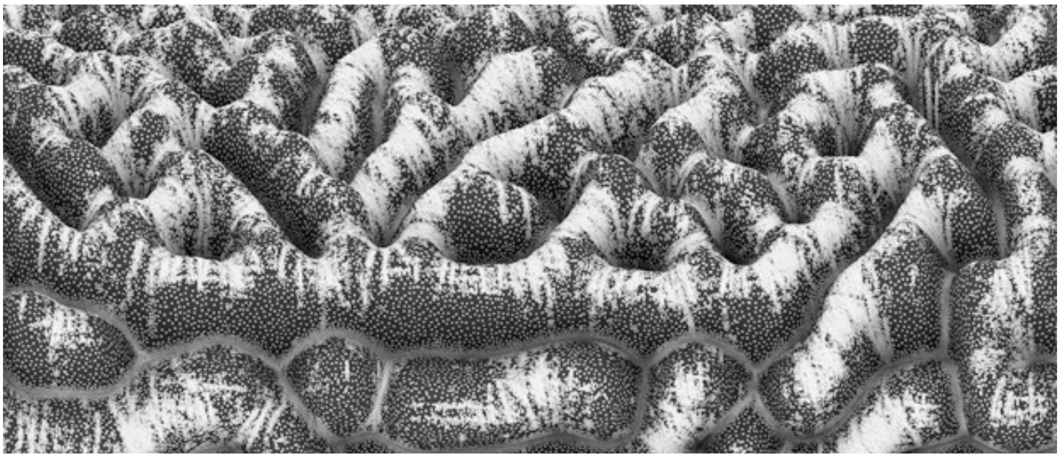

Figure 11 - Neri Oxman - Fabricology "Variable property 3D printing" MIT media Labs. Image source - http://web.media.mit.edu/~neri/site/projects/fabricology/fabricology.html - Accessed 10th August 2011

New capabilities are also emerging with the extension of additive fabrication capabilities through fabrication with multiple materials. The majority of additive fabrication systems today fabricate with one or two materials during a single build, often the second material is used as a support material. The objet™ Connex350™ 3D printer can fabricate with two materials while also having the capability to mix these materials during the printing process, this enables the Objet printer to create up to 48 different 'digital' material formulations with properties between solid and elastic (Wohlers, 2010). This is in effect enables the creation of functionally grading of materials which can have varying properties in different locations of the object to respond to the forces that are acting on the object. Functionally graded materials (refer images Figure 10 a & b) have also been demonstrated in metals with the ultrasonic consolidation technique (Kumar, 2010, Kong and Soar, 2005) and have the potential to significantly improve the performance of fabricated objects through the optimisation of metal characteristics such as thermal conductivity and mechanical strength as required.

A further extension of the capabilities of multi-material fabrication is represented in the work by Malone et al. who developed the inexpensive Fabber™ Additive Fabrication machine mentioned above (Malone et al., 2009, Periard et al., 2007). The machine utilizes syringes to extrude feedstock onto a build platform. One of the most compelling examples of the fabber™ machines' capabilities is the fabrication of a zinc air battery; this battery begins to generate a current before the object is complete (refer image Figure 12 a). (Malone et al., 2004).

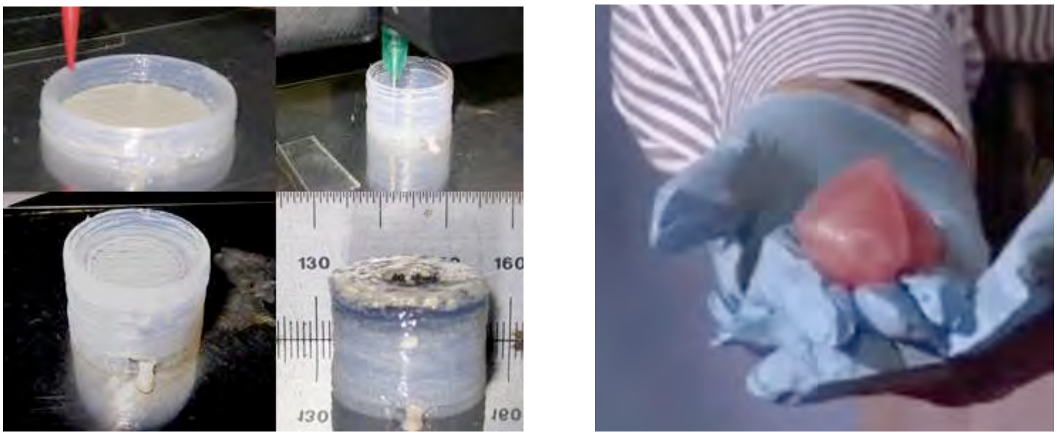

Figure 12 – (a) Zinc air battery printed on the Fabber Machine - image source www.fab@home.org - Accessed 10th July 2010 (b) A prototype 3D printed kidney. Image - screen shot from TED talk hosted on website http://www.livingdesign.info/2011/04/14/3d-bioprinting-of-human-organs-whats-next/ Accessed 9th August 2011

The medical industry has now taken the lead with the additive fabrication of human organs. Organs have in the last decades been grown from fabricated scaffolds using a patients own cells[47], there is now increased research and

[47] The benefits of using a patients own cells for growing

development in the direct additive fabrication with living cells of entire organs such as the Kidney shown and described by Anthony Atala on TED (TED, 2011).

When the first additive fabrication techniques emerged twenty years ago, the possibility that they might evolve to fabricate structures with living human cells directly from a computer was barely imaginable. Such ‘file-to-factory’ devices can now be desktop-sized and available at a price that enfranchises even students. Such additive fabrication techniques are now being scaled-up for the manufacture of construction components and whole buildings.

3.1.5. Construction 3D printing

Deriving from the field of Additive Fabrication, Construction 3D Printing techniques have been referred to under a number of terms such as Construction Scale Rapid Manufacturing, Freeform Construction and Construction Additive Fabrication (refer index of terms ‘construction 3d printing’ chapter 1.5).

“*Large scale automated layer manufacturing systems are not entirely new to the field of construction. In fact, the term layer manufacturing was coined by Shimzu Corporation, one of a number of Japanese companies exploring alternative ways of constructing skyscrapers in the in the late 1980’s and 1990s.”* “ *Shimizu’s SMART system is based on a moveable automated factory formed by robotic systems that is gradually lifted up in the process of erecting a building*”(Menges and Hensel, 2008) p44

Construction 3D printing techniques have been in development since the mid 1990’s with two separate techniques published in that decade, the first was a novel technique based on the deposition of sand and cement with selective curing of this material using steam (Pegna, 1995), the technique was not developed. The second was a gantry controlled concrete deposition technique named Contour Crafting™ (Khoshnevis, 1996) (refer image Figure 13 a).

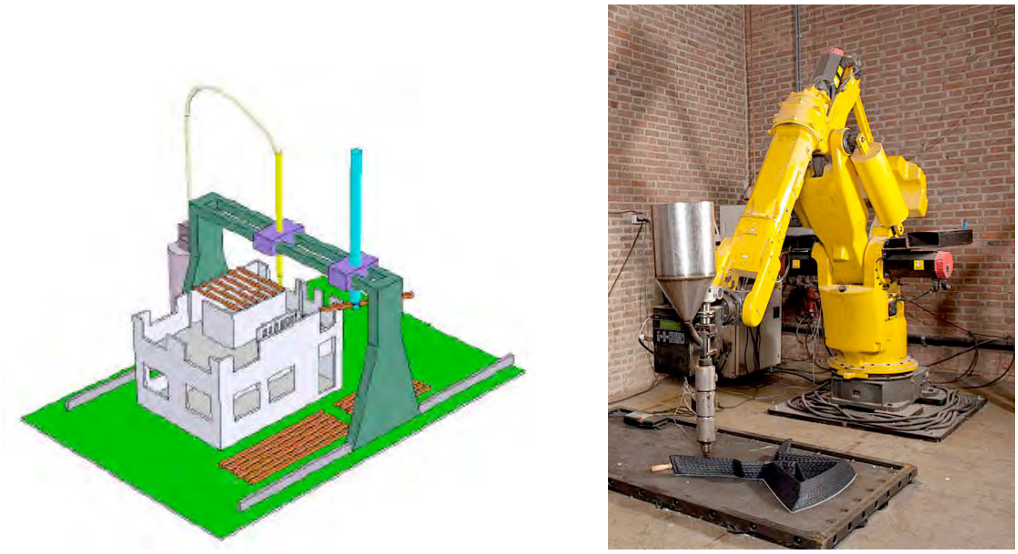

Figure 13 (a) Contour Crafting - Image source http://www.contourcrafting.org/ (b) Endless polymer 3D printer - Image source - http://www.coolhunting.com/design/dirk.php - Both websites access date 2nd August 2011

Since the turn of the millennium additional techniques have been invented; including a crane based concrete deposition technique (Williams et al., 2004), a gantry based selectively activated sand bed technique by D-Shape™ (Dini et al., 2008), the 'Concrete Printing' another gantry controlled deposition technique[48] (Buswell et al., 2007a, De Kestelier and Buswell, 2009). A further three techniques have since been developed including; one a concrete deposition technique by the Maxit Group™ for which no published description or material is available (it is unclear whether this technique is still under development), another technique being developed by Freeform Construction[49] called Mineraljet™ (Freeform_Construction, 2011) which is awaiting development funding[50] and the Endless machine (Figure 13 b) is a scaled up polymer deposition technique

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[48] 'Concrete Printing' is also referred to as 'Freeform Construction' (De Kestelier 2009). An issue arises with this alternative name as the company that has developed Mineraljet™ is called Freeform Construction™. The Loughborough based fabrication technique will be referred to as 'Concrete Printing' for purposes of clarity within this exegesis.

[49] The name Freeform Construction appears to have been taken by Rupert Soar when he left the leadership of the Additive Manufacturing Research Group at Loughborough University to develop the Mineraljet™ technique.

[50] Based on email response from Rupert Soar 16th July 2011

mounted on an industrial robotic arm (Klein, 2010). The Endless machine is not strictly a construction 3D printing technique as it has only demonstrated fabrication of furniture to date, the technique does however demonstrate how techniques (fused deposition modelling) developed at smaller scales can be scaled up, this is the first such polymer based technique to be scaled up with the potential to fabricate construction scale objects (such as polymer window or panels).

In total eight separate construction 3D printing techniques have been conceived, of these techniques: Concrete Printing[51], Contour Crafting[52] and D-Shape[53] have been developed, are focussed on construction purposes and are operational today. These techniques are described and discussed in detail below.

The Contour Crafting technique has been developed under the principal direction of Dr Behrohk Khoshnevis at the University of Southern California Viterbi School of Engineering in the USA . The technique was unveiled in 1996 and is the oldest technique under development. To date the team have demonstrated a number of straight and curved wall sections (CRAFT, 2010) and a scaled down adobe type structures (Figure 15 a & b). The development team, headed by Khoshnevis have published proposals including single dwellings, multi storey buildings and shelters for construction on the Moon or Mars (Khoshnevis et al., 2005).

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[51] Additive Manufacturing Research Group, Loughborough University UK
url: http://www.buildfreeform.com/

[52] School of engineering, Viterbi, University of Southern California
url: www.contourcrafting.org

[53] D-Shape private company. url: www.d-shape.com

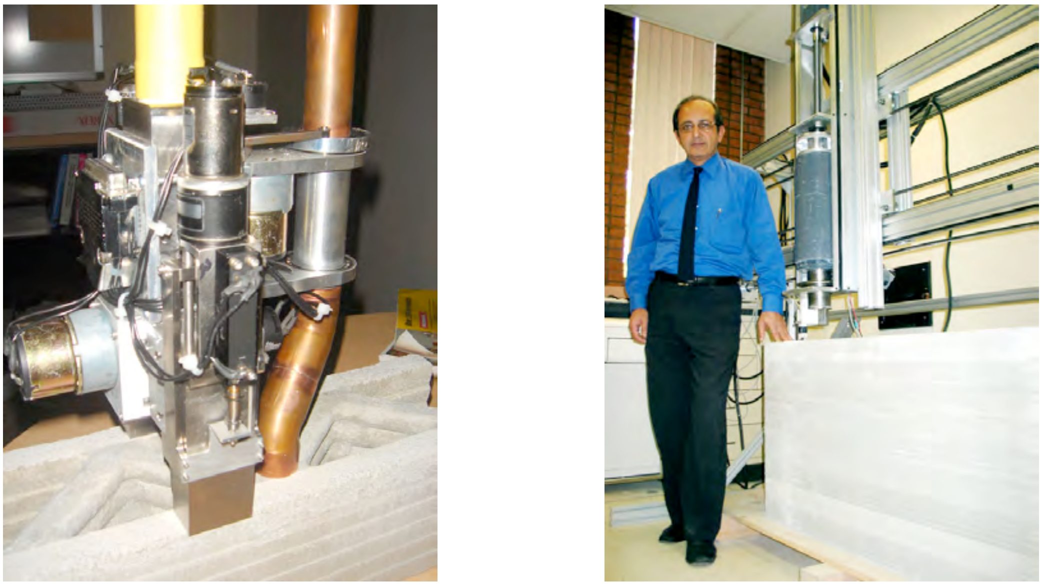

Figure 14 (a) The Contour Crafting deposition head. (b) Early version of the extrusion nozzle and machine. Images courtesy of Dr Khoshnevis, USC.

The Contour Crafting extrusion/deposition technique is designed with the capability of fabricating elements with two materials. There are two outer deposition heads (refer image Figure 14 a) which deposit a modified cementitious paste and a internal pivoting deposition head which can be used to deposit the same material as an internal structure, or could be used for bulk filling material into the cavity.. This second material could be potentially used to include material properties to assist with insulation, acoustics, waterproofing: although published material to date indicates that the primary purpose of the secondary material is to create internal structure. (Hwang, 2005, Khoshnevis, 2011).

The extrusion Nozzle, of which there have been at least four separate designs (Khoshnevis, 1996, Khoshnevis, 2009b, Khoshnevis, 2009a, Khoshnevis, 2011). The earlier designs incorporated moving top and side trowels which enabled raked smooth surfaces to be fabricated on one side, leaving a stepped finish on the interior of the object, later designs have removed this feature in favour of fixed side trowels. This shift in the design of the extrusion nozzle has occurred as the extrusion head has become more sophisticated; shifting from a single to quadruple extrusion heads, two to extrude the outer skin, one to extrude internal geometry and a fourth outlet to place bulk fill into the internal voids created by the first three extrusion heads.

Although it is claimed that the contour crafting machine has the capacity to extrude a wide range of materials (Haymond, 2008), only two materials types have been demonstrated using the contour crafting machine to date; ceramic pastes during prototyping stage and concrete as the machine has been scaled up. The concrete paste is specially formulated concrete containing Bentonite which "*dramatically decreased water seepage, increased the paste plasticity*" (Hwang, 2005). Although the use of Bentonite solved issues with the extrusion of concrete, it does not appear to have completely solved the issue of overhangs. As there is a conspicuous absence of overhangs, such as those which were earlier demonstrated using ceramic pastes at smaller scales; such capacity for creating overhangs has since only been demonstrated on stable geometries (lunar dome) in the modified concrete material at construction scale.

"*One of the key issues is how the build material maintains its desired form once it is deposited while it is curing: Contour Crafting uses thixotropic materials with rapid curing and low shrinkage characteristics*."(Buswell et al., 2007a)

Figure 15 (a) Contour crafting - wall test (b) Contour crafting - Scaled down adobe structure test - Both images courtesy of Dr Khoshnevis, USC)

The Contour Crafting team had by 2001 demonstrated the contour crafting techniques' ability to fabricate (at reduced scale) limited 2.5 dimensional objects (Haymond, 2008), such structures are only now beginning to be demonstrated with the construction scale Contour Crafting machine. The walls demonstrated to date at full scale have all been vertical (2.5D[54] geometries), without variation between the top and bottom profiles. The scaled down dome structure (Figure 15 b) demonstrates a three-dimensional object, although the surfaces are not double curved; the object rakes in steps from the initial base geometry toward the centre. The absence of demonstration of three-dimensional freeform elements at construction scale, after demonstration of limited three dimensional objects at smaller scales and clear research effort in this subject area (Yeh and Khoshnevis, 2009), indicates that the contour crafting technique is currently limited in its ability to create objects with unsupported overhangs and hence true three dimensional forms.

Although this may appear to be a significant limitation of the Contour Crafting technique, it should be considered that the vast majority of buildings today are rectilinear or are largely 2.5D-extruded forms; hence there is potentially a huge market for such a technique.

Integration of reinforcement and the automated integration of electrical and plumbing fixtures have also been proposed by the contour crafting team. From an Architectural perspective these proposals, which have not been demonstrated to date, would in my opinion, require significantly more development to be considered as a viable proposition for service or structural requirements of modern buildings.

The ‘Concrete Printing’ technique has been under development at the Additive Manufacturing Research Group at Loughborough University in the United Kingdom since 2004 within the Wolfen School of Mechanical and Manufacturing Engineering; the project was first conceived under the name ‘Freeform Construction’ machine with the assembly of the first machine commencing in 2006. Dr Rupert Soar originally led the project with Dr Richard Buswell assuming

[54] Refer to 2.5D definition in the index of terms (chapter 1.5)

the project leadership soon after the project received funding[55]. Freeform Construction is defined by Buswell as a "*Processes for* (the fabrication of) *integrated building components which demonstrate added value, functionality and capabilities over and above traditional methods of construction.*"(Buswell et al., 2005). Although this quote says little specifically about the technique, it does however give an indication of the aspirational capabilities of Concrete Printing technique.

Figure 16 - Concrete Printing Machine. Image courtesy of Dr Richard Buswell

Fabrication with the Concrete Printing machine (refer image Figure 16) works on the basis of selective deposition of a paste material through an extrusion nozzle, in a similar way to that of Contour Crafting discussed above. The major difference between Contour Crafting™ and Concrete Printing is due to nozzle design. The Concrete Printing nozzle (refer image Figure 17) is designed to have the capacity to vary its resolution to allow the deposition of both bulk materials and fine detail within the same process (Buswell et al., 2007a).

[55] As per email correspondence with Dr Richard Buswell, dated 2nd March 2011

Figure 17 - Concrete Printing nozzle. Image source - http://www.rationaloptimist.com/blog/print-your-own-organs - Accessed on the 9th August 2011

The materials used to date by the Concrete Printing team have included cement-based mortars and gypsum materials[56] with the use of commercially available binders for transforming the paste to solid, these materials are deposited in layers of between 6-9mm in thickness[57]. The team is working toward the integration of support material that would allow for the creation of overhangs and true 3D freeform geometry[58]. With a build volume of 2m x 2.5m x 5m[59] the Concrete Printing machine is designed for the fabrication of panels and large building components rather than whole buildings, with added value, functionality and capabilities over traditional construction techniques (as quoted above).

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[56] As per email correspondence with Dr Richard Buswell, dated 1st March 2011

[57] As per email correspondence with Dr Richard Buswell, dated 1st March 2011

[58] Based on telephone discussion 24th April 2009

[59] http://buildfreeform.com/index.php accessed 20th February 2011

Figure 18 - Example of Concrete Printing test print resolution. Image source http://smarchitecture.blogspot.com/2009/04/freeform-construction-update.html - Image accessed 9th march 2011

The opportunities for re-design of complex assemblies into integrated panels is one area in which the research team has focussed; with the development of the ‘homeostatic wall’ (Modeen et al., 2005) and later the ‘Wonderwall concept’(Buswell et al., 2007a). These concept designs focus on adding performance and functionality to walls, while reducing the number of materials and construction trades required. Additional value added functions include optimisation of structural, acoustic, thermal and ventilation properties. Although construction performance based design research has continued for many years (Pasquire et al., 2006, Godbold et al., 2007, Buswell et al., 2007b, Pendlebury et al., 2006, Modeen et al., 2005, Soar, 2006b) within the AMRG such design strategies were not tested as part of the recent ‘Freeform wall’ prototype (Figure 19) (De Kestelier and Buswell, 2009).

Figure 19 - Concrete Printing Freeform wall test - image source http://www.buildfreeform.com/index.php - Accessed 5th July 2011

The majority of test piece examples demonstrated using the Concrete Printing and Contour Crafting techniques have been to date 2.5D geometries, rather than true 3D freeform elements, which are usually associated with the use of Additive Fabrication techniques. (Refer images Figure 15 b & Figure 19)

The third of the techniques discussed here, D-Shape™ (refer image Figure 20) is significantly different from both Contour Crafting™ and Concrete Printing. Enrico Dini, the inventor of the D-Shape™ technique and founder of the private company D-Shape lodged his first construction 3D printing technique patent in 2006 (Dini et al., 2008). The initial technique described in the patent relied on synthetic resins to selectively bond sand within a build platform. The machine built up elements in a layered sequence; unbonded sand was then removed revealing the solidified object[60]. The problem with the process Dini stated was "Epoxy resin sticks to anything – including the machine that is applying it. This led to high maintenance costs for the machines as well as inefficiencies when they were used." (Abrahams, 2010) Issues such as flammability, toxicity and cost were also issues facing Dini with his first choice of binder material. (Corke, 2010)

[60] The process works in a similar way to Z-Corp additive fabrication process.

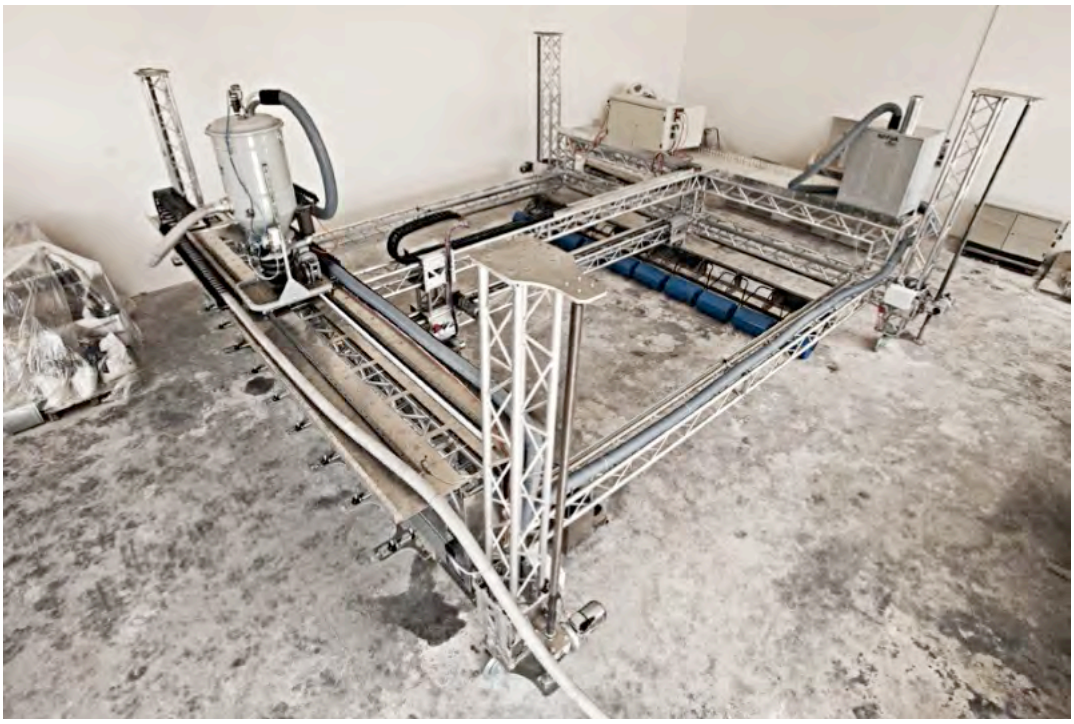

Figure 20 - The second-generation D-Shape machine - Image courtesy of Enrico Dini

A second patent (Dini, 2009) revealed a shift in focus away from polymer binders to inorganic binders, which operate through chemical reaction, to bind sand into a synthetic stone material. This was a significant shift for the potential of the process, moving away from a potentially high cost, problematic and toxic process toward one that is environmentally benign and has relatively inexpensive feedstock materials: predominantly sand and oxides and chlorides derived from sea water[61].

[61] Based on first hand observation and experience working with the D-Shape™ materials and processes in Italy between July – September 2009.

Figure 21 - Radiolaria designed by Andrea Morgante fabricated by D-Shape™. Photo by James Gardiner

Unlike the Contour Crafting™ and Concrete Printing, the D-Shape technique by selectively printing a inorganic liquid material onto a bed of sand mix material, the liquid creates a chemical reaction with the catalyst within the sand mix and the printed sand transforms into a sandstone like material (Dini, 2009). During this transformation process from granular sand to sandstone, which takes approximately one hour, subsequent layers of sand are deposited over the last layer on build platform and the next layer is printed. There is no requirement for a rapid transformation of the catalysed material to reach a solid state, as the materials undergoing transformation are supported within the build platform. Subsequent layers can proceed rapidly, while the catalytic reaction is continuing in the layers below. This fabrication method provides support for overhanging geometry, as sand is selectively transformed to stone within a bed of untouched sand, allowing freeform 3D geometries (refer image Figure 21) to be fabricated.

The D-Shape technique has been able to demonstrate its ability to fabricate freeform objects such as the Radiolaria and the Chaise Lounge (refer Figure 21 & Figure 22) quickly; relative to the number of years the technique has been under development in comparison to Contour Crafting™ and Concrete Printing.

Figure 22 – Root Chair designed by Kol/Mac fabricated by D-Shape for Materialise (Image courtesy of Enrico Dini)

The Root Chair (Figure 22) demonstrates the capabilities of the D-Shape technique for creating virtually unrestricted three-dimensional objects; limited at present only by the strength of the materials and printing resolution approximately 5dpi (with minimum detail limited to approximately 20mm in the X and Y axis and 5mm in the Z axis).

Figure 23 - Full scale Radiolaria under construction (image courtesy of Enrico Dini)

The Radiolaria sculpture (refer Figure 21 & Figure 23) is a significant scaling up of the demonstrated capabilities of Construction 3D printing techniques to date. The sculpture is now planned to reach a height of 8.5 meters (Corke, 2010) and will be installed in a Roundabout in Pontedera in Tuscany, Italy.

The types of projects that D-Shape is involved in at present include; large scale sculptures[62], furniture[63], testing for Luna construction[64] and a house in Sardinia[65]. This range of projects indicates the broad application for this technique within a number of industries.

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[62] 6m high Radiolaria sculpture for a roundabout in Pontaderra, Tuscany Italy, designed by Andrea Morgante.

[63] D-Shape has fabricated a number of furniture prototypes for materialise including a Chaise Lounge and coffee tables.

[64] First stage feasibility study for the European Space Agency. Prime contractor Alta space, Pisa in association with Monolite UK Ltd (D-Shape), Foster + Partners and Scuola Sant'anna.

[65] Villa Roccia. Project discussed as case study in (chapter 5).

Two principal methodologies are implemented by the three techniques. The first two: Contour Crafting and Concrete Printing are deposition techniques, selectively depositing mixed materials to build objects in layers. The second method implemented by D-Shape, selective state change[66], deposits layers of raw material onto a build area with selective printing to create a state change of the base material to form the object within the bed of un-catalysed material. These two different methodologies are also used in additive fabrication techniques, such as paste deposition (Fabber technique) and powder bonding (Z-Corp) although using different materials and slightly different processes.

This crucial difference between the first two techniques; Contour Crafting, Concrete Printing (selective deposition) and the third D-Shape (selective state change) is useful to understand the reasons behind, both the relatively slow development of the first two techniques and their current capabilities/limitations for creation of true freeform geometries. Selective deposition relies heavily on rapid transformation of liquid (paste) to solid, or the use of a second additional support material. The time interval between deposition of material and transformation of the material to solid, limits the ability of Contour Crafting™ and Concrete Printing techniques to create significant overhangs (transformation of geometry between layers). Neither Contour Crafting™ nor Concrete Printing has demonstrated the use of additional support material, although this is an important aspect of similar additive fabrication techniques. At present the inability to solve the issue of supporting overhanging geometry, either through fast material transformation or through use of support material appears to be limiting the types of geometries that are achievable with these processes (without significant geometric distortion during fabrication). The D-Shape™ technique does not rely on rapid transformation or curing of materials during fabrication as unprinted material on the build platform acts as support material for the printed material.

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[66] Refer to chapter 3.1.2 for categorization of additive fabrication techniques.

3.1.6. Conclusion techniques: Additive Fabrication and construction 3D printing

Developing Construction 3D printing techniques it not merely a matter of scaling up existing rapid prototyping techniques

"*A key point is that as you increase the build scale, the volume flow of material will force the design of a new process: it cannot simply be scaled up*"(Buswell et al., 2007a) p6.

This statement appears to be true of all three construction 3D printing techniques discussed above, for example for Contour Crafting nozzles demonstrated at small scale were significantly modified for full scale production. Support material, as implemented in smaller scale deposition machines (such as Stratasys fused deposition modelling) has not yet been integrated within Concrete Printing to support overhangs despite an intent to integrate support material within the technique (De Kestelier and Buswell, 2009), the D-Shape technique has shifted away from the use of polymer binders (as used by additive fabrication technique such as Z-Corp) due to machine maintenance and safety issues (Dini, 2009).

The focus of the three development teams has been markedly different, this divergence in attention and specialisation relate to differences in each of the three construction 3D printing technique teams market/product focus and the strengths and limitations of their techniques: the Contour Crafting team has directed its energies primarily on replacing standard construction methods within existing US housing typologies (Khoshnevis, 2004). The Additive Manufacturing Research Group that is responsible for Concrete Printing has focussed instead on creation of building elements and panels (Pasquire et al., 2006, Soar and Gibb, 2007, Rapid_Today, 2009) rather than entire structures; predominantly wall panels (to replace or enhance existing systems). D-Shape has focussed on the fabrication freeform elements, such as large sculptures, furniture and houses (Rapid_Today, 2009, Abrahams, 2010).

3.2. Design

This sub-chapter considers three aspects of design that are of concern in this research; design for Additive Fabrication, architectural design and design for construction 3D printing techniques. The three of these aspects become connected with the design for construction 3D printing. As design for construction 3D printing is an emerging field, for which few examples exist and even fewer have been constructed, information needs to be gleaned from related fields in order to identify the starting potentials and limitations. It is not within the scope of this research to analyse and comment on the full spectrum of contemporary industrial and architectural design; precedents have been selected from a very large pool of talent.

The criteria for the selection of design examples is based on the following:

1. Original and novel contributions to the field of design and architecture

2. Designs that focus on exploiting the capabilities of specific fabrication techniques

3. Performance oriented design: based on "the integral relationship between form generation, material behaviour and capacity, manufacturing and assembly" and in the case of architecture includes "environmental modulation and a type of spatial conditioning that is set to deliver a richly heterogeneous space." (Menges and Hensel, 2008)[67] p44

4. Designs that explore natural forms and biological organisms for inspiration

This set of criteria both aligns with my own sensibilities as an architect and serves the purposes of providing a rich and relevant set of precedents from which to

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[67] This definition is from Michael Hensel and Achim Menges definition of 'Morpho-Ecological' approach to design.

establish the relevance and contribution of the case studies presented later in this exegesis. The precedents discussed will likely relate to only one or more of the criteria listed above rather than all of them.

Each of the subjects: additive fabrication, construction and construction 3D printing will be considered in isolation first to understand current practices and then these practices will be considered against opportunities and constraints of construction 3D printing techniques. In some cases related fields or industries have been studied, as discussed in the methodology chapter, in order to understand how others have adapted their practices for digital design, off-site fabrication and automated fabrication.

3.2.1. Design for Additive Fabrication

Emerging applications using Additive Fabrication techniques range from the minute; experimental additive fabrication of tissue and organs built cell by cell (Song et al., 2010) to the automated Additive Fabrication of entire buildings and assemblies (Gardiner, 2004b), both of these potentials are possible today although they are still at a prototyping stage in their development (TED, 2011, Gardiner, 2009). These new opportunities are changing the way we think about the things we create. Not only can we customise to the highly specific needs of the user, we can optimise our use of materials, as does nature, and respond with high specificity to the environment and the forces acting upon the object.

Commercial applications for additive fabrication are maturing with a growing line of distinctive ‘designer’ products that focus on setting themselves apart from other goods by taking advantage of the some of the unique characteristics of additive fabrication. As noted above, these benefits and potentials of additive fabrication include; small fabrication runs, highly complex geometries, reduction of fabrication constraints, part consolidation, fabrication for assembly and customisation of material properties (as listed in more detail in chapter 3.1.2). A blossoming of design in the last decade has resulting in a plethora of designs leveraging the qualities of additive fabrication. The following examples illustrate how some of these characteristics have been leveraged to create unique and desirable products.

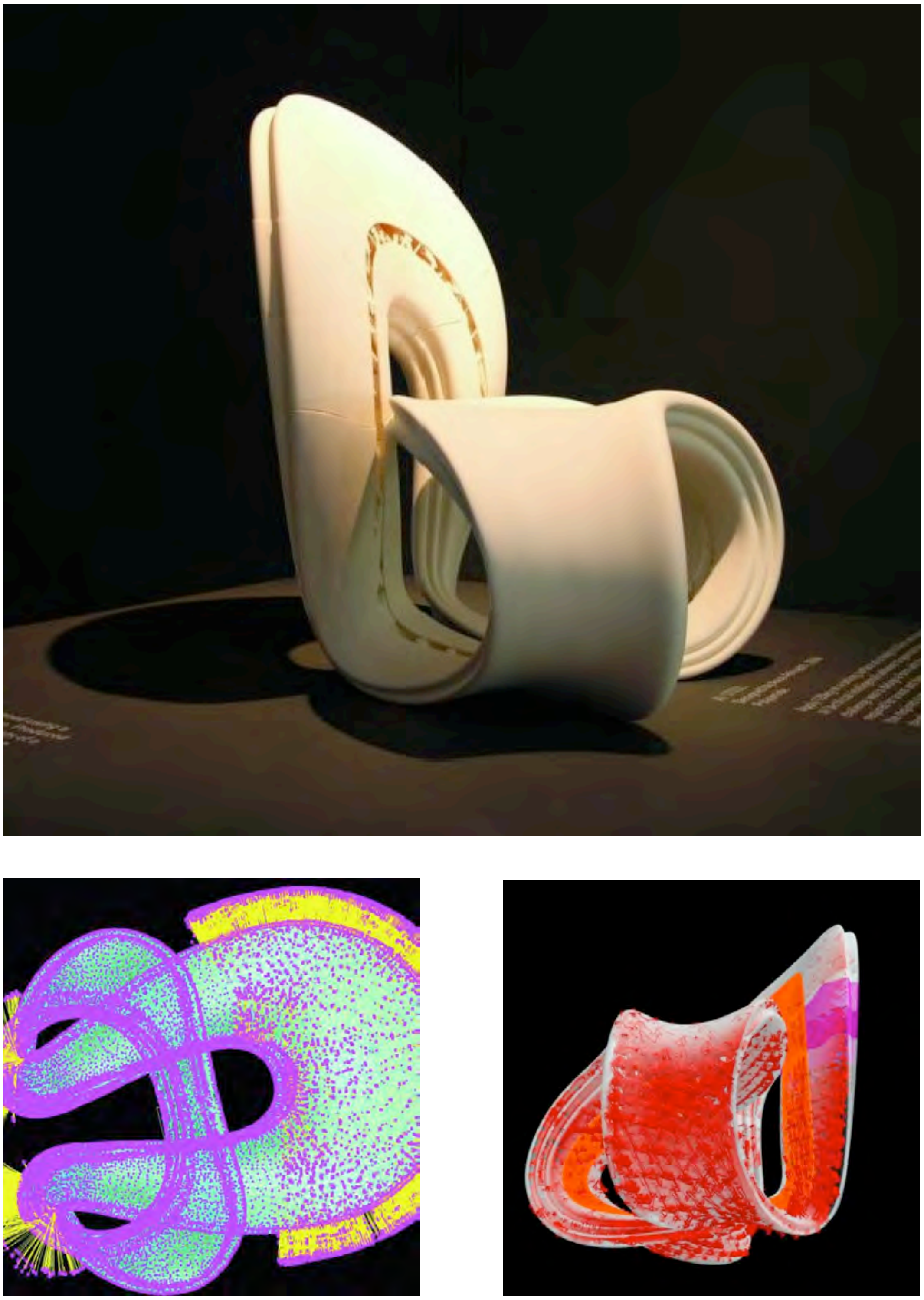

Figure 24 - (a) Front view of the additively fabricated Osteon chair by Assa Ashauch 2006. (b) (c) Digital wireframe view showing internal structure Osteon Chair (c) Fabricated cut-away of the Osteon Chair. Images source http://www.assaashuach.com/osteonchair.php Accessed 11th August 2011

The Osteon chair was designed by Assa Ashuach in 2006 for Materialise .MGX design product range. The chair is laser sintered from a bed of polymer powder using an EOS machine. The design is described by Ashauch as being modelled on biological structures such as bone by minimising through '*artificial intelligence*' material volume through a process of finite element analysis and optimisation (Ashauch, 2011).

The chair design takes advantage of a number of the identified potentials of additive fabrication; the chair is made up of an outer skin and an internal optimised lattice structure leveraging the capabilities of additive fabrication to create highly complex geometries, the reduction of fabrication constraints of additive fabrication makes possible the opportunity to create geometries which would be impossible to create using alternative fabrication techniques, the chair also takes advantage of fabrication for assembly (refer image Figure 25).

Figure 25 (a) Osteon chair by Assa Ashauch 2006, note that the top section of the chair assembly has been lifted off and rests on the seat. fabricated cut-away version of the Osteon Chair. Images source http://www.assaashuach.com/osteonchair.php Accessed 11th August 2011

Another design by Ashauch is the AI light, first exhibited in London in 2007 (refer image Figure 26). The design was sponsored by EOS, a German company focused on design and development of additive fabrication machines[68]. AI light is spooky to say the least, I was captivated by it the first time I found a video of it on the internet (Siaboo, 2008), the light has sensors that "*track changes in its environment and slowly it develops a set of behaviours that indicate a new character to each light*" (Ashauch, 2011), these sensors mechanically actuate the lamp changing its form like a strange sea creature.

Figure 26 - AI Light by Assa Ashauch first exhibited in 2007. Image source - http://www.assaashuach.com.php Access date 11th August 2011

[68] Refer to EOS website - http://www.eos.info/en/about-eos.html

Details regarding the fabrication and or assembly of the AI lamp are not available and it is not clear whether the lamp is fabricated in two or three pieces or in many. What can be said about the lamp is that design for assembly and mechanical fixing has been considered, as there are clearly three distinct parts not including the cables, light source and electrical wiring (refer image Figure 26).

If this lamp were to be fabricated using alternative fabrication techniques, for example laser cutting, the design would be sliced into a series of ribs (which are present in this design, for cutting from sheets of acrylic or other sheet polymer. This approach would require a reasonable amount of assembly and requirements for hundreds of fixings to join the flat pieces together to form the three dimensional object. In this case, although I am speculating for want of more information, the wings (the two lower branches) could be fabricated as single entities either with small joins between each of the ribs or with interlocking geometries to allow each rib to be effectively free in space from the next. The ability allows for highly flexible objects to be fabricated without the need to separately fabricate and assemble separate parts.

The lamp takes advantage of additive fabrication to create a relatively complex assembly, while minimising assembly, parts which would have had to be fabricated separately using alternative methods (ribs) have likely been consolidated into a single 'print' requiring minimised assembly.

Janne Kyttanen founder of Freedom of Creation™(FOC) has designed a series of similar lamps including the Palm, Lilly and Lotus since 2000 (Freedom_of_Creation, 2011), some of which are available through FOC and others available through companies such as materialise as part of their .MGX range of products. The Lilly lamp (Figure 27 a) has received numerous awards since 2003 for pioneering design for additive fabrication and its elegant design (Ginema, 2006, Freedom_of_Creation, 2011).

The lamp is fabricated using Selective Laser Sintering (SLS) as a single element into which the stainless steel base is fixed which holds the lamp. The lamp 'shade' itself is quite small measuring only 18cm in height (Saskia, 2008).

Figure 27 (a) – Lilly lamp by Janne Kyttanen Image source - http://www.archiexpo.com/prod/mgx-by-materialise/design-floor-lamps-4344-17754.html Access date 12th August 2011

(b) Quin Lamp designed by Bathsheba Grossman. Image source - http://www.bathsheba.com/gallery/mgx/ Access date 11th August 2011

Although the lamp geometry is not as complex as the lamp by Bathsheba (Figure 27 b) the geometry would have been difficult to fabricate as single element using alternative fabrication methods. The main contribution of this lamp is as a 'trail blazer' after which other designs for additive fabrication have followed. The lamp can be said to consolidate parts into a single element for fabrication and take advantage of the illumination characteristics of the Polyamide material from which it is fabricated.

The Quin lamp designed by Bathsheba is an excellent example of the beauty and applicability of mathematically generated design for additive fabrication. Bathsheba studied sculpture with mathematical sculptors Erwin Hauer and Robert Engman (Materialise, 2011). This lamp would be impossible to fabricate by alternative means with such precision and repeatability. There are two distinct levels of detail within the lamp, both a course level that defines the mathematically derived shape of the shade as well as a medium level of detail, which is present in hexagonal filigree infill panels. This hexagonal pattern appears to be randomly generated while following a rule set that can be discerned from the regularity of the size and disposition of the pentagonal mediating geometry between ribs of the course profile geometry and the infill panels.

Figure 28 - Fugu vase by Hani Rashid. Image source http://no-retro.com/home/2009/05/26/mgxs-e-volution-collection-shows-three-categories-of-exploration-of-design-for-rapid-manufacture/ - Access date 11th August 2011

The Fugu Vase (refer image Figure 28) by Architect Hani Rashid of the practice Asymptote was one of a number of sculptures and installations exhibited under the title Atmospherics at the Philips de Pury & Company gallery, New York in June 2008. The practice Asymptote oscillates around a central concept 'm-scapes' (motionscapes) and the firms work is derived from an "*ongoing exploration of objects subjected to speed and movement*" (Moss, 2011). The vases, a product of this theme are described as "*appearing as tornadoes and whirlpools in constant motion*" (Moss, 2011). These vases are fabricated through Materialise™ using Stereolithography for the outer shell and Selective Laser sintering (SLS) for the central core. This product is also sold and branded through the .MGX™ Materialise™ brand, as are most of designs featured in this section.

The fugu vase is most notable here for manifestion as a highly complex geometry and taking advantage of a lack of fabrication constraints, the design again would be virtually impossible to fabricate by conventional fabrication techniques: such as CNC milling due to the thin shell structure which is as expressive in shape internally as it is internally, making tool access impossible.

The design also purportedly expresses natural forces ‘tornados’ and ‘whirlpools’ although this has none other than aesthetic function here, it hints at the possibility for expressive responsiveness to forces such as wind and water. The fugu is none other than an exceptional product, beautiful and seductive, while also suggesting future directions for design.

The Guadi chair by Bram Greenen (refer image Figure 29) is a further expression of function (seating) and efficient force distribution using catanery curves.

The chair was “*Designed using the same methods as Antoni Gaudí, who made models of hanging chains, that upside-down showed him the strongest shapes for his churches. In the chair, the chain-models are combined with a software script to generate the structure of the ribs. This is necessary because of the complexity of the forces in a chairs backrest.”* (Worldhouse, 2010)

The chair is unique in its construction; this is the first of the designs to combine 3D printed (selective laser sintered glass filled nylon) structure with another, to take advantage of the properties of both. The Gaudí chair, which weighs only 1kg, uses the additively fabricated object to create a structural depth for the stiffening of a carbon fibre shell (Greenen, 2011) (refer image Figure 30). This chair uses the expression of the forces active in the chair as an integral part of the chairs aesthetic. The additively fabricated structure has two levels of structure, the first is the catanery structure and the second is a fine tessellated mesh, which interfaces with the carbon fibre shell. The chair can be considered to take advantage of the fabrication of complex geometries and consolidation of parts; taking a form which would traditionally be fabricated by joining ribs together[69] to fabricating a monocoque structure of a similar form.

Figure 29 – Gaudí chair by Bram Greenen. Image source http://worldhousedesign.com/furniture/Gaudí-chair-by-bram-geenen-lightweight-chair-with-high-end-materials-and-techniques/ - Access date 12th August 2011

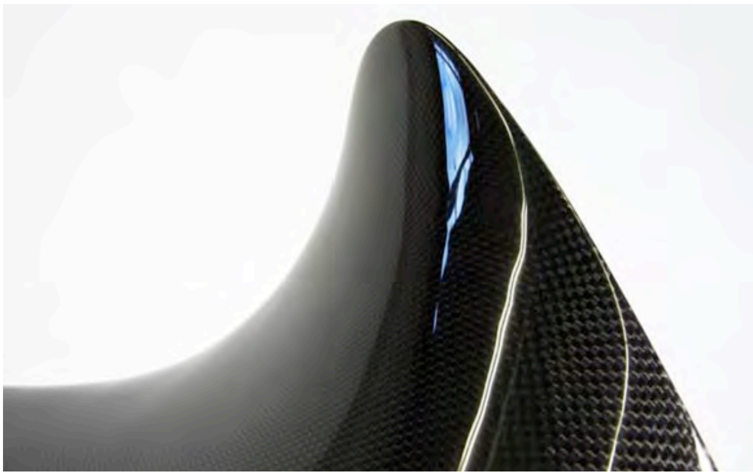

Figure 30 – Detail of Gaudí chair by Bram Greenen. Image source http://worldhousedesign.com/furniture/Gaudí-chair-by-bram-geenen-lightweight-chair-with-high-end-materials-and-techniques/ - Access date 12th August 2011

[69] This type of construction is common for fuselage construction of monocoque airframes used in shipbuilding and aerospace industries. More recently this has been utilized by architects such as Future Systems (Kolarevic 2003)

Figure 31 - Root Chair by KOL/MAC. Image source - http://i.materialise.com/blog/entry/5-amazing-full-sized-furniture-pieces-made-with-3d-printing   Access date 5th February 2011

The Root Chair (refer image Figure 31) by Sulan Kolatan and William MacDonald of KOL/MAC designed in collaboration with materialize “*is the largest 3D printed (built on a Materialise Mammoth stereolithography machine) item of furniture made in one single piece*” (Franky, 2010). The chair is said to be inspired by Asian tree root furniture, where individual pieces are modelled from tree roots to produce individual pieces of furniture (Materialise, 2009).

Continuing with this tradition of individuality each chair is generated digitally and is unique, similar in the way that a tree grows in interpretation of its DNA parameters in response to environmental variables. “*the root chair project represents a large family of related chair forms rather than a single design. Each chair is digitally “grown” with variable parameters that adapt to each customer’s desires and conditions.*” (Materialise, 2009).

The chair pushes the limitations of additive fabrication by making use of one of the largest additive fabrication machines available, this is however one of the few designs that could be fabricated relatively efficiently using an alternative fabrication technique, 5 axis CNC milling. The chair shape could be fabricated by cutting the geometry from a large piece of Styrofoam, with a composite structural shell of fibreglass/gelcoat applied to create the surface finish. This approach would probably be more labour intensive than using Stereolithography, although a finish coat has clearly been applied to the 3D printed chair to finish and polish it up to its final form (refer image Figure 31. What is unique about this design is the use of ‘variable parameters’ to create serially unique products.

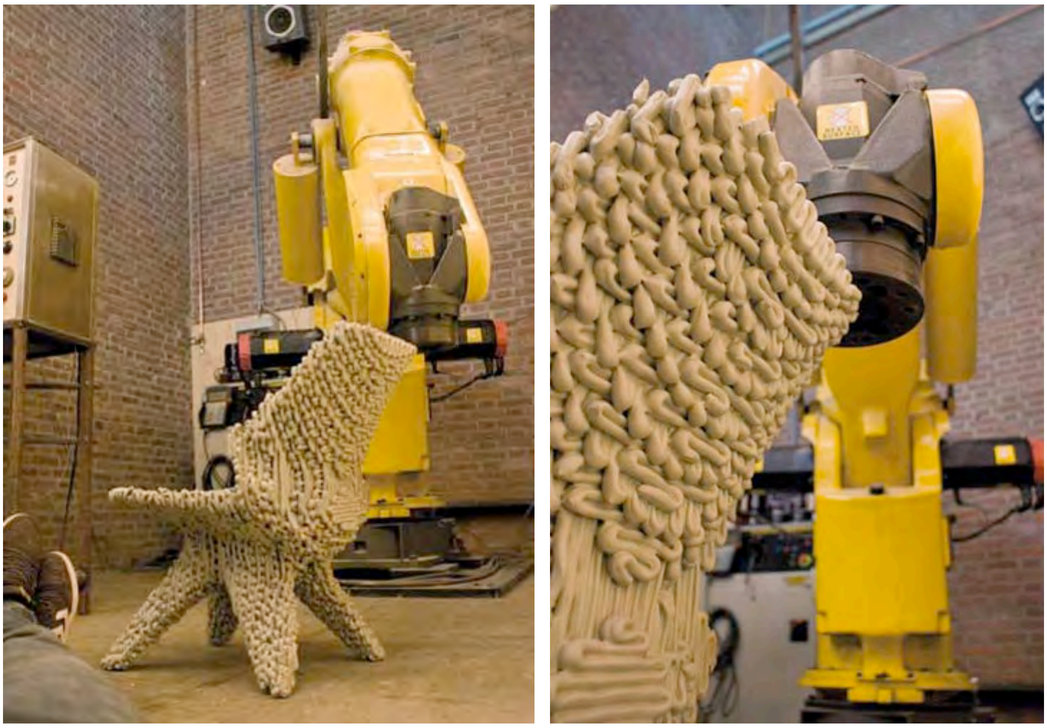

Figure 32 (a) New version of the Endless Chair by Dirk Van Der Kooij. (b) Detail of endless chair. Image source - http://www.designboom.com/weblog/cat/8/view/12595/dirk-vander-kooij-new-version-of-endless-chair.html Accessed 11th August 2011

The second Endless chair designed and fabricated 2010 by Dirk Van Der Kooij continues the embrace and enhance the figuring of fabrication process as part of the aesthetic of the object (refer image Figure 32 a & b).

“*by combining different techniques, I was able to design an automated but very flexible process. I taught a robot his new craft, drawing furniture out of one endlessly long plastic string. this opened the possibility for me to design in the good old-fashioned way, making a chair, evaluating, refining, making a chair,* *evaluating, refining and making a chair. or developing an infinitely large collection of variations. endlessly*." (Designboom, 2010)

Although the Endless chair seems like a novel concept it is essentially the way objects are made with Fused Deposition Modeling (FDM), the novelty here is in the scaling up of the technique (a feat in itself) and embracing the method of fabrication as being a key defining attribute in the products design.

The DLA vessel designed by David Sutton in 2006 is generated through a digital fractal growth algorithm called Diffused Limited Aggregation, this is simulation method which can closely mirror the form of natural a phenomena such as river networks, plant branching, lightning and coral growth (Bourke, 2004a). The design of the object, in this case a bowl, is the easy part; this bowl creates a containment boundary from within which the growth algorithm can be seeded and grow. (Detnk, 2011) The design uses software developed by Paul Bourke in 2004 (Bourke, 2004a) based on his research on Diffused Limited Aggregation (Bourke, 2004b, Bourke, 2006).

Figure 33 – DLA Vessel by David Sutton Image source - http://www.detnk.com/node/167 Access date 11th August 2011

The design by David Sutton (refer image Figure 33) is an example of one of the high complexity that could not be achieved using alternative fabrication techniques. The issue of fabrication constraints is interesting here because, in my opinion, only a few additive fabrication techniques could fabricate such an object (stereolithography and selective laser sintering – both state change). Therefore this design is pushing the boundaries of even additive fabrication techniques.

All of the designs discussed in this section can and most likely take advantage of small fabrication runs, due to the limited size of additive fabrication machines today.

Figure 34 - i.materialise prototyping for Citroen. image source - http://www.solidsmack.com/fabrication/3d-printing-concept-cars-i-materialise-is-the-secret-this-is-the-process/ Access date 12th August 2011

3.2.2. Architectural Design

This sub-chapter on Architectural design is a highly selective discussion that focuses predominantly on contemporary architectural theories and working practices that have been identified through literature review to be relevant to the design for construction 3D printing. Identification of theoretical relevance (or irrelevance) is based applicability of the theory to construction 3D printing scenarios and also to revealing how the digital and other tools can be utilised and/or understood within the current human paradigm in the 21st century.

My intention in developing a detailed understanding of construction 3D printing has been to take a very different approach from the usual 'design it and let someone else sort out how to detail and build it'. This approach of leaving the very difficult documentation and design for construction process to others is common with ground breaking architectural projects and their architects' (such as the Opera House by Jorn Utson, The Water Cube by Chris Bosse and the Radiolaria by Andrea Morgante).

The principal of my approach, which is described in the following case study chapters, has been to learn about the capabilities of construction 3D printing (its limitations and potentials) through engaging with it through detailed digital design and physical prototyping. This approach of critical action based engagement with construction 3D printing has been from both a design and construction perspective. I believe in many cases more about a new material or process can be learned from physically testing its performance and properties, as long as you are engaging from a creative and experimental place. This approach of detailed engagement with the materiality, buildability and tectonics is not however new and this sub-chapter will, among a broader discussion of architectural theory describe other action based precedents and motivating theoretical frameworks that resonate with the way that I approach my work and which inspire me.

The relevance of architectural theory and working practices is again judged on applicability to construction 3D printing (the central topic of this PhD) and how such practices might be adapted to design for construction 3D printing. Selected theories will be discussed and evaluated in reference to how such principles can or may be useful to informing working practices and project thinking.

Eisenman's 1976 paper Opposition 6, is here reinterpreted within the current architectural context. Eisenman explains the shift from the humanist theoretical framework, of the "*opposition of form and function*" (Jencks and Kropf, 2006) p267, to modernism as "*displacement of man away from the centre of the world*" (Jencks and Kropf, 2006) p266, which enables a "*dialectical relationship within the evolution of form itself*" (Jencks and Kropf, 2006) p267. This enables the 'co-existence' of "*non-corroborating and non-sequential tendencies*" (Jencks and Kropf, 2006) p267. This 'new modern dialectic', Eisenman suggests, can allow for theoretical alternatives to functionalism which "might serve as a framework for the deployment of a larger theoretical structure".

Although Eisenman's (post)modernist architecture manifested 'dislocation, destabilization, and rupture among other things' within a "*psychological void which provokes individual and social anxiety*" (Blank, 1998), the pluralistic theoretic framework that he discussed in Opposition 6 can be interpreted quite differently from the complete disassociation of function of Gehry and Eisenman (Hensel, 2010). This reinterpretation can rather focus on what one chooses to include and/or consider in the design of architecture. Such alternative issues, generators and inputs have since been explored in contemporary architecture in almost every conceivable form: in movements such as deconstruction (Frampton, 1997), through the use of and consideration of a broad range of issues through the use of mapping and diagramming (Stoppani, 2004) and through learning from or mimicking biological processes digitally (Leach, 2009).

Greg Lynn architect and theorist in 1999 described in his manifesto 'Animate form' the emerging design territory for architects working within the digital environment.

"*Issues of force, motion, and time, which have perennially eluded architectural description due to their "vague essence", can now be experimented with by supplanting the traditional tools of exactitude and stasis with tools of gradients, flexible envelopes, temporal flows and forces*" (Jencks and Kropf, 2006) p329

This changed the, perceived, potential of architecture to reflect and respond to its environment and the forces acting on the building or structure:

"*The context for design becomes an active abstract space that directs form within a current of forces that can be stored as information in the shape of form. Rather than as a frame through which time and space pass, architecture can be modelled as a participant immersed in dynamic flows.*" (Jencks and Kropf, 2006) p328

Lynn in describing the idea of the ‘fitness landscape’ as a model for design, which can be interpreted as either a surface or a solid entity of a building, ‘within which organisms can evolve’ (including humans) states

“*A landscape is a ground that has been inflected by the historical flows of energy and movement across its surface. These historical forces manifest a geological form of development that is inflected and shaped by the flows that have moved across it. These slow transformational processes result in forms which are oriented with motion, both the virtual motion of their history and the actual motion they initiate through their slopes and valleys. This animation of slow form with the historical processes of gradual geological becoming is a paradigm of motion and time that renders substance virtually animated and actually stable.*
”(Jencks and Kropf, 2006) p330

Figure 35 - Experiment by Frei Otto and team for the new high-speed Stuttgart train station - Image source - http://architecturehabitat.blogspot.com/2010/10/final-submission.html Access date 26th August 2011

These theories which signalled the opportunity to create a responsive architecture through the use of digital tools, by this time, had already been demonstrated in physical form by architects using analogue techniques such as Frei Otto and

Antoni Gaudí. In the case of Frei Otto through the study of biological systems, natural formations and experiments that have resulted in a variety of structures. The most notable of these are Otto's minimal surface structures which have been developed using a number of analogue techniques such hanging chain models, draped cloth and the use of soap films (these have also been complimented with the use of digital tools as discussed later). Such techniques have been used to develop assemblies and surfaces that effectively respond to forces that are acting on the structure (Otto and Rasch, 2006).

Parametricism, as stated by Schumacher, is claimed to be the "*new long wave of research and innovation*" (Schumacher, 2008) p1 after the 'transitional episodes' of deconstructivism and postmodernism. This seems to be a grand claim, to be making for a tool, although we have had the age of the automobile and the personal computer. The movement is said to be based on the "*creative exploitation of parametric design systems in view of articulating increasingly complex social processes and institutions*" (Schumacher, 2008) p3. Parametric tools are capable of responding to a wide variety of parameters and inputs, which can be increasingly be drawn from a broad range of inputs from material capabilities, space relational requirements to time based user feedback. The question then becomes how can the scope and capability of parametric tools be framed, to allow some conceptual framework to emerge that can guide the why, beyond the how.

"*Schumacher calls for a conceptual reconstruction, meaning that we must disregard* (the definition of) ***style*** *as a matter of appearance, and move to understand style as "a design research program conceived in the way that paradigms frame scientific research programs."* (Cliento, 2010). This could perhaps be described as being similar to the development of applications and methods of using off-form concrete in the 20th century by architects such as Frank Lloyd Wright (Falling Water), Le Corbusier (Maison Dom-Ino and the Unite d'Habitation), Pier Luigi Nervi (Air craft hanger), Aero Saarinen's (TWA terminal), Carlo Scarpa (Brion Cemetery) through the development of applications and methods for the use of a software tool to produce an outcome, rather than in the case of the examples listed above for the application of a material and process to produce applications and new built forms and typologies.

Although Schumacher states “styles are design research programmes”, in his manifesto for Parametricism (Schumacher, 2008). If the design research he speaks of is based on his manifesto, the results are likely to be heavily oriented visually or aesthetically. His five points for future development of Parametricism can be summarised by his own stylistic words and phrases, listed from his manifesto (Schumacher, 2008) below:

1. ‘Inter-articulation’ - to produce ‘differentiation’ between sub-systems.
2. ‘Parametric Accentuation’ - ‘overall sense of organic integration’
3. ‘Parametric Figuration’ - ‘latent with multiple readings’
4. ‘Parametric responsiveness’ - to result in ‘semi-permanent morphological transformations’
5. ‘Parametric urbanism’ - modulation of the buildings morphologies to produce ‘powerful urban effects’ and to facilitate ‘field orientation’

Point 4 and to a lesser extent point 5, of the 5 point manifesto, are the only items that appear to have any reference to creating a response, result or outcome to architectural inputs with the intention to create any more depth than can be perceived visually. Unlike many other manifestos there is no why (something should be done) but instead just how (“*interarticulate, hyberdize, morph, deterritorialisze, deform*”) or what (creating ‘*semi-permanent morphological transformations*’) (Schumacher, 2008).

The parametricist manifesto, as a conceptual framework on which to base design is devoid of reason or logic. As with the post rationalised explanation of the sources of inspiration for Hadid’s inspiring architecture: based on ‘*explosions, compressions, swarms, aggregations, pixelations, carved spaces and excavations’* (Jencks and Kropf, 2006): there is little stated reasoning behind the why certain patterns and forms are used, thus providing little more than a stylistic roadmap rather than a framework with which to interpret a project and its challenges. It would appear that if Schumacher’s

Parametricism manifesto were taken seriously, a student could be given a piece of parametric software, with 5 or more functions described by Schumacher; inter-articulation, accentuation, figuration, responsiveness and urbanism: if they used this software in any way it would manifest Parametricism, as there is no logic behind the use of these tools on which to measure success or failure.

Frei Otto states of the recent emergence of research in architecture "*Normally the aim of the architect is to produce architecture. They have forgotten how to research. And yet latterly architects have committed themselves to research as never before. Instead of planning buildings or cities they want to pursue the processes of change and self-origin in man made objects*" (Otto and Rasch, 2006) p17. Otto is one of the most active and committed researchers in the field of architecture, engineering and biology as evidenced by his long and fruitful career since the 1950's and his lead research role through the institute for lightweight structures (Otto and Rasch, 2006). It would appear to me from the statement above that he sees the emergence of the new 'research agenda' within architecture as often being removed from the act of designing buildings due to the act of doing research as an end in itself and the lack of robust research methodology.

Otto further describes the potential issues of using digital tools: "*We have used the computer since* (the 1970's)*, but I continue to use models as well. Our models, in combination with iterative calculations, have really helped us make better and more beautiful buildings. I am not against digital processes at all, but emphasise the importance of understanding what you are doing. Solving problems with software programs that are not specially written for the particular problem one is dealing with may lead to a lack of understanding of what is shown on the screen. Something may look perfect on the monitor, but that does not mean that you understand it or that it is functioning in real size*" (Hensel et al., 2004)

Otto's criticality of digital tools is based on his long experience using these tools and most probably a fair amount of trial and error, the value comes from making sense of the result rather than merely accepting this on face value. As also discussed above Otto relies on a feedback loop between digital tools, physical testing and consultation or engagement with experts within the field being studied (Otto and Rasch, 2006). Such testing and use of responsive digital modelling tools is stated as best achieved "*through objective, level headed research with a clear aim*" (Otto and Rasch, 2006) p22

Figure 36 - (a) Colonia Guell interior, Barcelona 2009. Photo by James Gardiner (b) Frei Otto Munich Olympic Stadium 1972 Image source - http://www.worldofstock.com/stock_photos/AAB2116.php Access date 22nd August 2011.

Otto's stated aim, his disguised manifesto perhaps, is "*Tomorrow's architecture will again be minimal architecture, an architecture of the self forming and self optimization processes.…this must be seen as part of the new developing ecological system*" (Otto and Rasch, 2006) p14. The aim of this approach is intended to form a new ecological system, on earth, that brings man back into harmony with the natural world and break down the barriers between man, technology and nature (Otto and Rasch, 2006). This minimal architecture is a response to what Otto has discovered and observed from the study of organic and inorganic systems and in 'primitive architecture, where no material is used to excess and where decoration makes sense if essential' (Otto and Rasch, 2006).

The understanding of the minimal is not necessarily to the exclusion of redundancy, the minimal amount of material possible or least complex solution. In taking into account the multiplicity of forces and factors of the 'ecological system' that need to be accommodated within a work of architecture, compromise solutions need to be adopted, as they are in nature.

"*If only one structural parameter needs to be considered, for example in Gaudí's hanging models, the performance of the model can be optimised to a specific force case.*

With multi-parameter set-ups each result is a negotiation towards a best-possible overall performance, with a great deal of overall redundancy (future potential) built into the material arrangement" (Hensel et al., 2004) p29

Michael Hensel and Achim Menges continue the practice of focused design research, pioneered by Otto, with the "*long term investment in design research that draws on the knowledge of a broad range of experts*" (Menges and Hensel, 2008) p5, through their involvement with the architectural practice OCEAN North and teaching at the Architectural Association in London. Their collaborative research, practice and teaching focuses on the study of natural phenomena (such as aggregation of timber modules and granules) and biological systems (the geometry of pine cones and the performative characteristics of timber) (Menges and Hensel, 2008, Hensel et al., 2004)

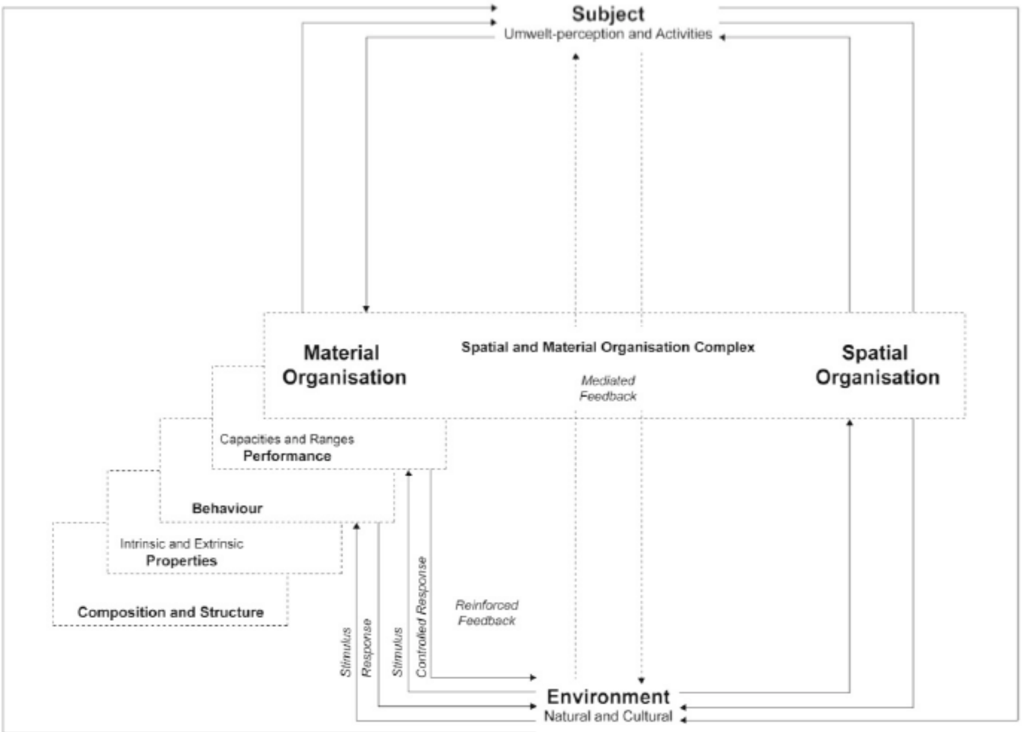

Figure 37 - Performance oriented architecture diagram by Michael Hensel shows a pluralist multi-criteria/feedback loop approach to architectural design. Image extracted from (Hensel, 2011).

In grappling with the ongoing form function debate and approaching a more robust theoretical framework for their architecture and future research, Hensel states "*architecture, environment and inhabitant all 'perform', that all can be seen to posses in an interrelated way 'active agency', and that all interact with one another yielding perpetually complex behaviour. This makes it clear that a synergetic understanding and approach is required to unlock these complex interactions for the purpose of an instrumental approach to architectural design*" (Hensel, 2010) p54.

This statement can be interpreted to mean that the consideration of function and performance need not be limited to environment, structure and spatial arrangement: as they almost always are in contemporary architecture: but can be extended to include other criteria such as material, program, action and interpretation (Hensel, 2010). These performative aspects should be considered together in order to find or develop the design. Finally "*form and function are not separately treated, and neither follows the other: instead, both are interrelated and interdependent*" (Hensel, 2011) p3.

Form is thus intended "*not as a shape of a material object alone, but as the multitude of effects, the milieu of conditions, modulations and microclimates that emanate from the exchange of an object with its specific environment – a dynamic relationship that is both perceived and interacted with by a subject*" (Menges and Hensel, 2008) p7

Thus the 'performance orientated architecture', often also referred to as 'Morpho-ecological design' (Menges and Hensel, 2008): which grew out of emergence manifesto developed with Michael Weinstock (Jencks and Kropf, 2006, Hensel et al., 2004): is a pluralistic 'instrumental approach' to architecture, that aims to not only form a synergy between form and function but to also create synergy between man, nature and technology through 'interrelation' and 'interdependence' (Hensel, 2011).

Hensel states of Architecture "*In order to develop instrumental approaches to architectural design, architects invariably operate on a set of categorical items that allows them to break complex and often dynamic relations into smaller subsets, so as to be able to make them intelligible and instrumental. In itself this constitutes no problem as long as categorisation as an intellectual tool is not* *mistaken as anything other than artificial dichotomy for the sake of intelligibility - an entirely known and yet often uncared for fact"* (Hensel, 2010) p42.

This issue: of the self serving use of abstraction, simplification and categorisation as generators for architectural design has appeared, until recently, to be almost all pervasive in 'digital architecture' and prior to this in 'post-modern' movements of architecture. This can be described as the development of design methodologies, based on the use of digital (parametric, script based) or analogue tools (mapping, diagramming) based on limited or abstract input data. Such tools have proved very useful in the right hands (such as Foreign Office Architects), have in others become a self serving justification for the planning and design of projects, such as the 2nd gear housing project (Spuybroek, 2004) p120.

A number of theories and manifestoes have been discussed here, in an exploration to tease out a relevant and appropriate framework for design for construction 3D printing. The choice of subject matter has been self directed and thus reveals to an extent my own leanings as an architect.

In the limited discussion of post-functionalism we found that the fundamental shift in thinking that occurred between the 19th and 20th centuries brought with it a shift from human centric thinking to modernist thinking, that ignited the form function debate. This shift brought about with post-modern theories for architecture brought with it a broadening in the issues under consideration by architects, although the focus of architects often narrowed within functional aspects ignored altogether.

Lynn can be understood to have clearly marked the opportunity for architecture to respond to force, motion and time through the use of digital tools, which are said to extend the capability of architects to deal with complexity and make possible a new form of responsive architecture.

The parametricist manifesto by Schumacher sprukes the capabilities of parametric and other digital tools has been said by Schumacher to be the 'new long wave' style, replacing modernism after transitional 'episodes' of post-modernist movements. The parametricist manifesto redefines ‘style’ to relate to ‘design research’ but fails to define the aims (or the why) of the proposed research beyond visual or topological outcomes, leaving manifesto devoid of logic or guiding principles.

Hensel and Menges define ‘Performance Oriented Architecture’ continues the rigorous approach to architectural research, this theoretical approach has recently taken form based on previous theories of ‘emergence’ developed in collaboration with Michael Weinstock. The development of this theoretical framework is said to be in response to the need to clearly define the aims of both the ongoing research and the outcome in built form. The definition of performance is cast quite broadly to include program, action and interpretation as well as the more obvious elements considered within architecture, such as material and energetic performative aspects. The aim of Performance Oriented Architecture is to, similar to Otto is to create synergy between man, nature and technology through an ‘instrumental approach’ to creating architecture, while expressing the synergy between form and function. This theoretical framework, unlike Parametricism perhaps casts its scope a little wide, being almost all encompassing. I would expect with time that the ‘performance oriented architecture’ framework will be tightened and focused, just as the experimental approach is in continual redefinition.

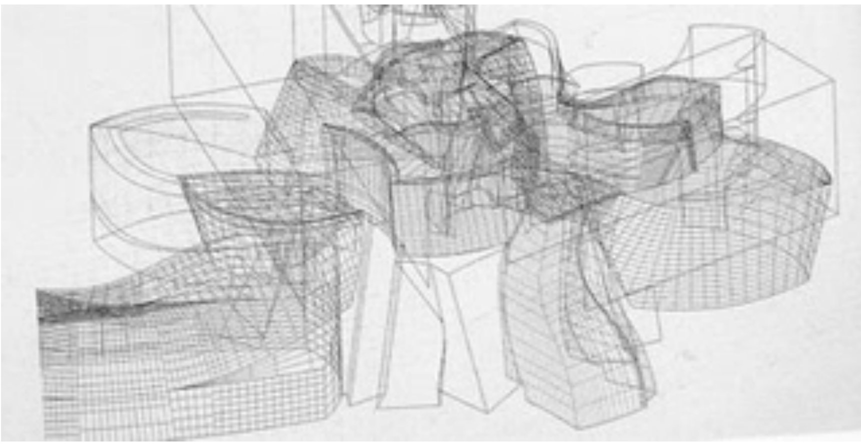

Figure 38 - Guggenheim Bilbao designed by Frank Gehry. Image source http://loguestudiodesign.blogspot.com/2008/09/part-4-of-5-convergence-of-disciplines.html Access date 23rd August 2011

While the challenge of fabricating and constructing buildings of high levels of complexity is not new (Burry, 2007), the tools (such as Digital Project, Generative Components™, Rhino™ etc) that have recently become available have made fabricating such levels of complexity more accessible. To a point where architecture students can now design and fabricate (prototype or full scale) complex projects within their own limited resources (Downton et al., 2008, Hardy, 2008).

Design for digital fabrication of such geometrically complex building in most cases relies on subtractive fabrication techniques, such as: laser/plasma cutting of sheet materials and sections, milling or cutting materials such as blocks or slabs. In some cases formative techniques are used such as casting. There are relatively few projects that are purely additive fabrication, such as the Robotic bricklayer developed at ETH Zurich (Wertz, 2009). Although it can be said that in most cases once the pieces are digitally fabricated, they are then built additively by hand (with the assistance of tools, cranes etc). This has resulted in digital design software that is tailored toward the predominant means of fabrication. This has resulted in software that has strengths and weaknesses, the limitations can be found to lie generally in areas that are deemed less important to users (these issues will be discussed further in the case study projects).

Specific construction projects, such as the Sagrada Familia in Barcelona (Burry, 2002), the Barcelona Fish by Gehry Partners (Lindsey, 2001) and others discussed by (Kolarevic, 2003) have been implementing high level three-dimensional CAD design and documentation on geometrically difficult projects. These architectural practices adapted and customised techniques originally developed for other industries; specifically parametric design from the aerospace industry.

Figure 39 (a) Work site in the Sagrada Familia 2009. (b) Mercedes-benz museum in Stuttgart, designed by Ben Van Berkel. Photos by James Gardiner

The digital design and documentation methodologies (often one and the same but in many cases not) applied on the Sagrada Familia (refer image Figure 39 a) and other projects can be used as a precedent for design and fabrication using Construction 3D printing techniques. Although there are significant parallels in terms of CAD design, the production means applied on the projects mentioned above are largely subtractive and formative rather than additive, as is the case with Construction 3D printing techniques (Pasquire et al., 2006).

At present the three techniques Contour Crafting, Concrete Printing and D-Shape are limited to fabricating with one or two materials, this is in stark contrast to standard construction practice, which uses a plethora of materials. For example a double brick wall is not just made up of bricks, but includes mortar, insulation, brick ties, conduits, vents, damp proofing etc. This presents a limitation with Construction 3D printing techniques and also an opportunity: which will be discussed in the case study chapters 1 & 2.

3.2.3. Design for Construction 3D printing

Design for each of the three techniques discussed above, Contour Crafting, Concrete Printing and D-Shape, needs to take into account the strengths and limitations of the machine from which the design will be fabricated. As an example a freeform design such as the Radiolaria by Andrea Morgante (refer image Figure 21) cannot be fabricated by either Contour Crafting™ or Concrete Printing techniques, at their current stage of development, due to the limitation in fabricating unsupported overhangs.

Resolution is an important factor to consider in design for construction 3D printing: unlike additive fabrication techniques today the resolution of construction 3D printing techniques is quite course, due to the challenge of scaling up additive fabrication techniques and the large size of the objects being fabricated.

Subtle differences in the software used by the different techniques can also have an effect on whether a design can be fabricated, even on additive fabrication machines today. For example when preparing for an exhibition in October 2010, I approached the Industrial Design Workshop at UTS to fabricate a complex prototype artificial reef model (Case study 3 refer chapter 6) with their Stratasys™ fused deposition modelling additive fabrication machine. Due to the size and complexity of the files to be fabricated and more importantly to minor errors within the digital definition files the model could not be fabricated by them[70]. The Stratasys software that produces the G-code could not resolve or ignore these minor errors and therefore if the 'print' could be commenced the machine would crash when it encountered the error is the G-code. The error was related to very small areas with negative volumes, flipped faces etc, which were caused by the boolean operations necessary to complete the project. These issues will be discussed in more detail in case studies 2 & 3. The same file was instead

[70] The files had been fixed using both Netfabb™ and Magix™ prior to attempting to process the files.

fabricated at RMIT with a Z-Corp™ machine without any major issues. The difference, I was told by workshop staff, largely came down to differences in the software used by Stratasys and Z-Corp™: Z-Corp™ software is more forgiving of minor problems than the Stratasys™ software.

The Additive Manufacturing Research Group has been prolific in its exploration and quantification of the design and construction implications of Construction 3D printing (referred to by the group as Freeform Construction). This research has broadly covered the implications for design, construction, CAD/CAM interface, optimisation, sustainability and the maintenance and refit of old building stock.

3.2.4. Design project precedents - Construction 3D printing

Few published precedents exist of design for Construction 3D printing techniques, in 2011 there are, still only a very small number of construction projects that have been designed specifically for fabrication using these techniques. The designers of these projects include R&sie – I've Heard About, Andrea Morgante – Radiolaria, Foster and Partners - 3D Printing of Building Blocks using lunar soil, James Gardiner –Freefab Tower, Villa Roccia and (in)human habitat (discussed in this exegesis as Case Studies 1, 2 & 3).

Following on from my own projects, I have also run a series of Architecture design studios, which fore-grounded construction 3D printing (and other) techniques. These studios included Freefab Tower Masters Design studio (UTS Spring 2008) & Freefab Tower Masters Design studio (RMIT Autumn 2009) and Freefab (in)human habitat Masters Design studio (Spring UTS 2010)[71].

It seems strange that there has been so little focused attention to date by designers, culminating in design projects.[72] This has seemed odd to me, as I would have

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[71] The work from these three studios has not yet been published.

[72] I can only comment on projects that I have been able to find, through internet searching and constant contact with leaders in construction 3D printing.

thought that construction 3D printing would capture every architect's imagination. I can postulate two reasons for why there have been so few projects published. Firstly the techniques have not been around for long; Contour Crafting™ was developed in 1996 by Dr Khoshnevis (information about the Contour Crafting™ technique was very difficult to locate until after 2005[73]) and D-Shape and Concrete Printing have both been developed since 2005. This short history, of available information, leaves a window of approximately 6 years for the development of architectural projects.

The second reason may be due to the difficulty of designing something for a technique with so few (published[74]) construction constraints. At face value this reluctance to design for a technique with so few construction constraints seems ridiculous, as digital architecture projects often appear to have been designed, either intentionally or unintentionally, in ignorance of methods of construction and their limitations. I did however observe that the majority of my students from the Freefab studios[75] at UTS and RMIT found it initially quite challenging to design for a construction technique that seemed to have so few geometric constraints and fabrication limitations.[76]

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[73] Based on first hand experience in search for the Contour Crafting technique in 2004.

[74] None of the three construction 3D printing development groups detail the constraints of their construction 3D printing techniques, based on a survey of the Contour Crafting, Concrete Printing and D-Shape websites.

[75] The Freefab masters level studios, which reflect my own research interests in Construction 3D printing, were run by me at RMIT and UTS between 2008 and 2010.

[76] One of the principal themes the students were encouraged to use to get them over this issue of lack of geometric constraints was to focus on material constraints, material efficiency and building performance.

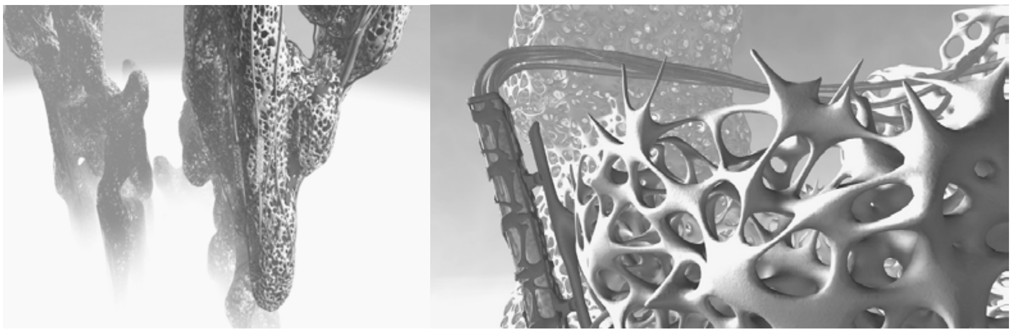

Figure 40 - I've heard about project by R&sie. Image source - http://www.new-territories.com/I'veheardabout.htm 10 June 2007

In the following section I will discuss the projects completed to date with an emphasis on the designers intent (where this can be ascertained), consideration of the construction 3D printing technique to be used and the level of detail resolution that the project was considered to. I have defined the level of detail in three increments of resolution; course (formal design or shape), medium (resolution of large features, such as doors, windows, structure, modules) and fine (the resolution of joints, services, finishes)[77]. This definition will be used throughout this exegesis to discuss focus and issues relating to design for construction 3D printing.

The most widely published project that considers fabrication utilizing a construction 3D printing technique is by R&sie (Francois Roche, Stephanie Lavaux, Jean Navarro) and Benoit Burandin. The project is titled ‘I heard about’ (perhaps they also had trouble tracking down information on the Contour Crafting after hearing rumours of it as I did), was exhibited in Paris at the Musee d’Art Moderne de la Ville between July and October 2005 (refer images Figure 40).

“The urban structure ‘I’ve heard about’ is a habitable organism. It develops by means of adaptive, transitory scenarios in which the operational mode is uncertainty. It is written based on growth scripts, open algorithms”(Roche et al., 2005) p93

[77] The consideration of increments of resolution is used to assist with describing, categorising and comparing the projects.

The project was highly adventurous, applying bio-mimetic generative growth scripts and algorithms to create designs for a city of towers (Roche et al., 2005) (see images Figure 40). The project is essentially a grand scheme and manifesto for the future of building and architecture, which may only possible in 100 years or so when construction science catches up. The project focuses on the use of scripts and algorithms to generate an architectural DNA which can be in a constant of flux and metamorphosis. This re-envisioning of construction is loosely based around the combination of the contour crafting technique combined with the ‘Viab’ as described below (Figure 41 b).

“ ‘I’ve heard about’ takes homebrewing your own life as a basic principle and makes transfer a general rule - transfers from machine to machine, from machines to nature and from nature to machines. When the Viab, a self- construction robot and computational radicalization of a machine developed by Behrokh Khoshnevis(modelled on machines that produce prototypes quickly by building up layers with a wax jet) establishes a new construction paradigm, it implicitly establishes the use of biological models for the creation of machines (biomimetism) and explicitly re-establishes, through the intermediary of its own technological creations, the close link between each individual and their architec-tural environment.”(Roche et al., 2005) p16

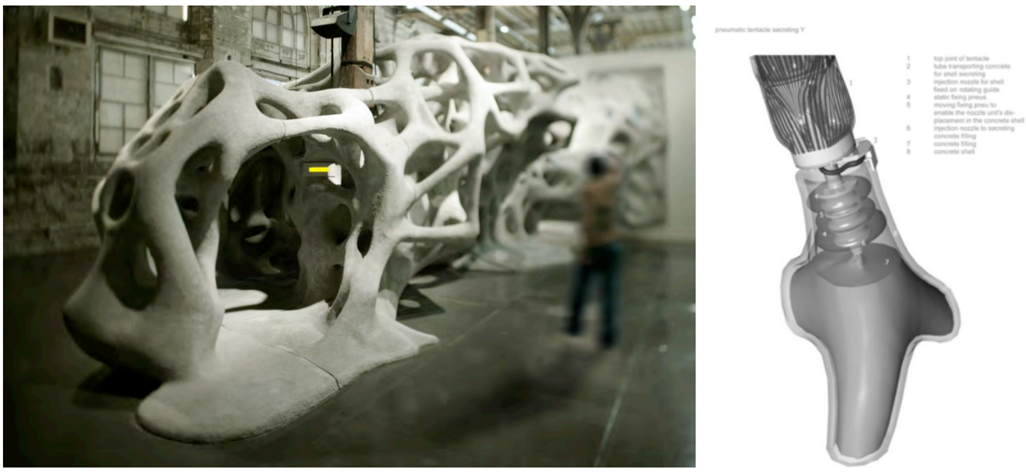

Figure 41 - I've heard about project by R&sie. (a) Hypnosis chamber. (b) Viab material deposition head diagram. Image source - http://www.new-territories.com/I'veheardabout.htm 10 June 2007

The ‘I’ve heard about Hypnosis Chamber’, also designed by R&Sie(n) and Benoit Durandin, was first exhibited the Modern Art Museum, Paris in 2005, was exhibited again in Singapore and Germany in 2006 and was re-fabricated for exhibition in Towada Japan in 2010. Although on face value the assemblage appears to be a full-scale demonstration of the contour crafting technique or combination of contour crafting with Viab, it is instead fabricated using CNC milling from large polystyrene blocks (Figure 42 b & Figure 43) which appears to be finished with a plaster or similar coating to make it look the part.

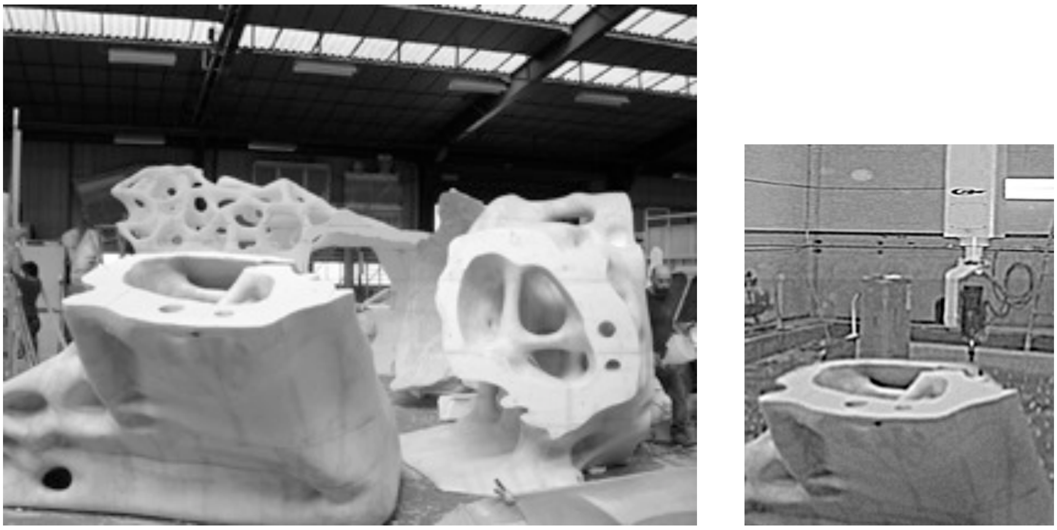

Figure 42 – (a) Large scale parts of the Hypnosis Chamber (b) Fabrication of the hypnosis Chamber sections using what appears to be CNC milling of polystyrene. Image source - http://www.new-territories.com/hypnosisroom.htm. 29 July 2011

Figure 43 - Hypnosis chamber detail. Plaster or similar textured finish. I've heard about project by R&sie. Image source - http://www.new-territories.com/hypnosisroom.htm. 29 July 2011

Despite my initial disappointment on discovering that the hypnosis chamber was a 1:1 mock-up[78] instead of the 'real deal' fabricated using contour crafting; the designs and models generated for the 'I've heard about project' and the hypnosis chamber are impressive. The use of generative algorithms and scripts (Roche et al., 2005) to generate the towers demonstrate a high level of capability in this area and exhibit how such tools can be used to generate highly complex geometries. The level of control that can be exercised over these scripts and algorithms is unclear, indeed control is probably antithetical to the stated aims of this project (Roche et al., 2005).

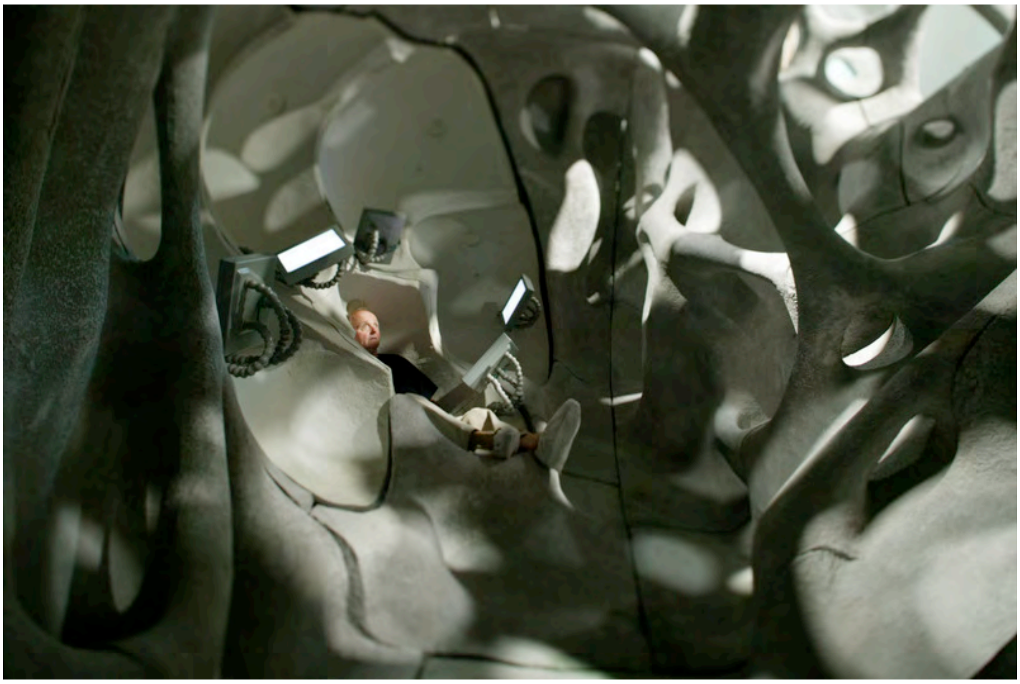

Figure 44 - Interior of the Hypnosis Chamber showing seating. Image source - http://www.new-territories.com/hypnosisroom.htm. 29 July 2011

It is unclear whether the same generative algorithms have been used to create the design of the Hypnosis[79] chamber, although the aesthetic language is very similar. The level of resolution for the design is through the scales of course to medium,

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[78] The contour crafting technique has not to date (August 2011) demonstrated the capability to fabricate 3D curved geometry.

meaning that the overall bone like trabeculae type structure has been generated and refined (course) and the design has been articulated with doorways (see image Figure 41 a) and internal seating (medium) (see image Figure 44).

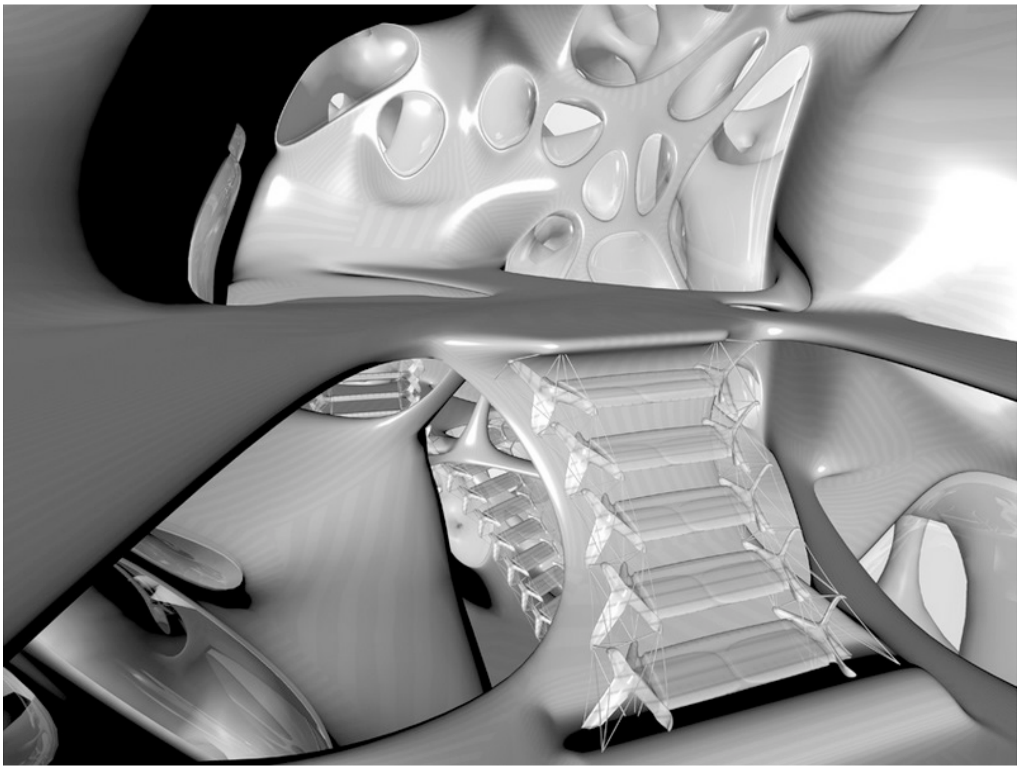
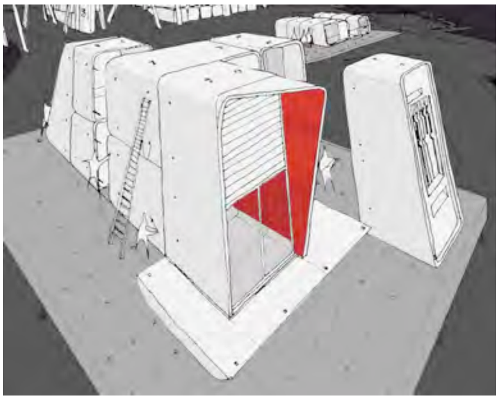


Figure 45 – Internal rendering Image source - http://www.new-territories.com/I'veheardabout.htm 10 June 2007

The level of resolution within the ‘I’ve heard about project’ is similarly mainly concerned with the course level or detail, with some examples of medium detail such as internal staircases without handrails (refer image Figure 45). The Fine level of detail is demonstrated only within the ‘I’ve heard about project’ in the design of the ‘Viab’ ‘self- construction robot’ (refer image Figure 41 b).

This fine level of resolution is required within functional architecture, such as housing and offices, to accommodate for human needs. Air seals to help control temperature, waterproofing between joints to keep people and possessions dry and integration of structural strategy and reinforcement, to ensure that the structure will remain as intended under live, dead and environmental loads (Salvadori et al., 1990). The fact that a fine level of detail was not demonstrated within the tower designs or the hypnosis chamber projects is consistent with the fact that the designs were not intended for construction and were speculative in nature, meaning that this level of detail expected in a completed project was not needed to demonstrate the concepts such as morphogenetic creation and transformation of urban environments (Roche et al., 2005).



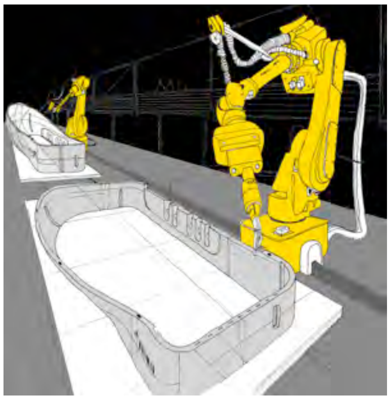


Figure 46 - Freefab project by James Gardiner (a) Module assembly on-site. (b) Production line fabrication

An earlier far less conspicuous project ‘Freefab Tower’ designed for my graduating project (Gardiner, 2004b) and published in future architecture (Spiller, 2008) was also designed in response to the emerging potential of construction 3D printing and specifically for a modified Contour Crafting™ technique (Figure 46 a & b). This project is presented as a case study in (chapter 4.1) and therefore will not be discussed here as a precedent.

In 2008 D-Shape™ commissioned the ‘Radiolaria’ Sculpture by Andrea Morgante (Figure 47 a & b), described as “*a proof of principle pavilion for a roundabout in the nearby town of Pontedera; a biomorphic eggshell named and designed after radiolarians, marine protozoa that produce intricate mineral skeletons*” (Abrahams, 2010).

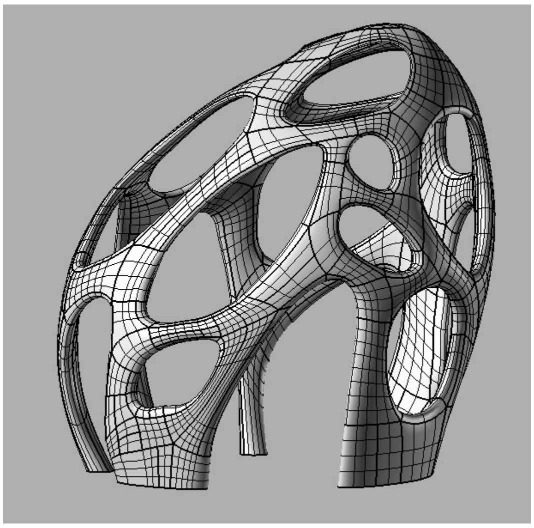


Figure 47 - (a) Radiolaria 3D model – image source http://www.solidsmack.com/fabrication/enrico-dino-3d-printed-structures-houses-Gaudí/ (b) Scale prototype of the Radiolaria – approx 1.8m tall. Image source James Gardiner

Blueprint Magazine quotes Morgante on his motivations for the design of the project

"*[Enrico] wanted something challenging that showed what the technology could do. I developed this model which I knew that in other construction techniques or methods would be either quite difficult or very expensive*" (Abrahams, 2010).

The design certainly achieved this aim and helped set the capabilities of D-Shape™ apart from those of Concrete printing™ and Contour Crafting™, being the first to demonstrate the fabrication of true 3D geometry with the D-Shape™ technique (as discussed in chapter 3.1.5).

The sculpture by Morgante demonstrates only the course level of detail in formal shape of the Radiolaria. The design of the Radiolaria was supplied by Morgante to Enrico Dini as a single shell object as per the image (refer Figure 47 a)[80]. For the scaled prototype fabricated in 2008 (Figure 47 b) D-Shape™, for the prototype, did not need to allow for object wall (shell) thickness, as the object was small

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[80] This was conveyed to me in discussions with Enrico Dini during my extended visit in August 2009, while considering strategies for assembly and reinforcement of the full scale Radiolaria.

enough to be fabricated as a solid. Prior to fabrication D-Shape added an external walled structure (refer image Figure 48 a) to the design file to assist with fabrication.

Figure 48 (a) Radiolaria scaled prototype after fabrication, note the external structure around the Radiolaria used to hold unconsolidated sand in place. Image source – D_Shape (b) Testing reinforcement and assembly strategy of D-Shape printed Radiolaria sections at D-Shape factory August 2009. Image source – James Gardiner

Moving on to full-scale fabrication of the Radiolaria after the prototype, the original file required further refinement, to reduce materials and weight and to allow for the fabrication of the structure efficiently. D-Shape™ was principally responsible for modification of the design file for 1:1 fabrication. The digital file was shelled (given a skin thickness of approximately 40mm) and broken down into slices (approximately at 500mm vertical intervals) for fabrication (refer to images Figure 48 b).

The first six pieces of the Radiolaria had been fabricated prior to my arrival in July 2009. After helping Enrico and Ricardo Dini to remove the pieces from the print bed (to ready the machine for printing my prototype column - refer chapter

5.2), we began to discuss strategies for how to create structural continuity between the pieces for the large Radiolaria assembly[81].

Figure 49 - Full scale Radiolaria assembly at D-Shape factory, Italy. Image source - Enrico Dini

The ad-hoc solution that we tested (refer image Figure 48 b) was to span the joints between the hollow Radiolaria pieces with lengths of rebar[82], then fill the pieces

[81] At the time of these discussions in July 2009 there was no clear strategy for how to reinforce the full scale radialaria.

[82] Rebar- Steel reinforcing bar

with D-Shape mix[83] so that each of the joints were overlapped by approximately 200mm. The exposed ends of the rebar would then be tied to the next lengths and the filling would continue. This strategy although workable at the small scale did not rely on calculation of loads to size the rebar nor take into account individual load cases of individual joints, as would normally be the case for projects of this size.

3.3. Digital design tools

This chapter is intended to focus on the application and potential of digital design tools rather than being about these tools: descriptions, definitions and some background information will be given to aid this discussion. The discussion here on digital design tools will be intentionally quite narrow. A broad description of the origins, types of digital design tools, the way they are used, applications and issues surrounding these tools will not be presented here. Contemporary use of advanced 3D digital design and analysis tools within and by architectural and engineering practices has been subject of recent discussion and description by others in recent times (Benton, 2008, Holzer, 2009, Shelden, 2002, Kolarevic, 2003).

This research is focused on the use of 3D digital design tools (instead of 2D tools) and largely focused on those tools that I have identified to have value, which may be transferable to design for construction 3D printing. This identification process has been carried out through literature review, professional exposure and personal testing of software.

[83] The D-Shape mix is the proprietary D-Shape material hand mixed. There were a number of mixes that we used at the time including cement and Styrofoam beads.

DDAA collated results Questionnaires

Aerospace	2	BA	
1	Catia V5		3D design to Manufacture
2	PC-DMIS		Generation of CMM (cordinate measuring machine) programs for inspection of parts)
3	mTMS		MRP system
4	Pro-engineer		Engineering Design
5	ANSYS		FEA Analysis
Aerospace	3	BO	
1	Catia V5		3D design to Manufacture
2	Delmia V5		
3	Quest		Discreet event analysis
4	Verisurf metrology		CMM for inspection of parts and assemblies (including planes)
5	Solidworks		3D design to Manufacture
6	Nastran		FEA Analysis
Shipbuilding	1	Ten	
1	Autocad		2D drafting
2	Inventor		3d Modelling of ships structure for production output (i.e. plate nesting data)
3	Ansys		FEA structural
4	Inventor		Assists Autocad & Shipconstructuor, faster tool for modelling detail and creating drawings
Construction	1	Seb	Con
1	Tekla		3D design
2	Steelproject		CAD to CAM
3	Fabtrol		CAD to CAM

Figure 50 - Collated list of digital design tools used by 5 companies. Chart by James Gardiner

I will briefly describe two broad kinds of digital design tools that I believe are pertinent to this research and why they are considered to be useful in the design for construction 3D printing. I will not describe some tools, such as Maya™ and Rhino™, as their application and usefulness is described within the case studies and further in the conclusion. As noted in (chapter **Error! Reference source not found.**) I am an architect and have had considerable exposure to 2D and 3D digital design tools during the course of my tertiary education and in my professional career.

The recent study of Parallel industry through the Delivering Digital Architecture in Australia research surveyed the types of software that each of the companies used at the time. Above is a listing (Figure 50) of some of those companies and the types of software they use. Note that there are three main types; 3D modelling tools, analysis and optimisation tools and tools used for automation of tasks. Some of the automation and modelling tools automate output for fabrication.

3.3.1. Adopting the digital definition as the primary work method

To understand the challenges and opportunities that present themselves when designing for Construction 3D printing techniques, one must first consider the current construction context and differences between the broad construction industry practices and the additive technique being introduced. The first and most obvious difference between current construction practice and construction using Construction 3D printing is the type of information required to fabricate building elements, Construction 3D printing requires principally three-dimensional CAD data in .STL format for translation to G-code[84] rather than 2D documentation.

Figure 51 - Thiess John Holland Facility in Victoria, DDAA research. Photo by James Gardiner

Within the Australian construction industry in 2009, only a tiny fraction of buildings or building elements are designed completely in three-dimensions or fabricated directly from three-dimensional data. In a the recent Delivering Digital Architecture in Australia comparative survey of construction and parallel[85] industries, it was found that leading representatives from the construction industry that use three-dimensional data, directly for fabrication, are clustered primarily in

[84] G-code or proprietary machine code, which is a layered translation of the three dimensional geometry, that takes into account machine movement, federates, material deposition, curing time etc.

[85] Parallel industries; Shipbuilding, Aerospace, Manufacturing and Automotive industries.

the metal fabrication sector (refer Figure 52). This trend was also confirmed in the international context, in an earlier international survey of construction and parallel industries[86].

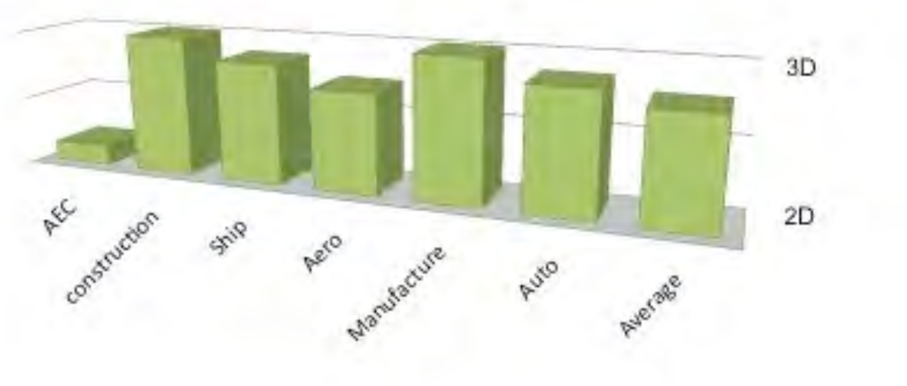

Figure 52 - Comparison between implementation in the use of 2D or 3D CAD within AEC, construction and parallel industries.

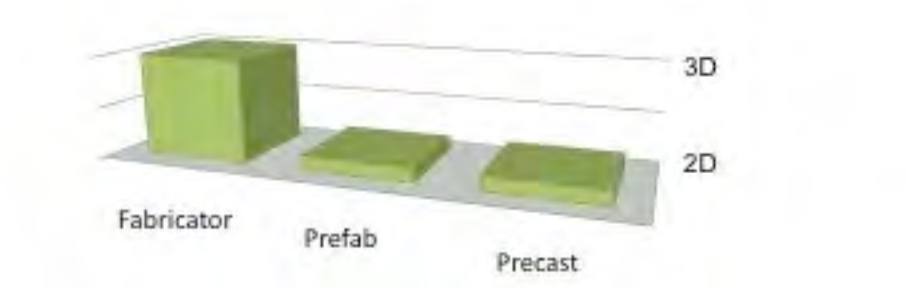

Figure 53 - Comparison within the construction industry in the use of 2D or 3D CAD. Note these three sectors were the only three sectors identified to use CAD data directly for fabrication, rather than relying on 2D drawings.

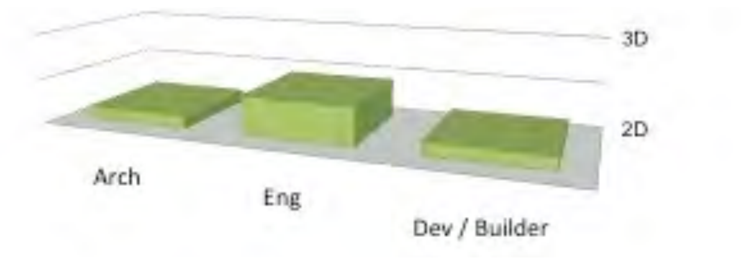

Figure 54 - Comparison within the AEC industry in the use of 2D or 3D digital design tools.

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[86] Byera Hadley and Jack Greenland international survey of construction and parallel industries 2006-2007.

Such direct fabrication using three-dimensional data is not however isolated to this sub-sector. 3D digital design data is being used increasingly by precast concrete companies, timber housing fabricators and others. Companies, including metal fabricators, create highly accurate 3D digital definitions primarily for their specific trade, with some modelling of interfaces between important secondary elements[87].

For example in the case of a steel fabricator, the complete steel skeleton of the building will be modelled in three-dimensions, complete with mitres, welds, bolt holes and element numbering. Interfaces between important elements such as connections with precast concrete elements or cladding systems will in some cases be modelled to ensure an accurate interface. The rest of the building will not usually receive the same treatment and instead be documented in 2D.

The reason for the uptake of 3D digital design software and implementation of it by steel fabricators is due to the competition within the industry and efficiencies gained (through the use of automated fabrication and its interface with 3D digital design tools). For example a beam line machine (automated cutting, drilling and welding machine) requires 3D digital input, software such as Tekla™ structures is designed to directly interface with beam line production, allowing a high level of automation directly from the 3D model.

Beyond this trade-specific 3D digital definition, the rest of the project will remain only partially documented, with standard and important junctions and details documented in two-dimensions[88]. This practice as described above, of partial documentation with some areas of full 3D digital design presents a problem for the construction industry, as the uptake of construction 3D printing will require in most cases complete 3D documentation. This shift in practice from partial 2D

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[87] Based on discussions with Australian precast and steel fabricators as part of Delivering Digital Architecture in Australia field interviews.

[88] Based on professional experience on a wide variety of residential, commercial and public projects.

documentation to full 3D documentation and creation of a digital definition model is beginning to occur within the construction industry and has already been replaced in aerospace and automotive sectors[89].

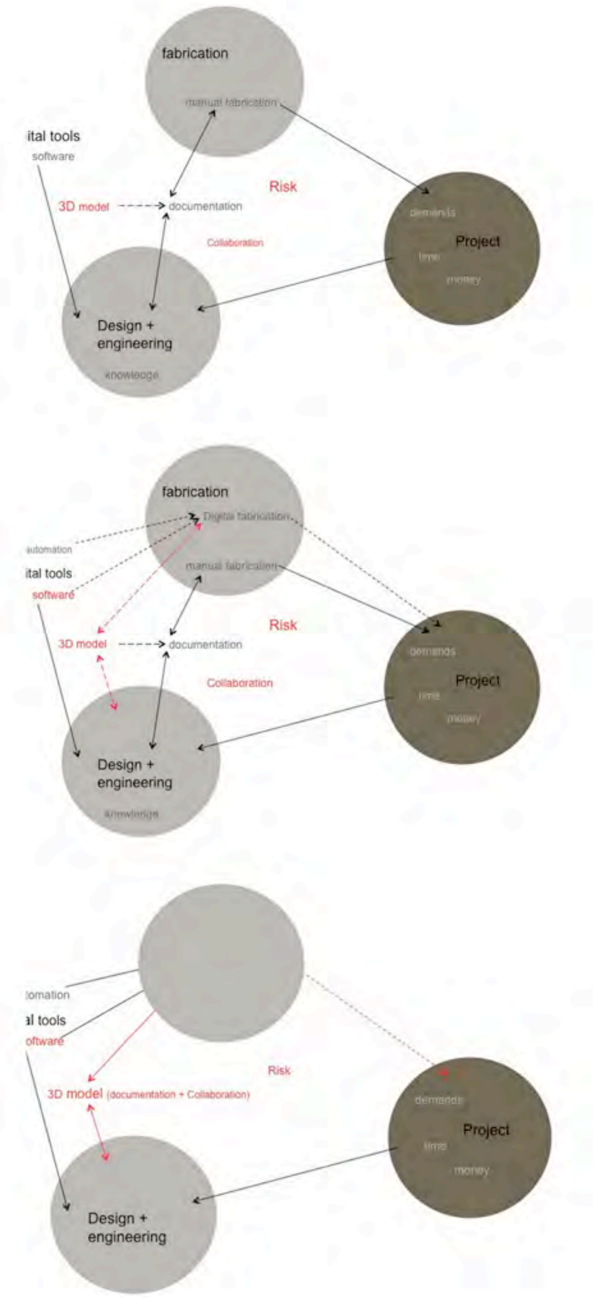

Figure 55. Design to fabrication loop. Top - Predominant use of 3D data in construction. Mid. - Leading companies in construction. Bottom – Current aerospace industry and the future of construction with Construction 3D printing.

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89 Based on Delivering Digital Architecture in Australia surveys and discussions.

Within the parallel industries, which differ significantly from the construction industry in product type and organisational structures, there is a much greater uptake of the practice of using three-dimensional data directly in fabrication processes. A number of aerospace companies interviewed now rely almost entirely on three-dimensional data throughout their company activities: tendering, design, engineering, analysis, production and maintenance[90]. The methodologies used currently within aerospace are applicable to Construction 3D printing, although this requires a significant shift in project team collaboration and organisational procedures from those currently used in the construction industry.

Greg Lynn stated in regard to the shift in focus to digital design tools "*issues of force, motion and time, which have been perennially eluded architectural description due to their "vague essence," can now be experimented with by supplanting the traditional tools of exactitude and stasis with tools of gradients, flexible envelopes, temporal flows and forces*"

and Lynn goes further to describe how these elements of force, motion and time are described within software

"*there are three fundamental properties of organisation in a computer that are very different from the characteristics of inert mediums such as paper and pencil: topology, time, and parameters*" (Jencks and Kropf, 2006) p329. These three issues of force, motion and time are to varying degrees explored within the case studies projects to follow organisational mediums have been used to varying degrees within the projects described later in the

3.3.2. Parametric tools

I have selected parametric tools for discussion here due to their demonstrated capability (Burry and Burry, 2006, Shelden, 2002) to deal with high levels of both

[90] DDAA op. cit.

geometric and organisational complexity, while allowing for manipulation and change with relative ease.

Holzer states '*Designing with the use of parametric values defines a way of structuring geometrical entities through associative variables, relations and dependencies*' (Holzer et al., 2007).

Through the definition of such 'variables, relations and dependencies' within a parametric model, the digital definition can respond to a large number of parameters and inputs to produce an outcome that may not, in some cases be, predictable. Unlike 'variational' models', which BIM software predominantly generates, parametric models can define a flexible sequence of operations, this flexibility in the sequence of operations can play a dramatic role in defining the geometric outcome (Shah and Mantyla, 1995).

There are a number of benefits to this approach, which can be listed as the following:

Flexibility - Geometry generated using this parametric software has a degree of flexibility; i.e. if the number, size and height of the columns change, the model will be updated reflecting these changes with very little or no re-work, which promotes a greater degree of variation and testing. However if a new parameter is needed to be added, that changes the way the model works, the whole or part of the model may need to be redefined from the beginning.

Responsiveness - can be integrated into the digital model and this responsiveness can be used to flexibly respond to a range of inputs, which may vary as the project develops. Burry states 'one of the principal aims of parametric modelling is to defer design decision making to be able to progress many impacting aspects of the design in parallel' (Burry and Burry, 2006).

Complexity – Complexity (not necessarily geometric complexity) can be accommodated relatively easily within parametric software packages such as Digital Project™ and Generative Components™. This accommodation of complexity within parametric tools can allow for a large number of variables to be included within the model, while each of these variables can easily be change or respond. The first two stated benefits can be considered efficient and beneficial for design and documentation, however when combined with the third benefit of complexity, they become exponentially more important as complexity increases and the time to rework a model made by other means increases.

I consider that one of the key methods to exploit the capabilities of construction 3D printing techniques is through taking advantage of the capabilities of digital design tools such as parametric software. Construction 3D printing techniques rely completely on the 3D digital definition (unless you create the G-code manually) to define the object to be fabricated. Therefore the capability of the digital design tools used are paramount to: the efficiency with which the object is created, the flexibility of the digital definition, the type of geometry and complexity of the model and the level of definition within the file (e.g. accuracy and surface texture/finish).

3.3.3. Optimisation tools

The use of optimisation software tools is wide spread within a number of industries such as IT, aerospace, manufacturing and is now beginning to take hold within the construction industry. The applications for software optimisation are also extremely broad with applications within the construction industry such as construction sequencing, passenger lift control and reinforcement bar sizing/location within precast panels. As architecture, engineering and construction continue to increase their reliance on digital tools the opportunity to overlay and integrate software optimisation tools into design and fabrication also steadily increases. The identification of the opportunities and benefits of using these tools within the construction industry is only just beginning in comparison to other industries such as aerospace.

Manual methods of structural optimisation have been in existence for many centuries, one example of this is the use of the hanging chain to predict catanery curves used to create stable compression structures. This method of manually predicting optimal structures was first used by Hooke in 1675, then adopted for highly complex structures by Gaudí and then further developed by Otto (Larena, 2009). Software has been developed since the 1960 is a number of fields to find optimal solutions to complex problems. Specific software has been developed for a number of fields, especially the aerospace and automotive industries (Herskovitz, 1995), which can optimise designs for specific forces or load cases.

I will use the term optimisation here in a general sense to encompass a group of software programs that; analyse, generate, kill, evolve and respond to input data to create or change 3D digital spatial objects. There are a large number of different tools available that perform different functions in different ways, overlaid onto this are many different terms, which creates confusion for a non-technical user like myself (refer image Figure 56). The issue at hand is to find ways to use digital tools effectively to analyse data and create solutions, to one or a set of problems, that would be difficult for designers to effectively negotiate on their own.

"*AEC practice today typically generates and analyzes a very small number of design options before choosing a final design. Design theory argues this leads to underperforming designs. The aerospace industry has overcome similar limitations using PIDO (Process Integration and Design Optimisation), resulting in improved processes and product performance. For the AEC case study presented, we found that PIDO enabled orders of magnitude improvements in the number of design iterations compared to conventional methods.*" (Flager et al., 2009)

Parametric and other digital design tools can be used to respond and optimise certain aspects of a design, through the use of routines, scripts, plugins, data mining, algorithms etc. Herskovitz describes the purpose and some of the methods used for software based optimisation.

"*Modern design techniques seek the best design to perform desired tasks. Structural Optimization deals with the optimal design of structural elements and* *systems….These tools integrate CAD tools for geometric modelling, general analysis methods, like finite element method and methods of design sensitivity analysis with mathematical programming or optimality criteria methods*"

Arup have developed and used custom optimisation tools paired with parametric software in this way:

"*on the Aquatics Centre project for the 2008 Beijing Olympics, without a new automated approach to selecting section sizes and checking them to design codes for all 25 000 steel sections, it would not have been possible for the team to find a working solution, and one that was near the targeted roof weight.*" (Luebkeman and Shea, 2005).

Although there are a plethora of different software types, methods used and forces accommodated, I will limit discussion to topology optimisation tools; although the use of responsive, evolutionary, generative and other such tools are also considered to have great potential. Discussion here focuses on standalone software, although the opportunities and benefits that I discuss here can be achieved through a range of methods. It is the result of the optimisation that is important to this discussion, not the means by which it is achieved.

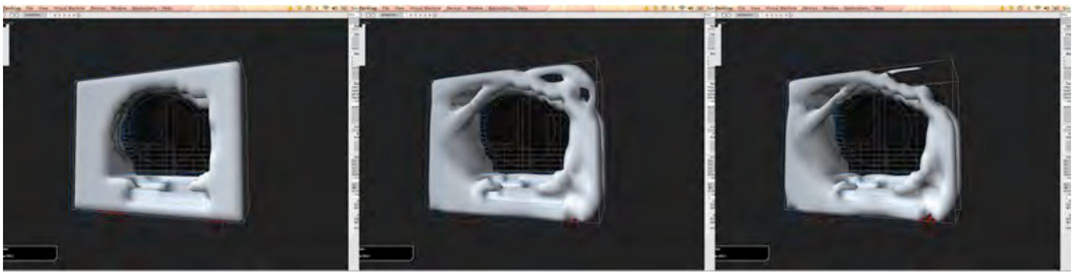

Figure 56 – Topostruct™ test on a shell structure. Image by James Gardiner

"*CDO* (computational design optimisation) *builds on and incorporates other emerging design computing technologies, including algorithmic design, 3-D parametric and associative geometry, performance-based design, integrated design tools, and design automation.*" (Luebkeman and Shea, 2005)

Optimisation software has been used since the 1960s with Kurokawa and experimenting with the application of tools for architectural applications. Kurokawa experimented with the use of computers for multi-criteria optimisation for the configuration of spatial units within the Toshiba IHI pavilion designed between 1967 and 1968:

"*A computer was used to select from five different types of 'tetra units' to meet various different functional requirements, and these were combined to create a 3 dimensional space frame*" (Kurokawa, 1992) p11

This work is likely to have influenced John Frazer's evolutionary and generative experiments in his award winning work at the Architectural Association (AA) in 1969 (Rattenbury and Lawrence, 2010). These experiments and the work of many others have seeded the creation of a large number of tools with highly variable working methods, objectives and outcomes.

Frazer in introducing the field of generative and evolutionary tools (which includes optimisation) stated:

"These techniques had previously been limited to easily quantified engineering problems. Only now is it becoming feasible to apply them to the complex problems associated with our built environment. To achieve this it is necessary to consider how structural form can be coded for the utilisation of genetic algorithms, how ill-defined and conflicting criteria can be described, how these criteria operate for selection, and how the morphological and metabolic processes are adapted for the interaction of built form and its environment." (Frazer et al., 2002)

Reading into this statement it would appear that parametric software is really just a subset, be it one that requires explicit interaction, of generative and evolutionary tools.

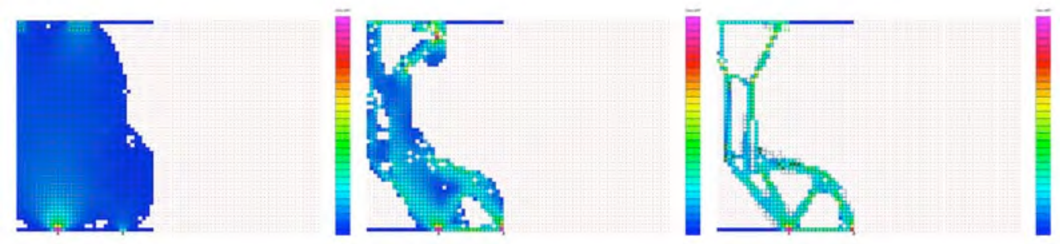

Figure 57 - ESO™ two-dimensional optimisation of an asymmetrically loaded column using software courtesy of the Innovative structures group. Image by James Gardiner 2008

A subset of these optimisation tools is structural topology optimisation techniques. These tools have been developed by a number of universities and individuals around the world, such as the Department of Mechanical Engineering, Technical University of Denmark (Bendsoe and Sigmund, 2003), Innovative Structures Group, RMIT University Melbourne (Huang et al., 2006), Sawapan in Japan (Michalatos and Kaijima, 2009).

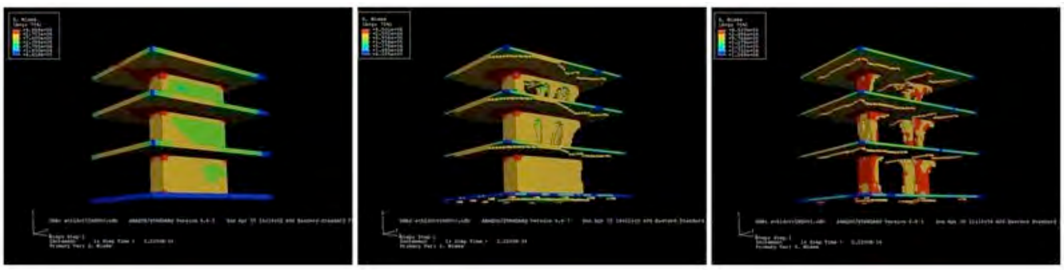

Figure 58. – BESO™ optimisation tests on a cantilevered 3-storey building using software courtesy of the Innovative structures group. Image by James Gardiner 2009

My interest in these tools is for their 3D capabilities and ability to find new topologies (structural envelopes), through the removal of material, in a process that reveals load transfer between loading and support, finding form that reflects the forces acting on the structure. Such tools can be used to optimise structures with a variety of load cases and boundary constraints within a design domain. A model can include ‘non-design elements’ which will not be modified in the optimisation process, such as floors in a building (refer image Figure 58).

Bi-directional structural optimisation (BESO™) was developed by the Innovative structures group at RMIT University (Huang et al., 2006). BESO™ is paired with Abaqus™[91] a finite element analysis software (FEA), with the BESO program running like a script with Abaqus™. The software program Abaqus™ analyses material stress levels at each step of the optimisation process, the data created is processed by BESO™ to define whether material is added or subtracted in each iteration of the optimisation process (Huang et al., 2006) (refer image Figure 59).

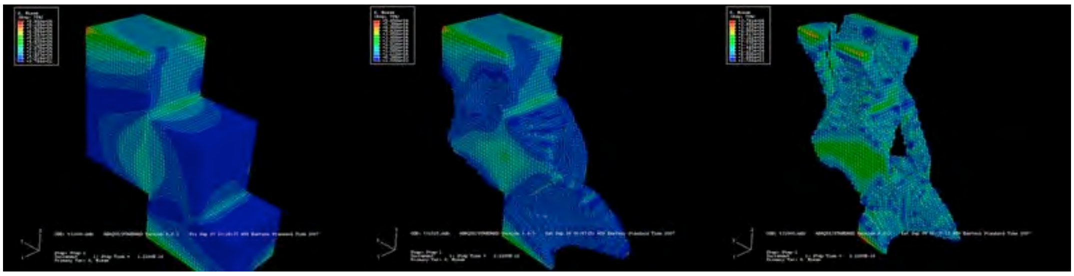

Figure 59 –BESO™ Test column. Image by James Gardiner 2008

Figure 60 - Topostruct™ optimisation test for Villa Roccia 2009

The use of structural optimisation software should result in structures that are materially efficient, though the result is usually more complex to build with conventional construction practices. For construction 3D printing the primary cost factors are build time and material usage, regardless of geometrical complexity.

Topology optimisation is therefore suited for combination with Construction 3D printing techniques, as complex non-Euclidean geometries (refer image Figure 60) can be fabricated using Construction 3D printing techniques without the cost

[91] Abaqus, Dassault Systemes. http://www.simulia.com/products/abaqus_fea.html

penalties that would be incurred using conventional construction techniques; such as forming concrete, bricklaying or using frame and cladding systems.

The additive manufacturing research group (Loughborough) has also investigated the potential implications of Construction 3D printing on wall panels. The image indicates a multi-material Construction 3D printing process (which is hypothetical), although the additional materials could potentially be added as a separate process (refer image Figure 61). The authors (Pasquire et al., 2006) indicate that this wall could be designed to respond to multiple criteria such as acoustics, thermal and ventilation requirements with a single fabrication method rather than relying on traditional procurement methods for a double skin wall which would require multiple trades.

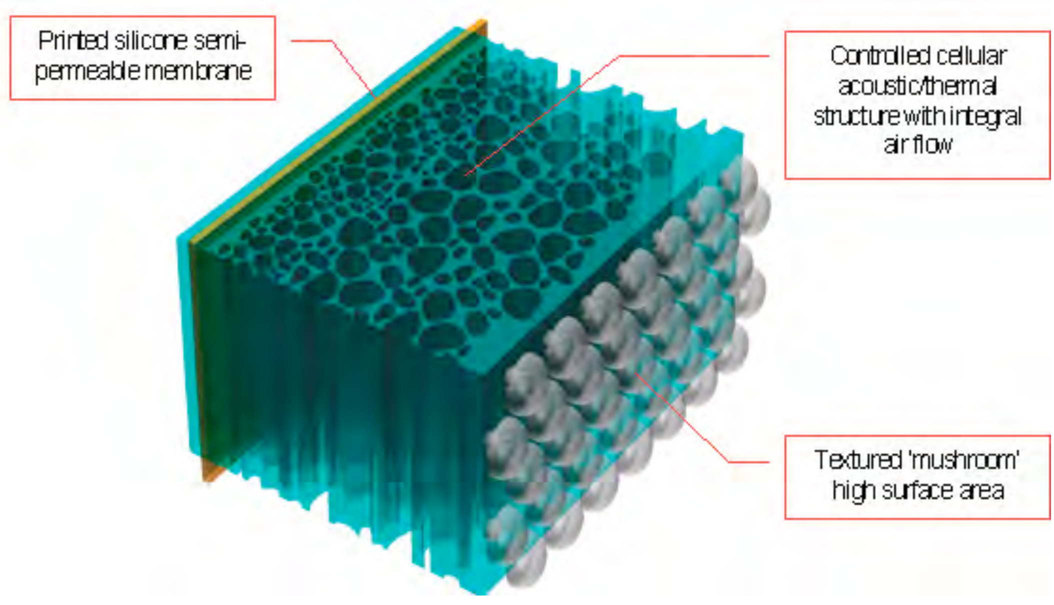

Figure 61 - Homeostatic Wall Panel. Image courtesy of Rupert Soar.

Topology optimisation techniques offer significant opportunities in the future for the development of designs, which are highly calibrated to, calculated loads, at the building scale and also at an elemental scale such as internal structures of columns or walls, which will be demonstrated in case study 2.

For example (Figure 62 left) below illustrates a fairly conventional multi storey building, which is then run through BESO optimisation, (Figure 62 mid) illustrates an early stage within the optimisation and (Figure 62 right) illustrates the optimised structure, based on the rejection ratio of 90%. Meaning 90% of the meshed design elements had been removed prior to the oscillatory state is reached "when a group of elements are removed and added back to the structure in successive iterations". (Huang et al., 2006). This raises an issue with the BESO technique, the program is primarily useful for determining optimal topologies, rather than determining the optimal topology and material required based on optimal material loadings, a much more complex issue[92] and one which will be extremely useful in the future.

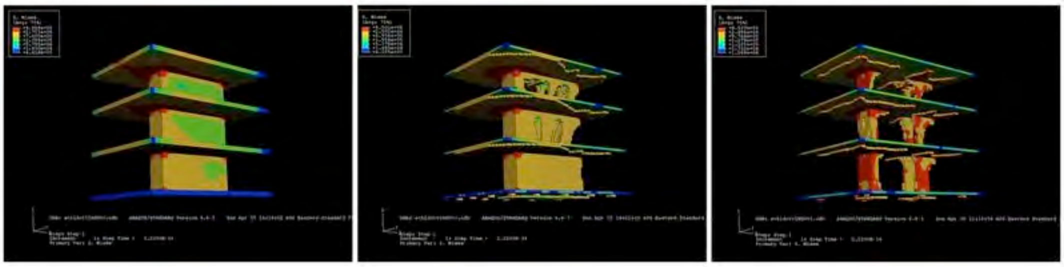

Figure 62 - BESO™ optimisation tests on a cantilevered 3-storey building using software courtesy of the Innovative structures group. Image by James Gardiner 2009

Optimisation tools are widely used by engineers within the construction industry today; for example in the design of the 30 St Mary Axe project[93] by Foster and Partners. The design of the project was optimised at a number of scales during the design of the project, especially in relation to its shape (Abel, 2004). The critical difference to the use of optimisation tools used within this research and in 30 St Mary Axe project is the use of topographic structural optimisation to suggest the form for the project envelope(s) rather than for tweaking it for other purposes.

It is important to note here is that optimisation tools are used within the framework of this research as a tool, within a broad range of tools and processes used to generate solutions. Optimisation outcomes are considered as a guide rather than the solution. In considering performance in this context it is:

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[92] Discussion with developer of the BESO software, Xiaodong Huang, RMIT University

[93] This project has also been known as the 'Swiss Re' and commonly called the 'Gherkin'.

'Based on multi parameter effectiveness rather than singe parameter optimisation and efficiency, must from the start of the design process include both the logics of how material constructions are made and the way they interact with environmental conditions and stimuli.' (Menges and Hensel, 2008)

In this light although optimisation tools are used, there are many other factors under consideration. The architect in many ways can be considered to do multi-criteria optimisation; through the consideration, evaluation and development of hierarchical decision making processes in the development of a design.

The benefit of this approach is that the type and topology of structures that result from this process are not predictable. Simple or complex geometries defined with loads and support cases can be calculated that result in structures that can be highly complex without significant repetition. Fabricating such complex structures would be uneconomical using conventional construction techniques for a number of reasons: such as a lack of conformity within the resulting geometry to standardised building materials, the requirement to use repetition[94] to minimise the number of unique elements within a project and the labour required to fabricate such structures. As mentioned above Construction 3D printing techniques have the capability to fabricate such complex structures, largely free from these constraints, therefore the pairing of optimisation tools for design for construction 3D printing increases the potential application for both construction 3D printing and optimisation techniques.

The benefit of using such optimisation tools is in the direct calculation of specific local inputs on a design and the subsequent generation of optimal or near optimal solutions that can lead to efficient, honest (in the revealing of these forces through form) and in many cases beautiful structures. The second benefit is that optimisation tools (of all types) opens a new area of exploration within architecture and one when paired with construction 3D printing offers what I

[94] This requirement for repetition is significantly reducing with the implementation and significant leveraging of the potential of CAM techniques.

believe to be the largest shift in design to fabrication since the industrial revolution.

After briefly introducing specific digital tools and the potential benefits of combining them with Construction 3D printing techniques it is now appropriate to consider the methods which can potentially assist with realising the potential of Construction 3D printing techniques.

3.3.4. Interoperability

The term interoperable or interoperation, for the purposes of discussion here, means the capability for digital design tools to send and receive information to and from other digital design tools without data loss and to have access to that data in a format that is easily useable for the tasks that the digital design tool needs to perform. For example interoperability would be present if a model of an column structure transferred from Rhino™ could read and usable within Topostruct™ without further change.

The issue of interoperability was discussed extensively in interviews initiated through the Delivering Digital Architecture in Australia research project and the issue of interoperability was found, from analysis of the transcribed responses, to be of great importance. Such interoperability issues were said to be responsible for major design and fabrication issues on the Airbus A380.

“It is generally recognized that within the aerospace industry that the reason why the A380 was late was due to bad data translation processes.” Aerospace engineer

Designlink™ is an excellent approach to this issue, through its modular approach to translation and interoperability. Development of translators is done as discreet modules made for specific software and digital design tools to talk to the central Designlink™ software, rather than between digital design tools. This means that if a translator is made for Rhino™ to talk to Designlink™ then when a translator is developed for Topostruct™ to talk to Designlink™, the two programs

Topostruct™ and Rhino™ should be able to pass information between each other through the central hub of Designlink™. (Holzer, 2009)

As will be demonstrated within the case study projects 1, 2 & 3 multiple software tools have been required to complete the wide variety of tasks, necessary within the projects, to achieve the desired design outcome and enable fabrication. For example these tasks include modelling of the external envelope, checking of tolerances and dimensions, creation of space filling geometries, splitting of elements and the creation of joints, joining of elements and fixing of errors prior to output of 3D printing. At present there is no single software tool that can perform all of the tasks listed above, therefore a level of interoperability is required. The level of interoperability and ease within which transfer of data or digital definition data can be achieved, between digital tools has factored significantly in deciding which software tools to use in concert with others. Software developers and venders have in many cases been slow to adopt interoperability standards such as IFCs[95] and often these standards can limit the capabilities of tools (Holzer, 2007). In some cases software being used new and/or experimental and so in many cases may only be able to output one file format, such as .dxf. The ideal situation is to choose the best digital tool for the task; this decision is often compromised by issues of interoperability. The Designlink™ tool has demonstrated an ability to by-pass or overcome the interoperability capabilities of specific software tools through the creation of translators as described above, this platform for interoperability becomes increasingly important as the task attempted moves further away from the industry modus operandi.

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[95] IFC – Industry Foundation Classes is a software platform independent format that is widely promoted as being the answer to interoperability. This file format achieves interoperability through the use of a standardised method of transfer and definition of digital definition information.

3.4. Construction Sustainability

To understand the challenges of construction sustainability, it is useful to understand some of the statistics for energy consumption within the construction sector. The Construction industry consumes much of the world's resources and produces approximately 30% of the worlds waste (Woudhuysen and Abley, 2004). It is also the most inefficient of the world's high capital industries(Kieran and Timberlake, 2004). To compound the problem, the products of this industry (buildings) are also wasteful and inefficient.

If the way we build can be fundamentally changed, huge gains could be made toward reducing our demands on resources and the environment and help our society move toward a sustainable future. The current rate of construction in China provides an alarming example where "more than one-half of China's urban residential and commercial building stock in 2015 is to be constructed after the year 2000"(Zhu and Lin, 2004). When you consider this statistic in reference to a population of 1.3 Billion people it is not difficult to realise that this is a global problem. Not only is this building boom consuming vast quantities of materials and energy, the houses that are built today to low sustainability standards will be consuming high levels of energy for decades into the future.

The UN climate change mitigation report states that for energy use *"there is a global potential to reduce approximately 29% of the projected baseline emissions by 2020 cost effectively in the residential and commercial sectors, the highest among all sectors studied"* (Mets et al., 2007).

To define sustainability one must consider where the terminology and thinking first emerged. The Brundlandt report, which is considered a preeminent and original source for the definition of sustainability, broadly defined the area more than two decades ago; *'Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs'* (United_Nations, 1987,Ch. 2.1).

This definition however is too broad for the purposes of this exegesis, as it includes all kinds of development.

'The satisfaction of human needs and aspirations is the major objective of development.....(including) *food, clothing, shelter, jobs'* (United_Nations, 1987,Ch. 2.4).

This report did however lay the foundations for understanding sustainability and from it emerged terms such 'triple bottom line assessment', based on the criteria of social, economic and environmental considerations outlined in the report.

It is therefore apparent that a more specific definition must be used to understand sustainability in terms of buildings, encompassing fabrication, operation, refurbishment and decommissioning. Construction sustainability is recently defined in the 'Sustainability in building construction' ISO standard as the

'state in which components of the ecosystem and their functions are maintained for present and future generations' (ISO, 2008).

Kibert goes into somewhat more detail by defining the principles of 'construction ecology' as "*buildings that (1). Are readily de-constructible at the end of their useful lives; (2) have components that are decoupled from the buildings for easy replacement; (3) are composed of products designed for recycling; (4) are built using recyclable, bulk structural materials; (5) have slow "metabolisms" due to their durability and adaptability; and (6) promote the health of their human occupants."* (Kibert, 2005)

However in my opinion Kibert's definition cannot be used as a complete definition of construction sustainability, as it conspicuously neglects a number of factors. These factors include: energy consumption in both processing of materials and fabrication of buildings, energy use through occupation, collection or recycling of valuable resources such as sunlight and water and the contribution to ensuring stabilisation or an increase in bio-diversity.

For the purposes of this exegesis the terminology ‘construction sustainability’ will adopt the definition of sustainability and be considered to apply to the following components:

Material use – raw and processed material inputs throughout the life of the building, sustainability of the resource, waste, recyclability.

Energy use – embodied energy of raw and processed materials, sustainability of the resource, fabrication of the building, operation of the building, decommissioning, capture of energy from the environment.

Air – pollution, recycling

Water – use, collection, waste and recycling

Bio-diversity – support and improvement of flora and fauna

Human factors – functional, thermal, acoustic, sunlight access, ventilation.

Reference to many of the items in the above listing will not be possible in this exegesis, but should serve as a guide to further consideration of the sustainability of construction, in reference to construction 3D printing. Construction 3D printing techniques are considered well suited to take advantage of virtual prototyping, analysis and optimisation techniques, due to their complete dependence on numerical data for deposition. An additional benefit is as David Rosen states

"*Since additive technologies only deposit or process material that will comprise the part (ignoring support structures), they are inherently efficient in their use of materials, particularly as compared to subtractive processes.*" (Beaman et al., 2004)

Construction 3D printing techniques have an intrinsic advantage over subtractive and formative processes in their efficient of materials, however there are other aspects to be considered when considering the potential sustainability of construction 3D printing. Many of the as characteristics of construction sustainability vary depending on the particular technique. The three construction

3D printing techniques described and analysed in (chapter 3.1.5) differ in the processes and the materials they use. As an example, the first iteration of D-Shapes technique used epoxy resins as a binder (Dini et al., 2008), this is in stark contrast to the inorganic binders used by the second iteration of the D-Shape™ technique (Dini, 2009). This difference in one aspect of the technique, the type of binder used, has implications to construction sustainability. Using epoxy resin instead of inorganic binders can be considered to effect: recycling of materials, water and chemical use through the increased cleaning requirements, minor air pollution through chemical off-gassing and embodied energy in the binder materials.

Therefore it is not good enough to say that construction 3D printing is superior for construction sustainability, due to the fact that it is an additive fabrication process and therefore produces less waste. A number of other factors need to be taken into consideration for the assessment of construction sustainability of construction 3D printing. Therefore each technique needs to be assessed individually to establish its own construction sustainability credentials. Consideration of the general construction sustainability aspects relating to fabrication, materials and process issues will be deferred pending individual assessment of techniques.

As discussed above however, construction sustainability relates not only to the fabrication process, the materials used in construction and the energy consumed to fabricate the building but also to the energy used in its operation after it is constructed. This aspect relating to the design of the building and its potential energy use (without taking into account the occupant habits) is an area where construction 3D printing could potentially make a significant contribution.

The implementation of ‘Passive design’, ‘Passive systems’ or ‘Passive strategies’ in building envelope and detailed design can dramatically reduce energy consumption and increase user comfort.

Jack Greenland in defining and describing thermal comfort of buildings:

“*one of the principle functions of any building is to modify the physical conditions in it and around it so as to make them more acceptable for the occupants in the performance of their various tasks*” (Greenland, 1998) p3/25

This definition can be applied more broadly to include solar comfort (management of glare and access to sunlight), acoustic comfort (management of noise levels from inside and outside of the building), humidity (keeping moisture levels adequate for humans and at levels where they do not cause issues with building materials or cause the growth of mould etc). Greenland further describes the means of achieving these goals as either passive or active:

“*A building should provide a controlled environment, and the means of achieving this are two fold…1. Passive control is achieved by the building itself through the appropriate disposition and treatment of its elements. 2. Active controls are mechanical systems and installations which consume energy…*” (Greenland, 1998) p3/25

The design of buildings, in terms of their operational energy requirements, is a key factor for addressing the challenges of construction sustainability. “*The largest savings in energy use (75% or higher) occur for new buildings, through designing and operating buildings as complete systems*”. (Mets et al., 2007) The method for achieving such energy savings relies on reducing the need for energy consuming active systems (such as air conditioning) and the reliance to a greater extent on designing a building to passively control its environment. Some examples of passive systems include: the use of thermal mass (which helps control the daily fluctuation of temperature within a building), the inclusion of fixed (or operable) sun shading designed to regulate thermal gain inside the building through the seasons, the use of insulating materials or materials that insulate through their arrangement (air cavities and voids), the inclusion of texture or surface articulation to dissipate sound reflection. (Greenland, 1998)

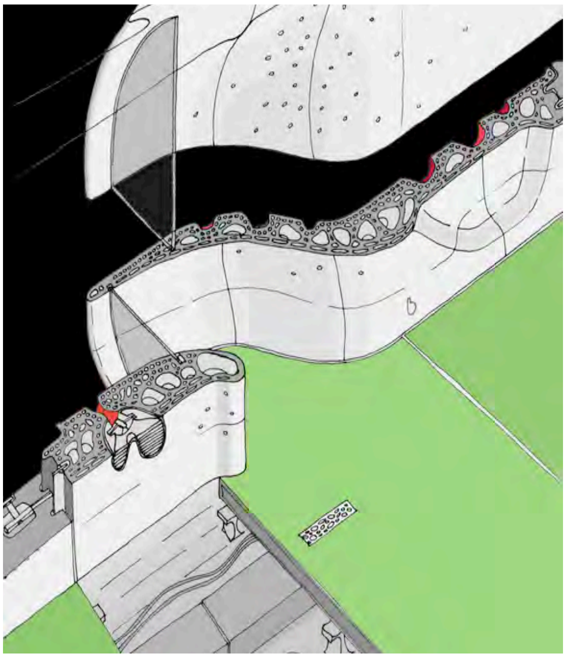

Figure 63 - Perspective showing potential benefits of Construction 3D printing techniques, including integration of passive thermal, acoustic and solar control. The integration of articulated integrally waterproof joints and the integration of services. Image by James Gardiner 2007

The adoption of ‘passive design’ principles cannot be considered standard practice by architects.

“*Only a few seem to actually consider that updating passive strategies to a contemporary technical context may be a very powerful opportunity for architecture to rethink its preferred spatial paradigm*” (Menges and Hensel, 2008) p49

The additive manufacturing group at Loughborough University has invested considerable efforts investigating the theoretical potential for passive environmental control with construction 3D printing (Pasquire et al., 2006, Godbold et al., 2007). Construction 3D printing, when it can demonstrate the ability to fabricate elements with a level of control that allows for detailed arrangement of materials (refer image Figure 63), has an inherent advantage over conventional construction techniques in its ability to fabricate highly responsive[96] passively designed buildings and elements (Gardiner, 2009, Soar, 2006a). Obviously the construction 3D printing technique can only fabricate, within its capabilities, what has been defined by the digital design tool and defined in the digital definition. The subject of passive design through design for construction 3D printing will be addressed in (case study 1). This potential capability to fabricate responsive buildings and building elements I believe will be one of the defining characteristics of construction 3D printing techniques and will be one of its 'added value' attributes.

I personally believe architects and the construction industry have a responsibility to respond to the global challenges that are present today and to look to alternative methods and procurement strategies for buildings in the future. As highly populous countries such as China rapidly develop and rebuild their habitable structures (Zhu and Lin, 2004), there is a very tangible need to ensure that sustainable building methods are adopted.

3.5. Methods

This sub-chapter will look at methods of construction (rather than research methods which are addressed in chapter 2.3). The method most important to this research is off-site fabrication and how this method of fabrication varies between industries. A brief summary of the development of off-site fabrication is presented, along with definitions of both the term off-site fabrication, as well as its sub-types. Differing practices are discussed from within both the construction and the parallel industries (shipbuilding, aerospace and automotive industries) as well as how off-site fabrication currently differs from standard construction practice.

[96] Responsive meaning here - as responding to the particular environment characteristic of the site; sunlight levels, temperature variation, noise levels, humidity etc.

As noted above within the sub-chapter (**Error! Reference source not found.**) I have discussed issues experienced first hand within the Australian construction industry, that are reflected in international reports focussed on the state on the construction industry (Egan, 1998, NAHB, 2001, Constucting_Excellence, 2005). The Egan reports called for a modernisation of the construction industry, citing the significant productivity, safety and quality gains of the parallel industries in recent years, and suggests off-site fabrication as one method among many to achieve this goal.

3.5.1. Off-Site Fabrication

Off-site fabrication is experiencing resurgence within the construction industry and importantly a renewed interest as an alternative to traditional construction practice by the press (Gerrity, 2011, Kaysen, 2011), public blogs (Koerner, 2011, Sylvester, 2006), government funded organisations (Venables et al., 2004), Museums (Bergdoll et al., 2008) industry professionals and academia (Fussell et al., 2007, Pan et al., 2005, Robertson and Ekholm, 2006). What is often not understood is that off-site fabrication, prefabrication and pre-assembly already permeates the construction and the parallel industries (automotive, manufacturing, shipbuilding and aerospace)(Gardiner, 2010).

Off-site fabrication has been defined in the index of terms (refer to definition chapter 1.5) a brief summary of this definition of; prefabrication, preassembly and off-site fabrication; have been included again here for the continuity of the chapter, as follows:

‘*Prefabrication is a manufacturing process, generally taking place at a specialised facility, in which various materials are joined to form a component part of the final installation*’ (Gibb, 1999a) p1

and

“*Pre-assembly is a process by which various materials, prefabricated components and/or equipment are joined together at a remote location for subsequent installation as a sub-unit. It is generally focused on a system*” (Gibb, 1999a) p1

The term ‘off-site fabrication’ is used within this exegesis to describe a broader practice, as defined here again by Gibb: “*Off-site fabrication is a process which incorporates prefabrication and preassembly. The process involves the design and manufacture of units or modules, usually remote from the work site, and their installation to form the permanent works at the work site.………off-site fabrication requires a project strategy that will change the orientation of the project process from construction to manufacture and installation.”* (Gibb, 1999a) p2

This section of the exegesis will focus on the historical background of off-site fabrication, important precedents and types of off-site fabrication. This section will not attempt to provide an exhaustive description of specific prefabricated projects as this has been covered extensively both by myself ((Gardiner, 2004a, Gardiner, 2010) these two documents are attached as appendices C & D) and by others (Gann, 1996, Gibb, 1999a, Davies, 2005, Bergdoll et al., 2008). Specific project examples will be referred to where appropriate to briefly describe practices within this section and in relation to projects in the case study chapters 1, 2 and 3.

3.5.2. Development of Off-Site Fabrication

There is little consensus amongst commentators on the origins of the offsite fabrication or prefabrication (Davies, 2005, Bergdoll et al., 2008, Gibb, 1999a); this lack of agreement appears to relate largely to the differing terms used and the particular definitions employed by the various authors. The development of off-site fabrication has been the gradual aggregation of the three elements (object, location and methodology) that have together formed what is defined as ‘off-site fabrication’.

Figure 64 - Joseph Paxton's Crystal Palace. Drawing of the assembly of industrialised components. Image source - http://ww3.barrington220.org/bhs/fine_arts_folder/AStevenson/Interrelated_Arts/EngineeringArchitecture.htm Access date 25th August 2011

Gibb cites that the ‘highly prefabricated structures’ can be dated to the roman era with the production of many of the early structures used for hospitals, barracks and defensive structures due to remoteness of outposts and conflicts and the need for armies to move regularly taking these structures with them (Gibb, 1999a). The British Empire and other colonial powers began shipping buildings around the world in the 19th Century, these building were often constructed entirely of iron, flat packed and ready for assembly in India, Australia or other colonies (Davies, 2005).

The ‘industrialization’ which can be said is the most important methodology incorporated into off-site fabrication, first occurred with the production of Sir Joseph Paxton’s ‘Crystal Palace’ built in 1851 (refer image Figure 64), which employed both a systematic approach to the design of the building elements for mass production and on-site assembly (Frampton, 1997).

“*The crystal Palace was not so much a particular form as it was a building process made manifest as a total system*” (Frampton, 1997).

This visionary achievement became an important precedent for 20th century industrialization and prefabrication within the construction and parallel industries. The early 20th century was a time of great optimism for the benefits of industrialisation and prefabrication. Many of the most prominent architects of the 20th century experimented with prefabrication in one form or another including Frank Lloyd Wright, Ray & Charles Eames, Walter Gropius, Paul Rudolph, Kisho Kurokawa, Moshe Safdie and Richard Rogers etc., yet none have been successful in delivering a cost effective, repeatable and scalable product to a large market. (Davies, 2005)

Figure 65 (a) Eames Case Study House by Ray and Charles Eames (b) Nagakin Capsule Tower, Tokyo, Japan by Kisho Kurokawa. Photos by James Gardiner

Buckminster Fuller[97] designed the Dymaxion house in 1928 (Figure 66) and Dymaxion bathroom in 1936, both were visionary pre-fabricated products.

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[97] Buckminster Fuller was not an Architect but is one of very few contemporary non-architects to be inducted in to the hall of fame of celebrated architectural history.

"*the space was divided like a cake into five slices – living room, two bedrooms, kitchen and entrance hall – by fat radial partitions that contained revolving storage devices*" (Davies, 2005)

Fullers prefabricated housing was never embraced by the mass market, as the product was considered to have "*no concern whatsoever for the idiosyncrasies of any given context and projected his house as though it were a prototype for serial production*". (Frampton, 1997)

Figure 66 - Dymaxion House by Buckminster Fuller Image source - http://sahstudytours.wordpress.com/2009/01/22/home-delivery-part-i-a-story-of-scientists-inventors-and-architects/ Access date 25th August 2011

The above example illustrates the problems of trying to apply mass production concepts, of repeated identical products, to the housing industry; which is widely considered to require a specific site response, not to mention an opportunity for individual expression. Le Corbusier wrote in 1931 that "*the right state of mind for living in mass production houses*" was needed. It is now evident that society does not want to adapt to mass production housing, as is evidenced by the rejection of much of the post war housing of the 60’s and 70’s. Mass production housing and off-site fabrication will change for us, as other industries have learned to accommodate choice into their production systems. ‘Mass Production housing’ will become ‘mass customised housing’.

The other of Fuller’s designs, the modular Dymaxion bathroom proved to be a precursor for the future of Modular bathrooms, developed and popularised by Toto (TOTO, 2011) now ubiquitous in Japan. Modular bathrooms are also commonly found in cheap hotels in Great Britain, especially London and parts of Europe.

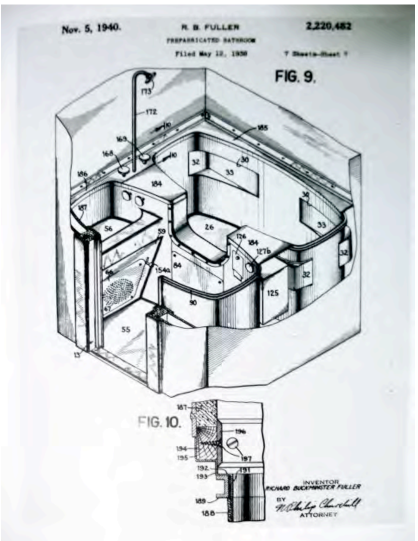

Figure 67 - Dymaxion bathroom designed by Buckminster Fuller image Source - http://www.scene.org/~esa/search/dymaxionpatents/dymaxion_patents.htm (b) Unit bathroom Japan Image source - http://www.dannychoo.com/post/en/817/Unit+Bathroom/ Access dates 25th August 2011

3.5.3. Types of Off-Site Fabrication

There are a wide variety of terms used to define the sub-categories or types of off-site fabrication, which are often defined by how they are used, transported, made of and even the codes under which they are governed. Such terms as relocatable, manufactured, system built, double-wide (transportation), HUD (US national HUD code, often also called a ‘trailor’), volumetric, sectional, pre-cut and Modular building. To aid clarity sub-groups are defined here based on the product or assembly delivered to site, the terms defined here; stick & panel, panelised and modular, are in common use in the USA, and have been chosen because they are easily understandable and largely self-explanatory.

Other authors define types of prefabrication differently; such as (Gibb, 1999a) who also defines three groupings; Non-volumetric off-site fabrication, Volumetric off-site fabrication and Modular building. This definition however is not particularly clear or self explanatory; with the last two groups both defined as 'enclosing space' with the difference between the two resting on whether the objects are load bearing or not.

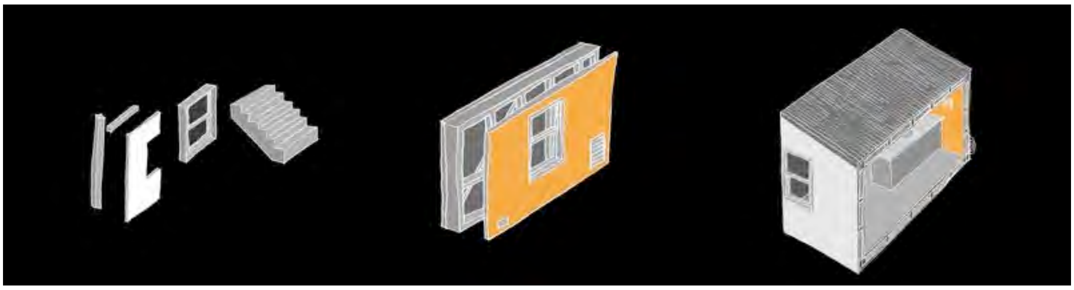

Figure 68 - Diagram three types of prefabrication: (a) stick & panel, (b) panelised and (c) modular. Image by James Gardiner

Stick and Panel

The use of industrially produced standardised products in buildings today is universally embraced by the construction industry and no longer considered prefabrication[98] but instead stick and panel (refer image Figure 68 a) has become standard construction practice. The group is defined by the use of standardised components that are often regulated by international or national standards (governing the standardisation of sizes, performance, tolerances, finish, composition, and in some cases material origin). Such elements include items such as; plywood, bricks, concrete, glass, steel and pre-cut timber.

[98] Note that the Crystal Palace mentioned earlier is considered the canon for the introduction of prefabrication and industrialised building methods. The Crystal Palace both used industrialised products and is still considered an example for modern prefabrication.

This definition of Stick & panel here refers to; the pre-processing of industrial elements to reduce on site labour. For example the use of; structural steel sections cut to size with welded connections, window assemblies, timber panels cut to size ready for installation.

Panelised

There are two main variants to this definition that can be labelled Precast and Composite. Precast (Figure 69 a) is the term used for panels that have been formed or cast, usually in concrete, off-site for rapid assembly on site. Precast panels will often include conduits and other services installations, that usually also require additional work on site, such wiring and finishing[99]. The composite panel (Figure 69 b) includes, in its most basic form, at its core either a structural internal frame, usually of timber or Steel or a substrate such as a foam panel. Sheeting material is then fixed to the surface of the frame or sheet. Such composite panels will usually include insulation as an additional layer or in the case of SIPS panels[100] the foam constitutes this insulation layer.

Figure 69 - Skanska Precast concrete panel factory in Stragnas, Sweden. Composite panels of timber and plasterboard being lifted into place on site in Stockholm, Sweden. Photos by James Gardiner

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[99] Based on direct personal experience; including observation of works at precast factories in Australia and in Sweden and in the design of panels for projects in Australia.

[100] SIPS is an acronym for ‘structural insulated panel’.

As is evidenced in this definition given by English partnerships of Panel Building Systems, there is a broad scope in the level of off-site labour with the use of panelised construction practices

"These comprise of walls, floors and roofs in the form of flat pre-engineered panels that are erected on site to form the box like elements of the structure that then require various levels of finishing. The most common approach is to use open panels or frames which consist of skeletal structure only with services, insulation, external cladding and internal finishing occurring on-site. Another system that is used frequently involves closed panels. These are more complex, involve more factory fabrication and may include lining materials and insulation." (Burwood and Paul, 2005)

The definition of panelisation can then be interpreted to be: The creation of panels that are cut size/profile, including openings such as doors or windows, which when assembled form buildings or building elements, these panels may include finishes, insulation, external cladding, services and sub-assemblies such as windows and finishes.

Modular

Again definitions and terms vary widely "*A method of construction that utilizes pre-engineered, factory-fabricated structures in three dimensional sections that are transported to be tied together on a….site*.[101] Gibb defines Modular Building as; "*unit that form a complete building or part of a building including structure and envelope. Most units are again substantially complete in themselves, leaving only a small amount of work to be completed on-site. However some systems, especially for multi-storey construction, provide only the structure and sometimes cladding, and are then finished on-site*". Neither of these definitions are particularly clear about what the include and in some cases are too specific and would hence exclude a wide variety of slight variations through the explicit reference to level of completion off-site or exclusion of both cladding or structure.

[101] Modular Building Institute – Construction Definitions

Modular construction (Figure 70 a & b) is simply defined here as; the prefabrication and pre-assembly of materials and components off-site to form volume-enclosing elements for assembly on-site. Modular buildings can be freestanding single modules, agglomerations of two or three modules to form a building or multi-storey assemblies that are self-supporting or have a separate structure. Modules can also be configured in a wide variety of ways and joined together using a variety of methods.

Figure 70 (a) Misawa modular production line near Nagoya, Japan. Photo by James Gardiner (b) Modules being lifted into place for project by Cartwright Pickard Image source - http://www.cartwrightpickard.com/project/live/murray-grove Access date 25th August 2011.

These three terms for types of off-site fabrication: stick and panel, panelised and modular, with some slight variation in exact words used, were generally recognised in interviews with Architects and Fabricators in USA, Japan, UK, Germany and Sweden. Hybridised forms are also widely used in practice, that include a mix of the above-defined practices; Stick and Panel, Panelised and Modular as well as the combination with standard construction practice (Gardiner, 2010).

With any building constructed through off-site fabrication, transportation is an important factor to be considered, preferably from the outset (Gibb, 1999c). This is largely a planning issue (transportation efficiency and design for transportation) rather than an issue of increased transport costs as often assumed (Gibb, 1999b).

The type of off-site fabrication to be used is an important factor to consider in relation to transportation and the costs that will be associated with this. As noted above the use of modular construction allows a greater proportion of the fit-out and finishing work to be done off-site, but modular construction also can have the disadvantage of being a less efficient method of transport due to 'shipping air'[102] in comparison to flat pack panels. Within the design of a project for off-site fabrication, detailed consideration should also be given to the logistics of moving panels and modules at different points in the workflow i.e. within the factory, onto the mode of transportation (usually a truck), onto the site for temporary storage (if required) and into final position within the building or site (Gibb, 1999d).

Another importation issue to be taken into account is the size of transportable elements, with reference to a number of factors related to transportation. The first is local transportation codes (RTA, 2008, Gibb, 1999c), which vary considerably between states in Australia[103]. These codes regulate the maximum transportable dimensions with and without an escort. Another issue is relates to the cost efficiency with which prefabricated and pre-assembled building elements can be transported; this generally relates to transportation codes, packing efficiency and in some cases shipping container dimensions (Levinson, 2008, Tomlinson, 2010, World_Shipping_Council, 2011).

3.6. Synthesising techniques, tools and methods

Adopting one or all of the techniques, tools and methods discussed above does not guarantee success. The parallel industries have demonstrated in recent years that a key feature to success is the development of robust systems, procedures and work practices. The report UK Construction 2010 (Constucting_Excellence, 2005) identifies modern methods of construction (MMC) and off-site fabrication as

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[102] A term used by one of the prefabricated housing interview participants from the DDAA research.

[103] Discussion regarding differing transportation with Modscape

being integral to the modernisation of the construction industry in line with proposals by Egan (Egan, 1998); resulting in "*savings worth hundreds of millions of pounds…….delivered throughout the supply chain*" (Constucting_Excellence, 2005).

Both reports however note that other changes in focus are also critical; such as training and retention of employees, logistics, focus on the customer and quality, building project team collaboration and forging ongoing relationships within the supply chain. All of these changes have been widely implemented within the parallel industries, with significant gains recorded in productivity, quality and profitability (Egan, 1998, Constucting_Excellence, 2005, Gardiner, 2010).

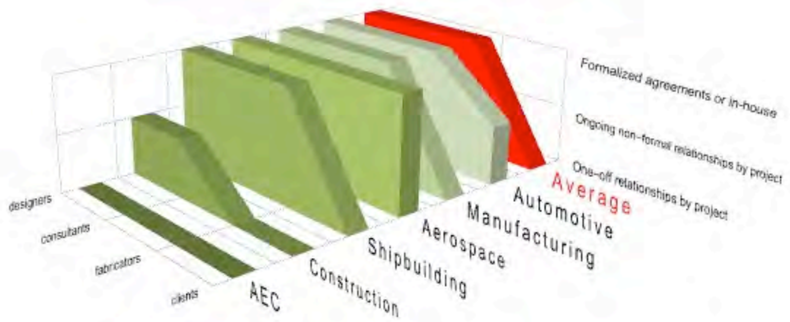

Figure 71 - Comparison of relationships within the construction and parallel industries.

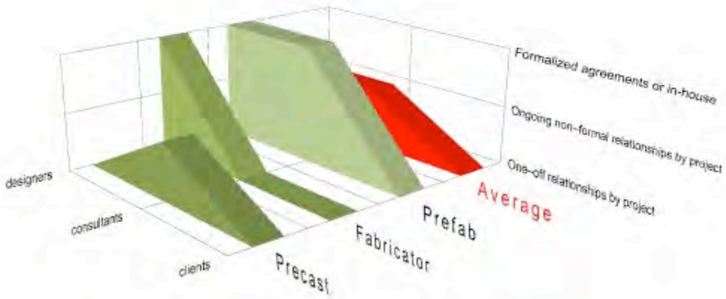

Figure 72 - Comparison of the relationships within the construction industry sub-sectors

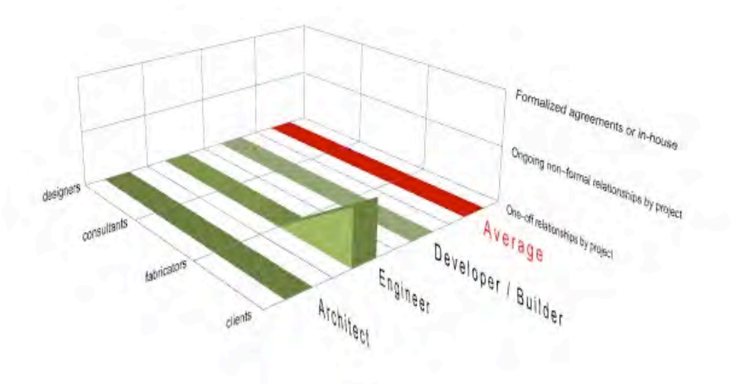

Figure 73 - Comparison of the relationships within the AEC industry.

One of the many surprising results of the Delivering Digital Architecture in Australia survey of the construction and parallel industries (Gardiner, 2010) was the comparative difference in relationships between the construction industry and the parallel industry. The results from the questionnaire are graphed for three groupings; the first (Figure 71) illustrates the results for each of the construction and parallel industries while also including a sub group of construction labelled AEC[104], the second grouping (Figure 72) illustrates the differences between sub-sector fabricators within the construction industry and the third grouping (Figure 73) compares the relationships of designers, engineers and developers.

There is a stark contrast between the construction and parallel industries companies surveyed in the nature of relationships between designers, consultants, fabricators and clients. As indicated in (Figure 71) there is a strong similarity between each of the parallel industries with close ties between each of the groups (designers, consultants and fabricators); with the client being the only party that is not either a permanent member of the team, through formalised agreements, or integration into the company (in-house).

These quotes by engineers, the first from an international aerospace company and the second from an Australian shipbuilding company, interviewed on the Delivering Digital

[104] The acronym AEC generally refers to Architecture, Engineering and Construction, in this case it refers to Architects, engineers and Developers.

Architecture in Australia research project indicates some of the motivations for developing close collaboration between team members;

"The way that we do it works best when you are working with a known supply chain and when you have got a known level of experience"

and working with in-house teams

"Most design and engineering is done in house, mainly to manage risk. This is primarily due to the need for (-----) *to warrant their product. External consultants can rarely afford to warrant their products". By working with companies, teams and individuals that are familiar with the design/fabrication/installation procedures"*

The parallel industries have developed sophisticated ways to work in teams, use and work with 3D digital design tools collaboratively, increase productivity, reduce accidents, automate fabrication, increase the quality of their product, reduce waste and at the same time constantly improve their products (Gardiner, 2010). The systems, practices and methodologies of these industries are the most important aspect of what they do. We, the construction industry, shouldn't be copying what they do, but instead learning from how they do it.

"*We have repeatedly heard the claim that construction is different from manufacturing because every product is unique. We do not agree. Not only are many buildings such as houses, essentially repeat products which can be continually improved but, more importantly, the process of construction is itself repeated in its essentials from project to project…research suggests that up to 80% of inputs into buildings are repeated…The parallel is not with building cars on the production line: it is designing and planning the production of a new car model*." (Egan, 1998)

4. Project Case Studies introduction – Exploring the Design Territory of Construction 3D printing

This chapter presents three case studies, which vary dramatically through scales from a 24-storey tower, to an individual villa and an artificial reef. The projects also differ significantly between project types, which include speculative design investigations to client specific detailed design and prototyping. These projects are among the first architectural explorations of design for Construction 3D printing, and are intended to fill an identified gap in construction 3D printing applications research. The case study projects have been used here to both tease out potentials and limitations of specific construction 3D printing and begin to map out the emerging territory of design for construction 3D printing.

The first of the projects presented here, Freefab, emerged from my final year architectural studio project in 2004. The second, Villa Roccia, from a commission from D-Shape for a house in Sardinia and the third, (in)human habitat, from seed funding for design research. Each of the projects has grappled with quite different problems at varying scales: from the design of a multistorey construction system, to developing prefabricated panel detailing strategies and creation of topographically diverse artificial reefs. From humble beginnings as a student project this research has transformed to become the key focus of my architecture studio.

As presented in chapter (3.2.3) there are few precedents within the emerging field of construction 3D printing and even fewer examples of architectural detail at medium and fine levels for construction 3D printing. Exploration in the form of application research and/or architectural practice of these course and fine levels of detail is an essential step to create example for analysis. Critical understanding of the potentials and limitations of construction 3D printing (also discussed in chapter 3.2.3) has been possible through analysis of the case studies created as part of this ongoing research.

Slightly different methods, comprising of a combination of digital tools, off-site fabrication methods, design strategies and construction 3D printing techniques, have been conceived and applied for each of the case study projects. Novel methods based on theories and design strategies have been developed through the method of conception, which is an outcome of other methods used within this program of study including; extensive background literature review, field research involving qualitative and quantitative analysis, ongoing embedded practice and action research. Analysis is presented within this chapter of both the case study projects as well as the methods used to create them, from this analysis potentials and limitations have been identified, which will further our understanding of the emerging field of construction 3D printing.

4.1. Freefab Tower – Project Case Study 1

4.1.1. Freefab Project Introduction

This project was developed prior to the commencement of my PhD, for the final design studio of my bachelor of architecture degree at UTS. It is important to discuss this project as a case study because it is the earliest architectural project conceived for construction 3D printing, as well as being the first of a series of my projects focussed on the possible design and construction implications of Construction 3D printing.

This research project was conceived from two distinct projects. The first was the writing of a dissertation (on a selected topic of investigation) and the development of an architecture design brief. This first project was completed during the first semester of 2004 and supervised by the head of Architecture Xing Ruan. The second project was the design of a project, based on the dissertation research and architecture design brief. This project was completed in the second semester of the same year and supervised by Sydney architect Philip Thallis.

Within the UTS design studios, we were as individuals free to develop our own brief for a complex building and select a suitable site for the project. The brief that I developed for the project was for a multi unit high-rise residential building to redevelop an industrial site on Sydney harbour adjacent to the ANZAC bridge. The aim of my project was to attempt to unlock the potential of off-site fabrication by developing a construction methodology for the fabrication technique Contour Crafting™; the first of the Construction 3D printing techniques developed (discussed in chapter 3.1.5).

The project, in my case, was used to develop and demonstrate this methodology for building with the contour crafting technique, within a design brief for a complex apartment building on a fairly tight site in Sydney. This was an unusual project trajectory compared with the other projects undertaken by students in my year. All of the other projects of my peers focused on researching a building typology and then designing a building of that typology on a given site. The outcome of the project was the development of novel construction system; the apartment building was used to demonstrate this system and was exhibited at the 2004 UTS Architecture graduate exhibition EXIT (refer to Appendix A - exhibition catalogue extract).

The project described below represents a world first architectural effort to design a building for Construction 3D printing techniques[105]. The project is also the first endeavour to develop a methodology for the combination of Construction 3D printing with off-site fabrication. The work discussed here represents the first of a string of projects that aim to develop the basis for future application of Construction 3D printing within the construction industry.

Five major aspects of the project are discussed below, based on literature review that was conducted prior to the commencement of this PhD. These aspects include off-site fabrication, fabrication with construction 3D printing, design and digital design tools. Although the current research has been conducted in a more scholarly manner (i.e. focusing to a greater extent on works such as journal

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[105] Diagrammatic axonometric images and animations illustrating the contour crafting construction technique for a generic two storey building were available on the contour crafting website in 2004, these images were neither architectural in conception, scope or detail (refer image Figure 13 a).

articles, conference papers and edited books), the basis of the preceding research on which this project was based has been found through this PhD research, focused on the same topics, to be largely sound.

The order in which the headings for this case study project are discussed here is the opposite to the way many projects are usually discussed, this follows the order in which the building was largely conceived (although there is always considerable concurrent consideration of factors in my architectural design process). Thus this order works well to discuss the project, because it reflects the trajectory of development of thinking behind the project.

4.1.2. Off-Site Fabrication and Metabolist Theory

Off-site fabrication was taken as a starting point for the Freefab project as the project was underpinned by the fundamental question “how can design and construction improve” (as discussed in the methodology chapter) and the focus on off-site fabrication as one of the practices that were identified as key to realising these improvements.

When considering my approach for the off-site fabrication for this project I looked to precedents and the theories of ‘metabolism’ for inspiration, due to the Metabolist movements’ relevance to the issues that I was considering: off-site fabrication, construction sustainability and design to accommodate change. I had been first exposed to the work of the influential Japanese architects Kenzo Tange and Kisho Kurokawa, who had produced for me the most inspiring Metabolist works, during research for previous projects. Although I was drawn to the Metabolist work and theories by the apparent similarities to the work and theories of Archigram and the work of Foster and Rogers, no formal influence has been identified (Frampton, 1997, Lin, 2010).

I was seeking to create more than just a building, I was looking to create a system for building, to try to unlock potential in off-site fabrication and perhaps create a new building typology. Therefore I wanted to develop this project from firm foundations. One of the main theories espoused by Kurokawa that appealed to me is contained in these words:

"*A work of architecture should not be frozen once it is completed but should be apprehended instead as a thing – or a process – that evolves from the past to the present and from present to future*" (Kurokawa, 1992) p10.

The metabolist movement sought to create 'symbiosis' between 'man' and 'technology', which is said to be in contrast with western philosophy which instead sees humanity and technology as opposing forces a 'dualism'(Kurokawa, 1992). By harnessing technology to create an organic entity the effect of this edifice on its environment and man would also change, enabling change through the design of a dynamic building system, enabling the dynamism of responsive change within man and reducing the buildings effect on the environment through constant change and recycling.

Figure 74 – Nagakin Capsule Tower in Ginza by Kisho Kurokawa 1970. Yamanshi Press building 1967 in Kofu by Kenzo Tange. Photos James Gardiner 2006

The Metabolists had been keen to adopt off-site construction methods (Figure 74), seeing this method as aligned with the theory that they were implementing:

"*during the 1960s and early 1970s architects of the metabolist movement embraced prefabrication through their espousal of manufactured elements that* *could be organically inserted and replaced within various supertructures*" (Bergdoll et al., 2008) p34.

The approach to architecture and the way buildings should be designed for off-site construction is described by Kurokawa

"*Architecture is a conglomeration of units which can be freely rearranged to change the expressive quality of the work. Two principles are at work here: that architecture has the capability of changing and regenerating in response to the future, and that architectural forms can be modified depending upon the way space is used.*" (Kurokawa, 1992) p11

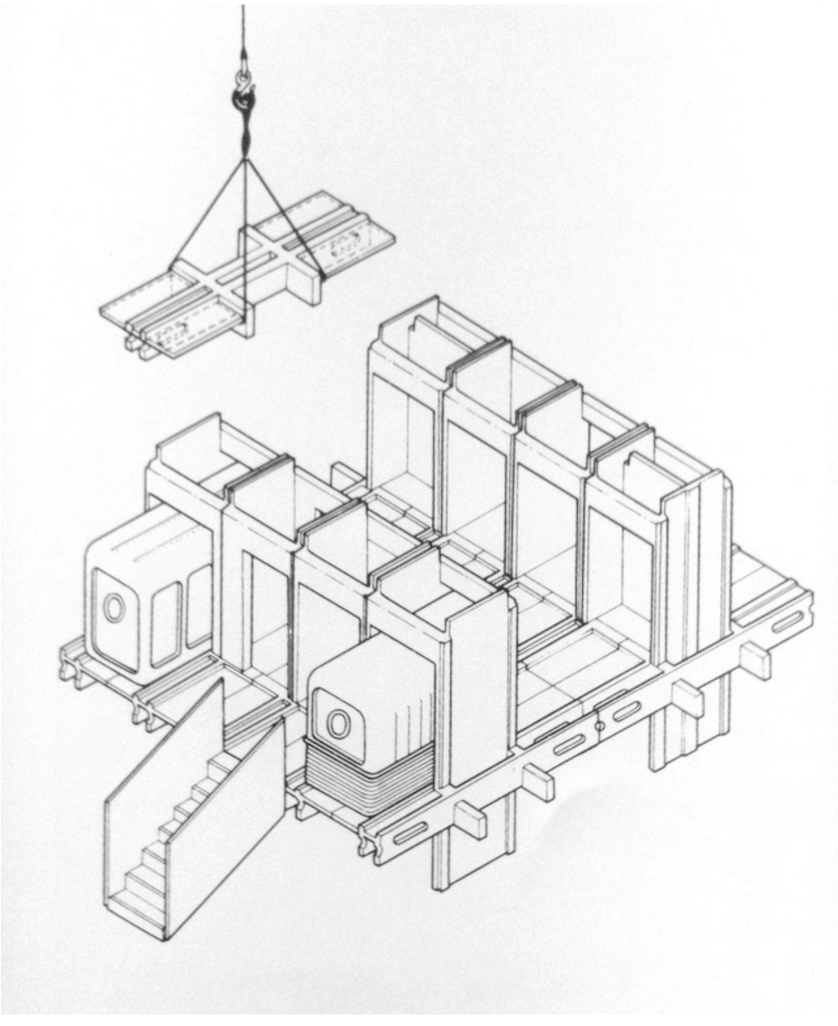

Figure 75 - Kisho Kurokawa Box-type mass-produced apartments project 1962. Image source – Kurokawa, 1992

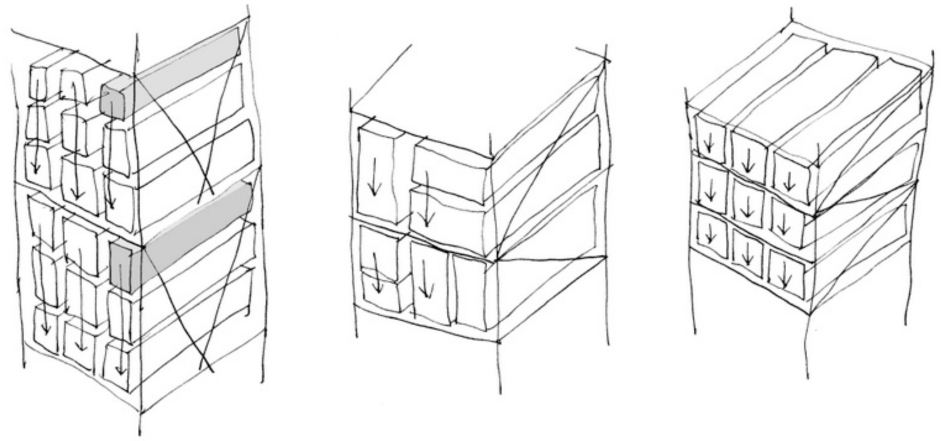

Figure 76 - Diagram of basic strategies for locating free modules within a superstructure. James Gardiner 2004

Based on this background review of Metabolist theories the following concepts were relevant for the Freefab project including ‘Symbiosis’ between ‘man’ and ‘technology’ (by harnessing the benefits of digital design tools, industrialised off-site methods while accommodating change in society and by man), integration of sustainability (through recyclability and transformative adaptation and reuse) and inspiration from novel design strategies of the metabolist projects such as the Nagakin Capsule Tower (refer image Figure 74 a), the Box-type mass produced apartments, (Yatsuka and Yoshimatsu, 1999) (refer image Figure 75) that demonstrated methods for implementation of the theory (Kurokawa, 1992).

Although the adoption of strategies such as: off-site construction, adaptive reuse of buildings, design for disassembly and recycling strategies are not on face value particularly different to the way that buildings are conceived and changed in the west: considering a project with these theories as the primary drivers of the project and design does shift the architectural design value hierarchy significantly.

The Freefab project was designed as an open system to allow for large-scale change within the building, while also being highly recyclable. These strategies were to be achieved by designing the building with a clear division between superstructure and the apartment modules, which would enable the removal or rearrangement of whole or part of the apartments within the structure. The Box-type mass produced apartments project from 1962 (Yatsuka and Yoshimatsu,

1999) were used as a precedent for the method of separation of structure from module.

To create a highly modifiable and recyclable building, which could respond to change easily, the project both used modules and created these modules, as much as possible, with one material: a hybrid concrete. This method of construction was considered possible through the use of a hypothetical modified Contour Crafting technique[106] (refer image Figure 14 & Figure 77a). Although the Contour Crafting technique is yet to demonstrate such capabilities, it was hypothesised that with refinement of the deposition nozzle and material deposition capabilities, most of the materials associated with construction of a typical apartment could be replaced by a single material, deposited precisely using Construction 3D printing techniques.

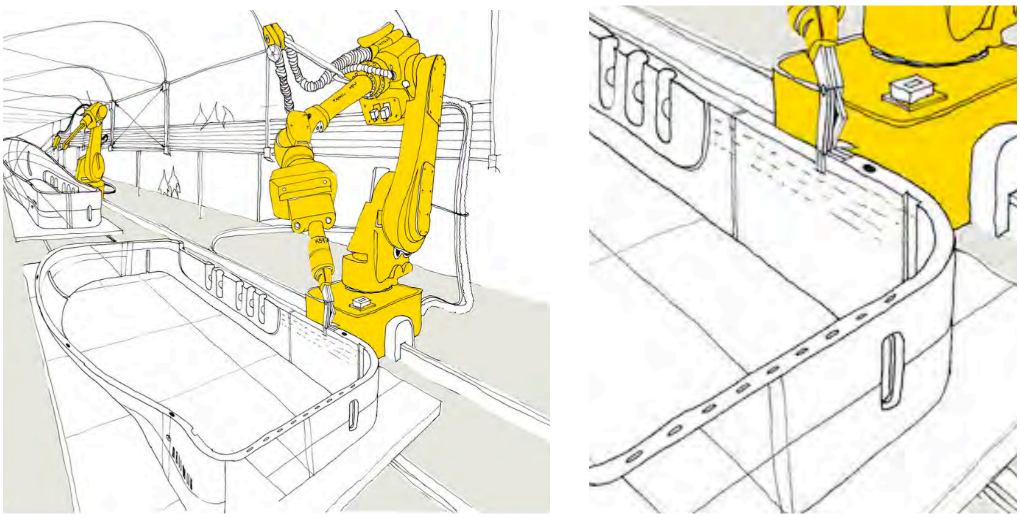

Figure 77 – (a) Sketch perspective of modified Contour Crafting technique adapted to jointed arm industrial robot and production line. (b) Detail of same image. Showing integral wall cavities, articulated windows and shading, conduits for wiring and structure. Image James Gardiner 2004

This theory of using a single material to replace the plethora of materials used in conventional construction has since also been posited by researchers at

[106] The hypothetical modified contour crafting technique, utilized a jointed arm industrial robot within a factory based production line, instead of an on-site gantry system for controlling deposition

Loughborough University first in theory (Buswell et al., 2005, Soar, 2006b) and more recently in scale prototypes (Corke, 2010).

The design postulated that it would be possible to create the following attributes in the modules using the Contour Crafting™ and a single material: the creation of window reveals, sun shading, acoustic treatments, wall textures, air vents, insulation properties, structural dowel rebates, post-tensioned reinforcement conduits (refer image Figure 77 b). This reduction in materials, through the incorporation of all of the above-listed characteristics, significantly simplifies the fabrication and construction process, as well as the possibility of recycling components. Within contemporary construction methods the build-up of a simple wall uses a large number of different materials (Buswell et al., 2005), which in many cases are fixed with adhesives. These adhesives are difficult to remove and make separation of materials difficult (Dolan et al., 1999). Reducing the number of materials used reduces the need for sorting of materials and reducing the number of adhesives required for fixing materials together reduces contamination of materials in the case of any future recycling process.

Once the approach of separating the structure and the apartments had been adopted, focus could turn to developing a strategy for prefabrication of the apartments. One important prerequisite in the selection of the prefabrication method was that the apartments should be both freestanding (i.e. they do not rely on the superstructure for their structural stability, as they should be reconfigurable) and take advantage as much as possible of off-site fabrication and fit-out. To fulfil these requirements modular construction was required, although it was realised that structural stability could be achieved through a combination of structurally stable modules and panels that span between these modules. This method had the benefit of increasing transportation efficiency (refer chapter 3.5.3), while also enabling the structural stability and re-configurability required.

As noted above, a combination of modules and panels were used in this project, this strategy was based on the following considerations:

- Modules allow for a maximum fit-out of complex spaces (such as service spaces; bathrooms, kitchens, laundries, staircases) to occur off-site within modules. This off-site production enables improved workflow between trades, working on multiple modules simultaneously within a factory environment, by specialised fit-out teams working on multiple modules simultaneously within a factory environment, and improved quality control supervision. Finished modules can be transported to site, reducing the on-site fit-out duration.
- Modules are useful for creating structure for the freestanding apartments
- Conversely modules are not particularly efficient for transportation purposes (often referred to as 'shipping air') due to the fact that there is air space within the modules that is difficult to fill if the whole project is modular.
- Panels can span between modules (referred to in this project as shells) to create simpler spaces, such as bedrooms, living spaces and to assist in the creation of double height spaces.
- False floor panels can also used to allow for easy access and re-configurability of electrical and other services
- Panels can be used to increase shipping efficiency.

The reasons stated above for the use of a combination of modules and panels align with distinctions made by Gibb (Gibb, 1999d) regarding the benefits and limitations of panels and modules, although this conclusions were drawn from project literature review (Gardiner, 2004a).

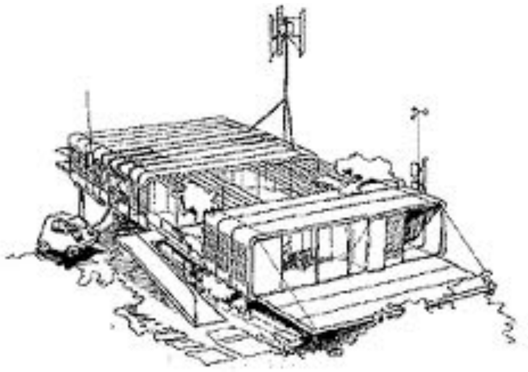

Figure 78 - Richard Rogers - Zip-up Enclosure. Image source - http://www.arcspace.com/books/Richard_Rogers/rodgers_book.html Access date 14th August 2011.

The division of modules into monocoque shells (and panels) was influenced by the architect Richard Rogers 'Zip-Up Enclosure' competition entries from 1968-71 (Powell, 1999) refer image (Figure 78). This project stood out, from other prefabricated building precedents, for its systematic ability to create continuous internal spaces and the implementation of a single skin, which formed both structure and enclosure. The 'Zip-Up' building concept is described as influenced by 'monocoque' construction in the aerospace industry, as the building was fabricated as separate stressed skin floor, wall and roof panels which were "*attached on site to create a structural ring 3 feet wide and 30 feet in length*" (Bergdoll et al., 2008) p148. Both the concepts of monocoque and slicing of spaces have become key components in the Freefab Shell system, despite being quite differently applied in terms of materials and method, to the 'Zip-Up' project.

Many modular prefabricated buildings typically have constrained rooms sizes based on either shipping container dimensions or maximum transportable sizes, set by shipping container dimensions and local transportation regulators (Gardiner, 2010). In a small proportion of cases, off-site construction companies opt instead to split rooms into two or more sections (Gardiner, 2010)[107] to minimise the effects of these transportation constraints. The Freefab project

[107] The term 'double wide' is used in the USA to refer to modules that split rooms in two for transportation purposes.

instead adopts the strategy employed on the ‘Zip-up Enclosure’, but takes this technique further by splitting spaces up into multiple slices, like a loaf or bread, (refer image Figure 79), which will be referred to as ‘shells’ in this chapter.

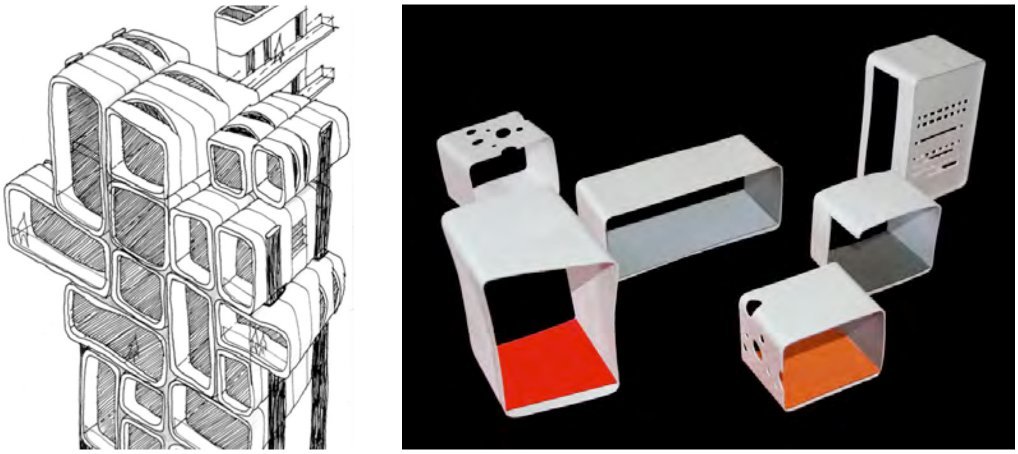

Figure 79 – (a) Concept sketch of sliced prefabricated modular shells. (b) Fine clay models of modules, which were used to demonstrate how different module types could be configured together to create a range of dynamic spaces. Images James Gardiner 2004

The primary dimensions considered for the module shells were those of the standardised ISO “high cube” shipping container (World_Shipping_Council, 2011). A secondary set of legal transportation dimensions were considered for larger elements that could not be divided into smaller modules (RTA, 2008).

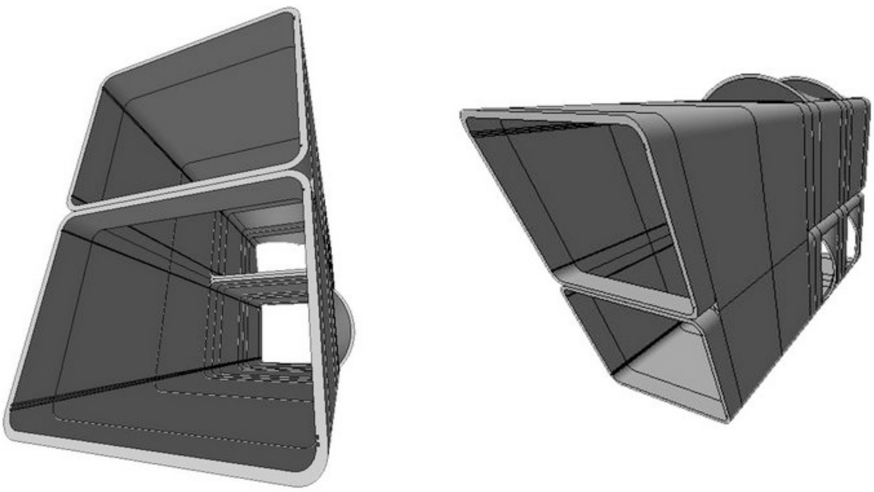

Figure 80 - CAD model of double height assembly, early test model created in Revit™. Image James Gardiner 2004

The image (Figure 80) shows how a combination of shell monocoque slices and panels combine to create a structurally robust double height room. The light grey lines generally refer to joints between shells and panels.

The construction process proceeds as follows: once the apartment shells have been transported to site by truck, the apartments or large subassemblies of the apartments are assembled at ground level and lifted into place onto the structural frame by crane. This assembly process is depicted in image (Figure 81), assembly is assisted through the use of large level platforms with embedded rollers to allow the shell modules to be manoeuvred into position by hand, reducing the need for crane assistance at this stage. The shells are designed to be mechanically fixed together with dowels and post-tensioned reinforcement. Services running between shell modules and panels through the false floors are connected at this stage.

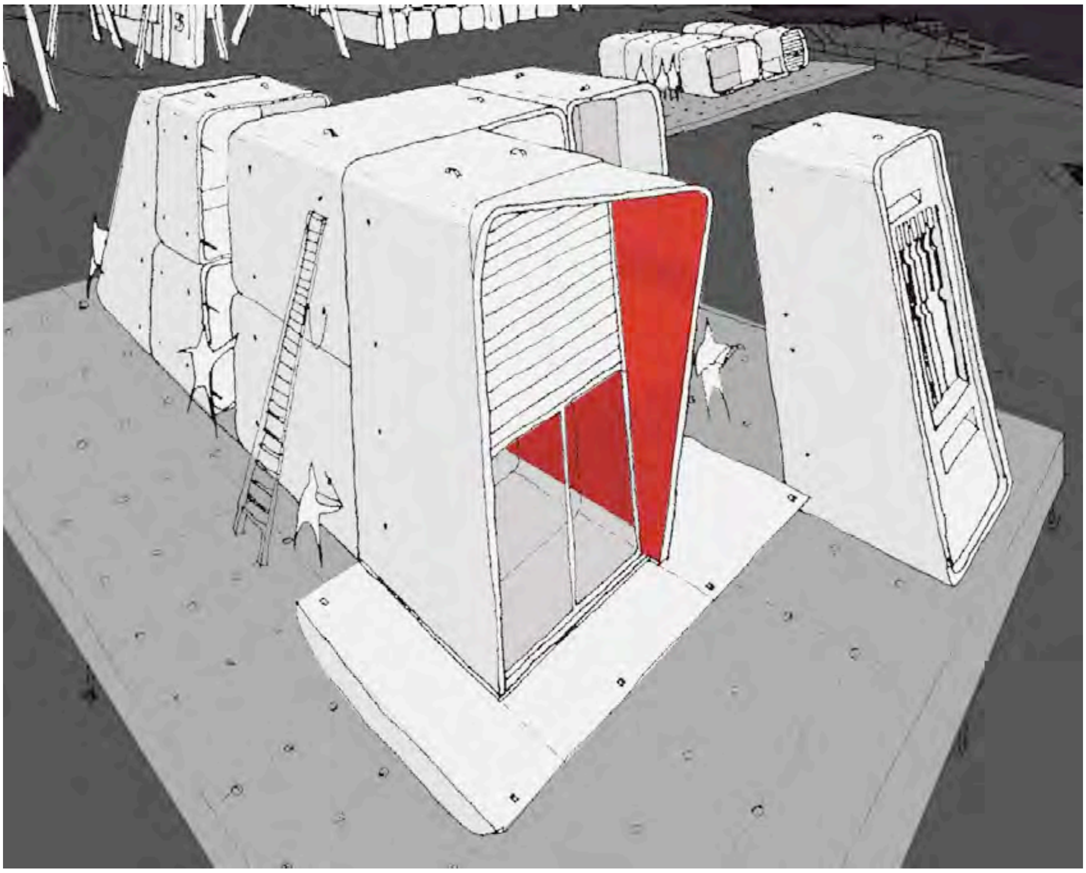

Figure 81 - Freefab – Assembly of shells into apartments James Gardiner UTS 2004

This methodology allows for as much of the labour to be completed off-site as possible, with the assembly stage consisting of four main activities (refer image Figure 82):

- Unloading and temporary storage of shell modules and panels
- Assembly of apartments or sections of apartments at ground level
- Lifting of the apartments into place onto the superstructure
- Commissioning, connection of services into the superstructure, defects inspection and rectification.

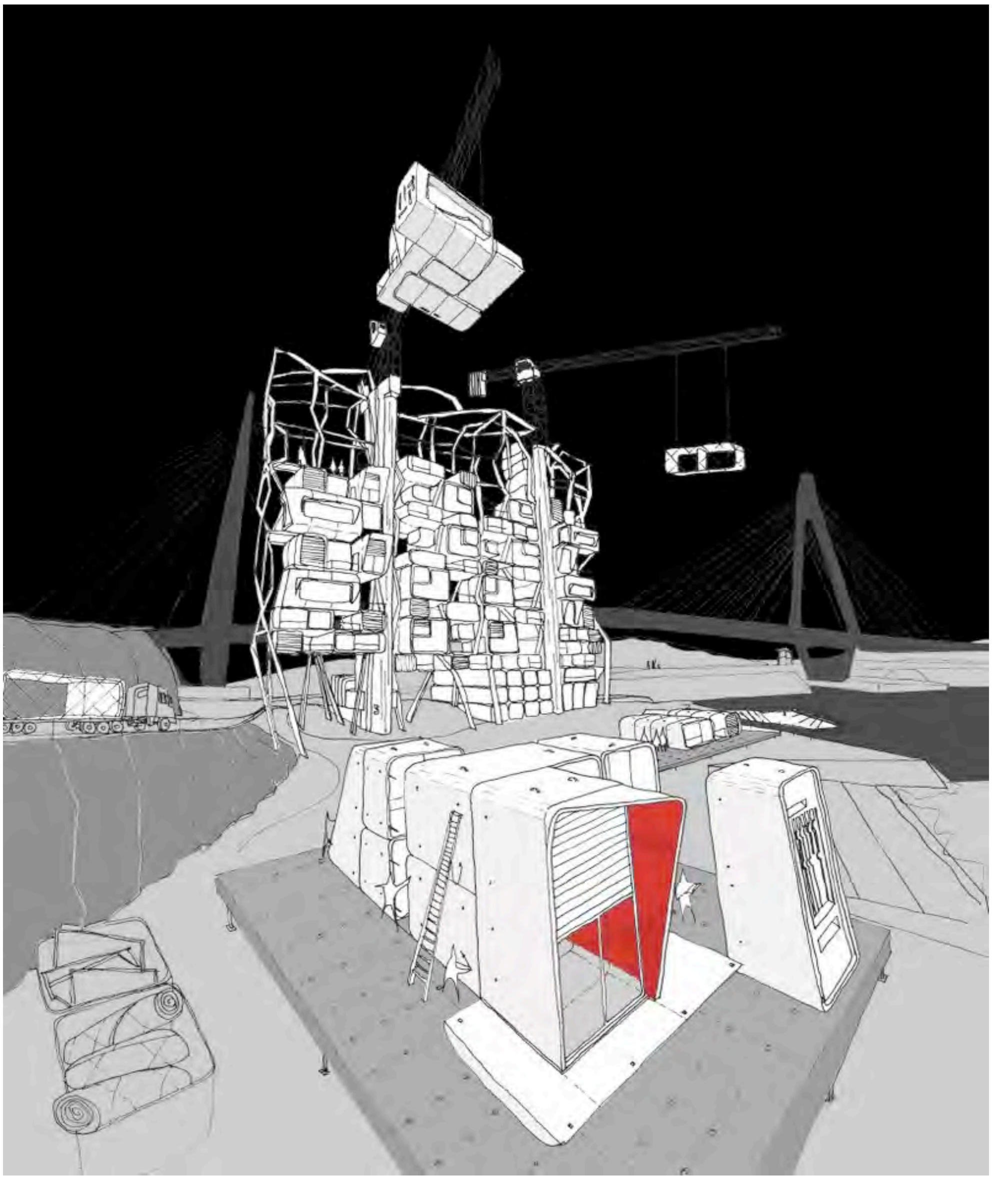

Figure 82 - Freefab Apartment Building under construction. James Gardiner 2004

This methodology keeps labour firstly focussed into specific work areas and secondly focused predominantly at ground level through the majority of the fabrication and assembly phases. This focusing of labour activities within safe environments is used widely already within the precast and off-site fabrication industry worldwide and is considered within the construction industry to increase labour efficiency and worker safety. (Gibb and Isack, 2003, Blismas and Wakefield, 2009).

4.1.3. Fabrication

The Freefab construction system is designed around a core Construction 3D Printing fabrication capability, utilizing a modified Contour Crafting technique (refer image Figure 83). The hypothetical modification of the Contour crafting technique was largely to allow for standard (Kuka™ type) Jointed Arm Industrial Robots to be used instead of the proposed gantry system and to locate these robots within a factory environment on a production line.

Figure 83 – Freefab shell production using a modified Contour Crafting system on a production line. James Gardiner UTS 2004

The Jointed Arm Robot has a proven capability to undertake a wide variety of tasks, the accurate deposition of cementitious material (as per Contour Crafting™ technique) was considered, by me based on its capability to perform other tasks such as milling and polishing to be, well within the capability of the large heavy-duty jointed arm robots. The main constraint within this context of these robots is reach, which could on further reflection be extended if the robot were to be hung above the work area rather than being placed to one side. Recent adaptation of a jointed arm industrial robot by Dirk Van Der Kooij in 2009 to fabricate furniture through the deposition of plastic filament (refer to image Figure 32 a) has confirmed this capability.

At the time of the development of this project in 2004, the contour crafting deposition process was considered be but one of a number of operations required to complete a Freefab modular shell or panel. It was therefore proposed that these robots could be arranged in stations on a production line within a factory environment, backup robots could kept in reserve and be swapped if one required unscheduled maintenance or broke down. The benefit of using such robots is that they can be fitted with any number of tools and programmed to perform a wide variety of tasks. Stations and operations that were considered potentially necessary to complete the panels and modules were the following: material deposition[108], curing, CNC milling and finishing, spray-painting or sealing[109], wiring and services, fit-out and lifting. The following tasks; material deposition, CNC milling and finishing, spray-painting or sealing; could be completed by the jointed arm robots.

The location of the modified contour crafting technique[110] within a factory environment was considered important for a number of reasons. Off-site

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[108] In this case Contour Crafting

[109] Refer image (Figure 83) the second robot on the line is illustrated as fitted for spray painting.

[110] Francois Roche published the project ‘I’ve heard about’ in 2006 postulating a technique apparently loosely based on the contour crafting technique that used enormous serpentine robotic arms to organic towers.

fabrication was the preferred construction method for this project. The level of control of the atmospheric conditions during deposition and curing is considered by me to be of vital importance to the control of the deposition and curing processes. None of the three construction 3D printing machines have to date demonstrated a capability for fabrication in outdoor environments[111], it may take years of research and scientific observation to fully understand all of the variables related to particular construction 3D printing fabrication and curing. Before such research is completed, in the interim, control of such variables will be more easily achieved within a factory environment. Material certification and quality control will likely become an important factor as construction 3D printing develops, these requirements can be easily fulfilled within a factory environment.

Deposition of material using the modified contour crafting technique would rely on four main factors:

- Highly accurate deposition of material, which would bond together horizontally and vertically (to the layer beneath).
- The ability to stop and start deposition (to form openings, rebates and conduits) with control of the finished surface of the stopped and started surfaces.
- The capability to vary the geometry three dimensionally as the shell or panel is developed. Rather than just extruding the base profile to create 2.5D geometry.
- For the material to remain dimensionally accurate and be self supporting from deposition to cured state.

4.1.4. Designing the Freefab Tower project

The cut away section perspective (Figure 84) illustrates the potential of Construction 3D printing techniques in enhancing the function and design

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[111] Based on literature review of both Contour Crafting and Freeform Construction techniques and first hand experience with the D-Shape technique.

potential of buildings elements.[112] One of the potential benefits with Construction 3D printing of panels or modules is the potential ability to fabricate weather proof joints between rectilinear or freeform panels, this robustness of the joints to weather reduces reliance on adhesives, which need to be regularly checked for degradation. Such weatherproof joint profiles are already used within the precast concrete industry for flat panels. However, from direct experience, such joints profiles add complexity and cost and are usually forgone with a reliance instead placed on adhesives to perform a weatherproofing function[113]. Weatherproof joints within the precast industry instead rely on gaskets and air seals (C.I.A, 1983), which are slotted into place during assembly and are usually not exposed to sunlight prolonging longevity; the Freefab technique also implements the use of gaskets and air seals.

Within the sketch (Figure 81 & Figure 83) dowels are illustrated as a method of mechanical attachment between modules and panels, the means of reinforcement is possible due to the potential capability of Construction 3D printing to fabricate voids within the fabrication of shells and panels.

[112] This image was drawn in 2007 to more clearly illustrate ideas originally developed in the Freefab design in 2004.

[113] This is based on five visits to precast concrete fabrication yards: Girotto 2004, Thiess John Holland 2006, Skanska 2007 (Sweden), Hansen 2008, Sasso 2008,

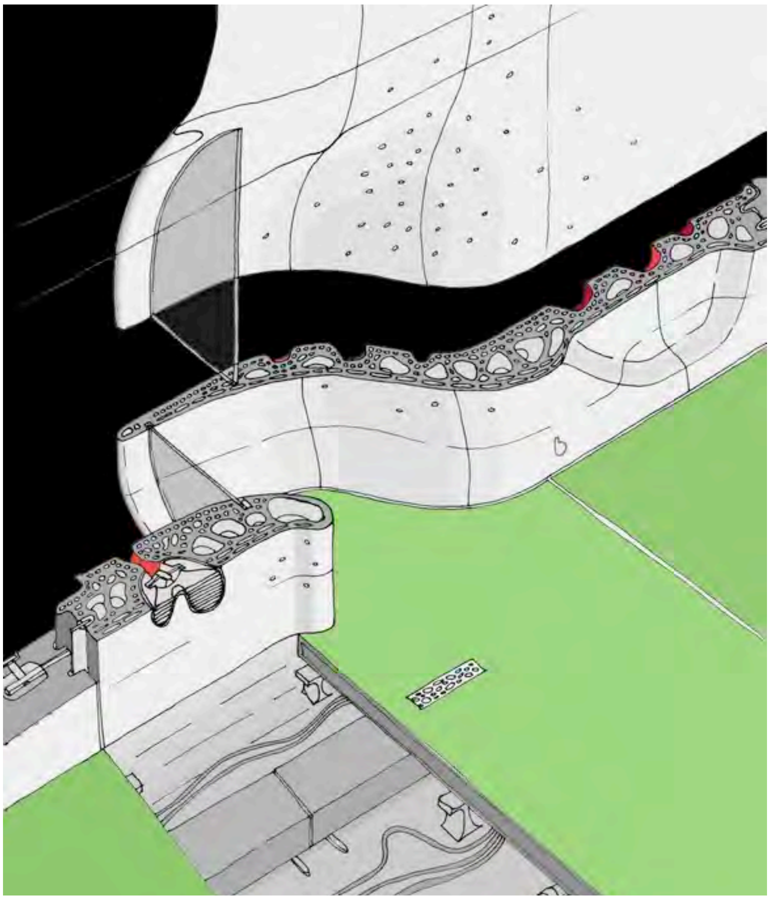

Figure 84 - Perspective showing potential benefits of Construction 3D printing techniques, including integration of passive thermal, acoustic and solar control. The integration of articulated integrally waterproof joints and the integration of services. Image by James Gardiner 2007

As stated by Hague in reference to Additive Fabrication; freeform elements would not necessarily attract an additional cost over rectilinear elements (such as walls):

"One of the major benefits of the Additive Manufacturing processes is that it is possible to make any complexity of geometry at no extra cost – this is virtually unheard (of)*, as in every conventional manufacturing technique there is a direct link to the cost of a component to the complexity of its design. Therefore, for a given volume of component, it is effectively possible to get the geometry (or complexity) for "free", as the costs incurred for any given Additive Manufacturing technique are usually determined by the time to build a certain volume of part that in turn is determined by the orientation that the component is built in.* " (Hague et al., 2003)

This theory of ‘geometry for free’ of additive fabrication is applicable for construction 3D printing of building elements. This enhanced geometrical and form vocabulary in production, essentially creates a value added scenario, which allows for a wall with complex internal structures, conduits, joints, freeform shape and external texture to be fabricated for approximately the same cost as a standard rectilinear wall of similar dimensions and material volume. This extra capacity in relation to costs enables the possibility to both respond to the seemingly mundane requirements of a building while also integrating increased expression on the building façade and interior.

In the design of the Freefab Tower these opportunities were explored in relation to purely functional aspects of the design (such as provision of conduit voids refer to image Figure 81) as well as to functionally expressive elements (such as sun shading and screening refer to image Figure 81 and Figure 85), in the freeform superstructure of the tower (refer image Figure 82) and to purely aesthetically expressive elements such as random raking lines (Figure 83). This cross-braced freeform superstructure was designed manually. No method of digitally ‘generating’ this structure was used and testing of the viability of the structure designed was not undertaken project due to a lack of knowledge of and access to generative software and the availability of resources to analyse the structure. The structure (refer Figure 85) can be considered purely speculative; the use of generative tools has been pursued much more vigorously in case studies to follow.

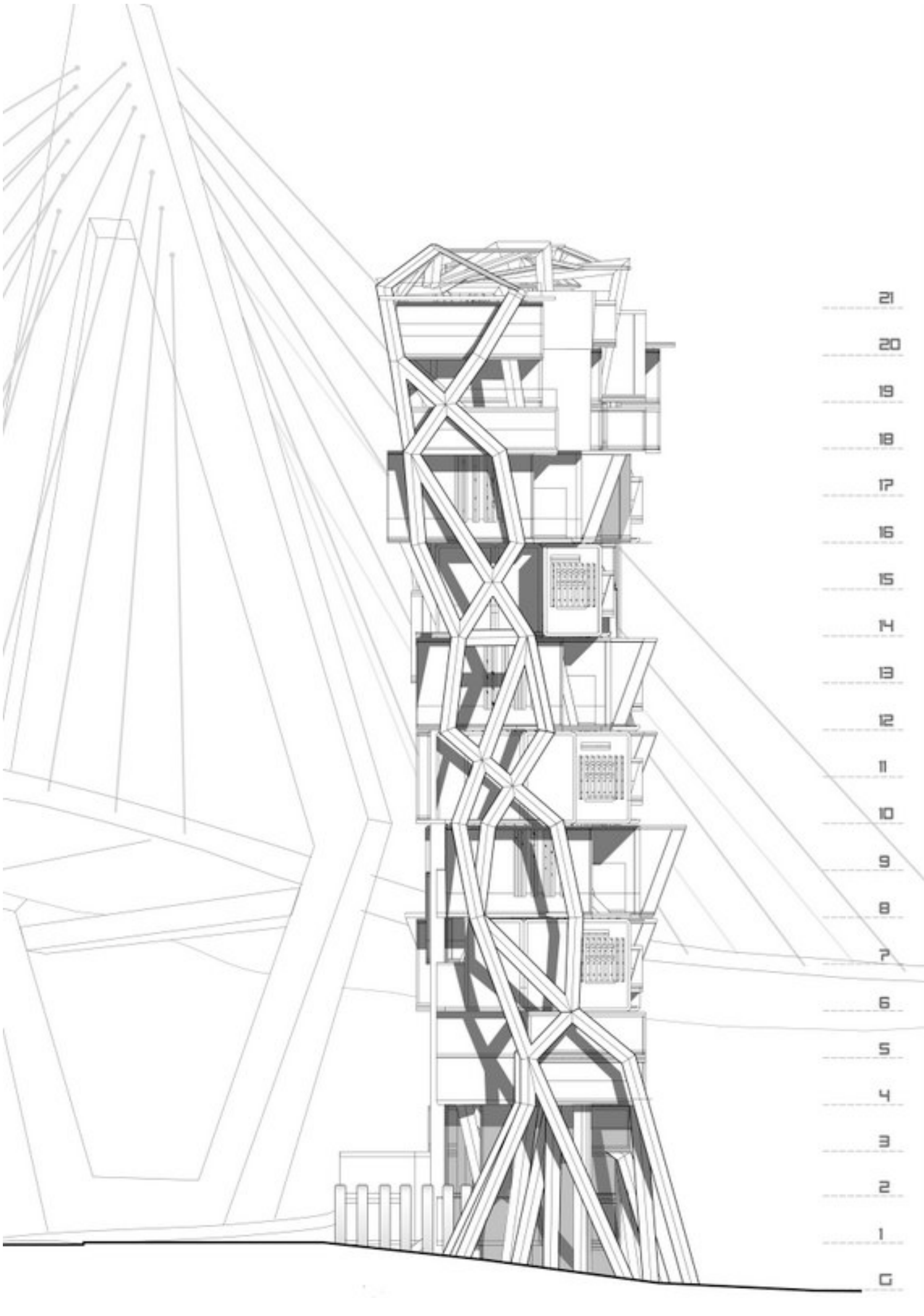

Figure 85 - Freefab Tower east elevation illustrating the freeform superstructure

A realization made during the design of the shell system had significant implications for the design of the tower. When considering the stacking of the non-load bearing modules, within the superstructure, it became apparent that placing modules together was essentially doubling up on materials. Each module had its own requirement for adequate structure for transportation purposes and it was also intended that each module should be self sufficient for thermal insulation; given the scenario that the building was designed for change and reconfiguration. It became apparent that if one placed half of the total number of modules in a checkerboard pattern, almost an equal quantity of space would be realized as if all of the modules were placed. When only half of the modules are placed although almost as much space is realized, half of this space is unenclosed (refer image Figure 86).

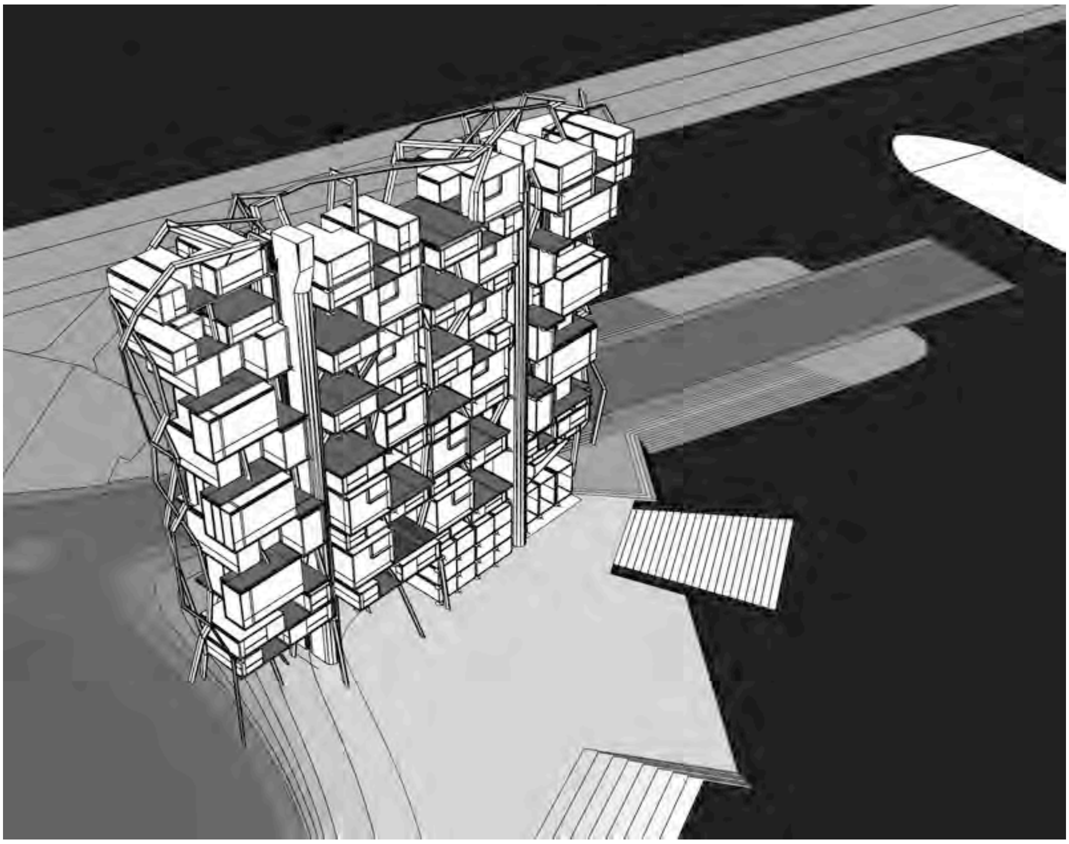

Figure 86 - 3D Autocad™ model showing checkerboard pattern of apartments.

This checkerboard apartment configuration could be used to advantage. Le Corbusier had illustrated such 'maisonette'[114] apartment configurations in his book Toward a New Architecture (Corbusier, 1931), the illustrations show significant

[114] My first contact with the term 'Maisonnette' was in 1998 while working on the Sydney Olympic Village, where two storey maisonnettes were designed into the top floors of the majority of apartment buildings.

two storey double height spaces. The meaning of the term 'maisonette' is not lost here, meaning "Small House"[115]. Such large outdoor spaces within apartment buildings (refer image Figure 87) could transform apartment living, especially in Australia where the temperate climate allows significant use of outdoor spaces for much of the year. In turn this improved liveability and amenity in apartment performance could allow greater densities to be achieved in Australian (and world) cities where it is today a widely held preference to live in a house.

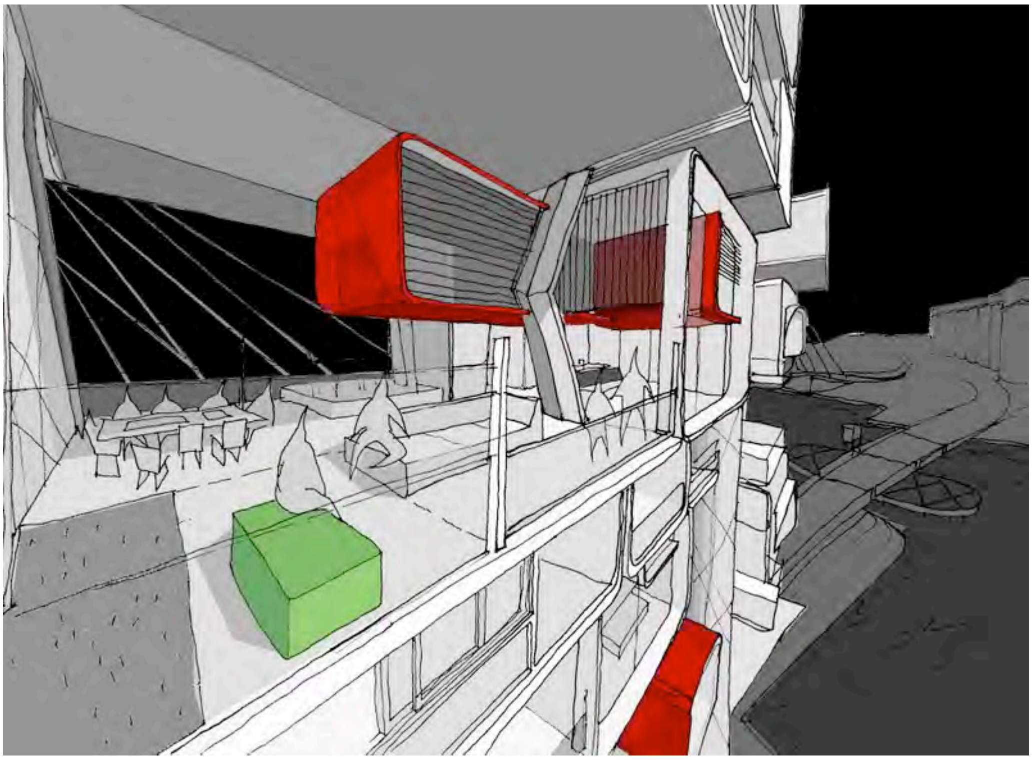

Figure 87 - Freefab Tower double height outdoor space resulting from the apartment checkerboard configuration.

4.1.5. Digital Design tools

The choice of which CAD program to use to document the Freefab Tower was largely governed at the time by the capability of the CAD program to export the

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[115] Maisonette - Google translate: http://translate.google.com/#fr|en|maisonette Access date 17th February 2011

completed 3D file to .STL file format, at the time 2004 unlike in 2011 this capability was not a common function.

Amongst the candidate programs tested (Autocad™, Revit™, Archicad™ and Rhino™) for the project, only Autocad™ was found to export .STL files from the native program. Third party add-ons and patches were available for a number of the other programs, though none were found to create repeatable results. Autocad™ was from the pick of the programs, the least desirable program to use for this project; due to its limited functionality between producing 2D drawings from 3D geometry in comparison to Archicad™ and Revit™; and its limitations both in generating 3D freeform geometry and performing boolean[116] operations.

Using Autocad™ the tower model was created using solids, created in most cases, using the extrude or sweep features. The seep feature which used a profile to 'sweep' along a path or polyline. This feature, although effective in creating the model geometry, was far from state of the art compared with features available at the time using alternative 3D CAD programs such as Rhino™. The lack of parametric features within the program at the time also meant that once the solid had been created from the 'capped' 'sweep' little further functionality was available within the object created.

Figure 88 - Freefab split plan level 11 and 12. Drawing James Gardiner

[116] Boolean in this context is the term used by CAD programs to denote additive and subtractive operations between surfaces and solids.

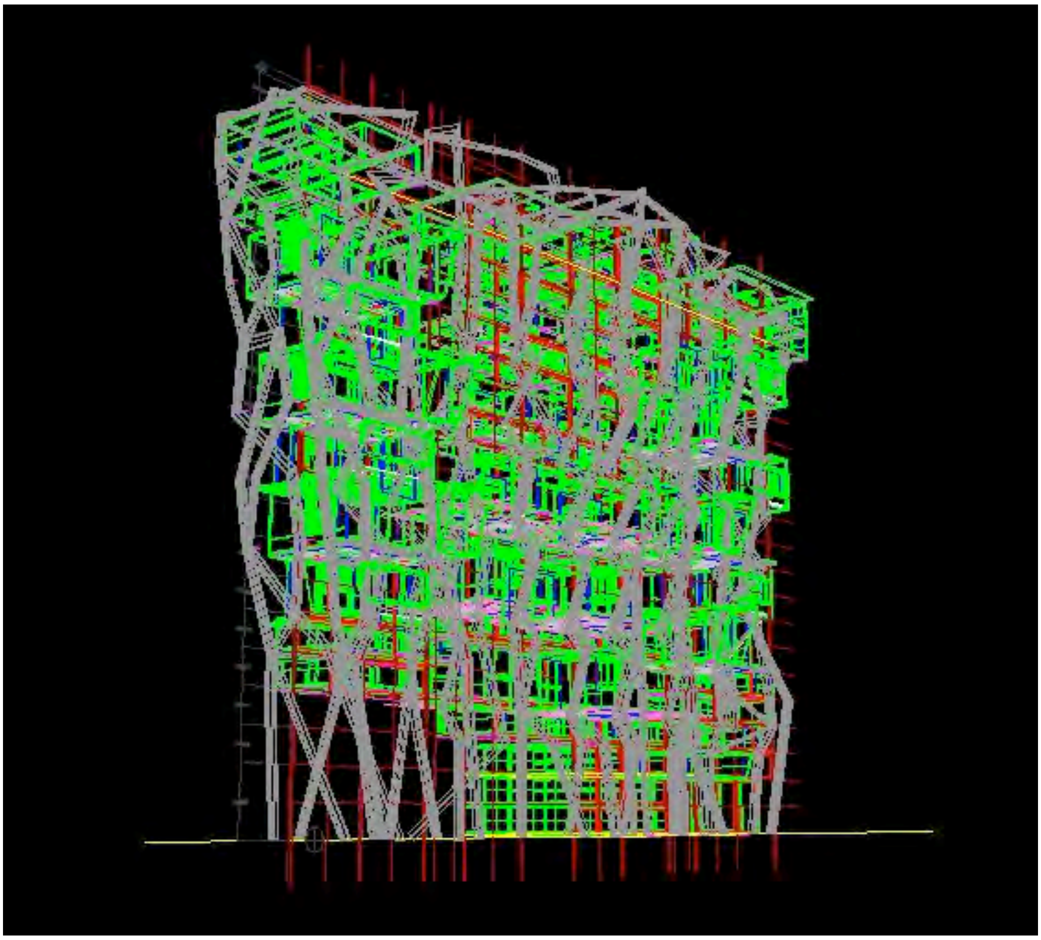

Figure 89 - 3D Autocad™ model made from solids

4.1.6. Freefab Tower Conclusion

The Freefab Tower project (refer image Figure 89), although modest in terms of demonstrating the geometrical potential of Construction 3D printing techniques, made substantial progress in demonstrating the potential of this emerging fabrication technique. The project will not be known for its innovative use of the available 3D Digital design tools at the time, although this may be one of the more complex models made using such methods within Autocad™.

The Freefab project helped to identify significant design and construction opportunities that Construction 3D printing has the potential to offer in the coming years; including the reintroduction of the ‘maisonnette’ in a similar form to that Le Corbusier originally proposed in 1931, fabrication of single material complex wall assemblies complete with the creation of window reveals, sun shading, acoustic treatments, wall textures, air vents, insulation properties, structural dowel rebates and post-tensioned reinforcement conduits. The project also explored the development of unique modules and panels that are designed to respond to the natural elements and forces as well as the aesthetic leaning of the designer.

The Freefab system relies heavily on the use of shells to form the apartment structure as well as to support infill panels. The shell as a prefabricated module is designed for fit-out off-site, which enable the benefits of off-site modular construction to be realised. The Shell is a direct response to the contour crafting technique, which is integrally inclined to create looped shapes, the benefit of this loop is in the creation of a monocoque shell which is both structurally robust as well as materially efficient. The modification of the contour crafting technique simply consists of the replacement of the Contour Crafting gantry with Jointed Arm Robots, which have proven efficacy as well as the ability to be swapped between different factory stations. The preference for fabrication using Construction 3D printing techniques within a factory environment has been substantiated and this theme will be further explored as a theme in case study 2.

Transportation is a key consideration for any off-site fabrication system; the Freefab building system is based directly on the ‘High Cube’ shipping container. Architecturally proportioned spaces have been demonstrated to be achievable through the method of slicing rooms, like a loaf of bread, into shells and using panels to span between them.

A number of significant potentials have been identified through the development of the Freefab project and can be briefly summarised as the following;

- Development of an integrated off-site modular and panelised construction system that could significantly increase the automated fabrication of buildings and components within a factory environment. This could significantly improve the capability of off-site construction through the integration of unlimited geometric freedom without substantial increase in cost, increased automation of the fabrication process and delivery of greater precision through automation based on digital design files.

- The creation of new building typologies based on precedents such as Le Corbusier's Maisonette. Through critical evaluation of the inherent potential within the construction 3D printing fabrication process and the use of off-site construction new building forms can emerge such as the 'checker board' building typology developed with the Freefab tower.

- The fabrication of monocoque shells and panels to form building elements that could significantly simplify the construction/fabrication process by integrating building skin with structure while integrating a wide array of functional requirements (such as ventilation, sun shading, structure, acoustic dampening, fire rating, accommodation of services through the provision of integrated conduits, thermal insulation) all using a single material and taking advantage the capability to achieve this with freeform geometry.

- The identification of articulated arm robots as the device used for deposition of material. This could have the benefit of allowing for greater flexibility in the fabrication process through the leveraging of the 4^{th} and 5^{th} axis during deposition of material and allow greater flexibility to swap out robots for maintenance or repair and the use of the same robots to fulfil other functions such as surface milling, finishing and spray painting.

The Freefab Tower project is important as the first project to explore the design and construction implications of Construction 3D printing, as well as the opportunities for combining construction 3D printing technique with off-site fabrication. These themes have been explored in detail and have created a platform for further detailed research presented in case studies 2 and 3.

The project culminated in the development of a construction system, rather than just a hypothetical tower as its outcome. The original principles and focus areas are still proving, with current professional projects, to be as valid as when they were conceived in 2004. The following case study develops the Freefab system into a system for housing and some of the strategies developed here have been tested as physical prototypes.

5. Villa Roccia Project – Project Case Study 2

5.1. Villa Roccia Project

This project commenced in 2009 with the sketch design of the Villa. The initial design was conceived over a three-week period, after Enrico Dini mentioned the Villa Roccia project to the London Financial Times and they requested images for their article on D-Shape. The design was at that point a series of ideas and sketches that were then developed in haste to meet the newspapers deadline. The client Alberto Farci approved the sketch design of the Villa, on its second iteration, prior to images being forwarded to the newspaper for publication. Unfortunately the images were not published, however the upside was that I had a great project.

Figure 90 - Panorama of the Villa Roccia site near Porto Rotondo, Sardinia

The site for the Villa Roccia is located near Porto Rotondo in Sardinia in an astonishing landscape of eroded granite rock formations and sweeping views of mountains and the Mediterranean Sea (refer image Figure 90). The brief for the villa, although quite vague, requested a design that responded to the natural environment of the locality of Porto Rotondo and specifically to the rock formations of the area. These rock formations are a significant and celebrated feature of the local environment: which is located on the Costa Smeralda coastline in the North East of Sardinia, Italy.

This project borrowed heavily from the Freefab project and then moved beyond this project as the requirements of the villa were addressed. Some of the key concepts developed for the Freefab project, such as the use of prefabrication for the fabrication of components, were found to be indispensible due to limitations of the D-Shape™ technique. While other concepts needed to be adapted and substantially changed as critical analysis of constructability and design for manufacture took place whilst the project progressed through into the prototyping phase. The project type differed substantially from the Freefab project that preceded it, a house rather than an apartment building, and hence the concepts for the villa evolved to take a very different form while still sharing in the accumulated knowledge of the Freefab project.

5.1.1. Design of the Villa Roccia Project

The Villa Roccia project is the culmination of the Alberto Farci's brief for a rock inspired building and my long-term interest in rock formations as a precedent for a new architectural language. Architect Marco Cerina, who is the Brother in-law of Enrico Dini, had brought the client to D-Shape seeking an extraordinary project that could do this site justice and had proposed his own designs at an earlier date. Marco Cerina has acted as the intermediary in the project especially in resolving the network of planning approvals required in Sardinia at the local and state level. Enrico and I first discussed this project in May 2009 at a conference in Chicago, after I had shown him a series of photographs of rock formations and discussed the potential of emulating such formations in buildings with the D-Shape machine.

Figure 91 (a) House built into a boulder in the hills near Nuoro in Sardinia. Image source - http://www.cyclelogicpress.com/S/rocksymbiosis.html (b) Domus de Jana in Sedini, Sardinia. http://www.stockphotos.it/image.php?img_id=12990168&img_type=1 Access date both images 15th August 2011

In Sardinia there is a long tradition of building houses around and into rocks (refer image Figure 91 a & b) and houses that mimic rock forms. While visiting the client in his hometown in Nuoro I was taken on a sight seeing trip where we stumbled upon this house (refer image Figure 91 a). Luckily the owner was home and we were able to have a quick tour. The house was just one long room with a low ceiling (of natural rock) that had been created by inserting the white wall under the boulder across a natural cavern under the boulder.

A number of contemporary and 20th century architects that have designed rock and landscape inspired houses in Sardinia including: Giani Gamondi, Jacques Couelle, Savin Couelle, Gerard Bethoux (Bianchi, 1999). The most interesting design is Jacques Couelle's own house situated located on Monte Mannu on the Costa Smeralda (refer image Figure 92).

Figure 92 – Jacque Couelle house on Monte Mannu, Sardinia. Image source - http://portocervo.exblog.jp/13753198/ Image accessed 14th August 2011

While not clearly resembling a rock, the forms of this house are certainly a response to the language of rock formations in the Costa Smeralda area (refer image Figure 92): with similarities to the random holes (like tafoni), which are expressed here as windows, overhangs and lips that form cave like openings and the undulation of the forms which mimic the randomly shaped and eroded rock formations of the area.

The "*specificity of the architecture Couëlle is its relationship to nature: its houses fit perfectly into their natural environment because they borrow their forms.*" (Hendel, 2011)

This building from reference to the photo (refer image Figure 93 a) was fabricated entirely by hand. Firstly a steel mesh structure was created providing a building profile, onto which concrete or cement was applied.

Figure 93 (a) Jacque Couelle house under construction. Image source - http://labyrinthe.revues.org/index1360.html
(b) Interior view of Jacque Couelle house http://utopies.skynetblogs.be/archive/2009/02/12/jacques-couelle.html Images accessed 14th August 2011

The architecture of Couelle's son is more literal in its creation of rock houses with the liberal use of stone while using a similar language to that of his father as described above. The interiors of his houses have a more restrained and refined language but again show his fathers influence (refer images Figure 94 a & b).

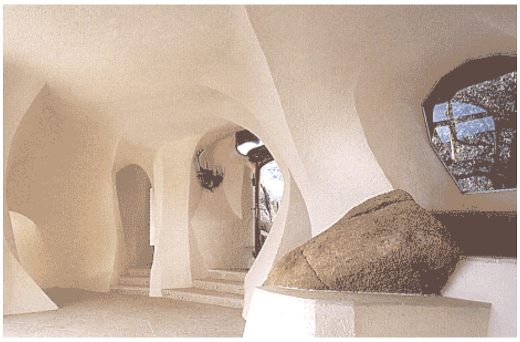

Figure 94 – (a) House by Savin Couelle. Image source (b) Image source - http://www.couelle.com/gallery.php?insFile=1&next=2

This work has obvious visual similarities to the earlier work of Antonio Guadi in the Casa Mila 1910 (Figure 95 b) and Fredrick Kiesler's Endless House (refer image Figure 95 a) 1952 (Yoon, 2004) although each of the projects by Guadi and Kiesler had quite different motivations and principles for the generation of form (Burry, 2007, Yoon, 2004) they can all be said to represent "Fantasticism" (Burry, 2007) p7 (Dezeuze, 2003) in architecture through their adoption and inspiration from natural forms. This movement and approach was at odds with the ideology of the 20th century modernist movement.

Figure 95 (a) Kiesler creating a large-scale mockup with mesh and plaster of the Endless House. Image source - http://www.shootyourstudio.com/?p=240 Access dates 15th August 2011 (b) The Casa Mila by Antonio Guadi 1910

Figure 96 – Photo of the model and a dplan of the Endless house by Fredrick Kiesler. Image source - http://archiveofaffinities.tumblr.com/post/2632459841/frederick-kiesler-the-endless-house-1960

The Villa Roccia project continues the tradition of rock houses in Sardinia, although the design is more aligned itself to the design practices of Gaudí: through seeking to understand and respond to the forces operating on the building, development of a system of design, designing to enable production (and keeping aspirations intact), working with the people that are charged with fabrication of building elements, while also attempting to synthesise a relationship between man, technology and nature (Burry, 2007).

This Villa Roccia project discussed and analysed here is the first house commission for a project using Construction 3D printing techniques. This case study explores three distinct stages of building design and prototyping: first the design of the Villa, second the design and fabrication of a prototype column and third the design of a building assembly.

5.1.2. Aspirations

The principal aspiration for the Villa Roccia project was to create a responsive architecture that could take advantage of the opportunities inherent in the D-Shape Construction 3D printing technique. The goal of this approach was to create a highly responsive digital design that could find a digitally defined best fit solution to a range of inputs such as structural load, thermal comfort requirements, sun-shading, water shedding, material minimisation, acoustic treatment, erosion etc.

Efforts to develop projects using multi-criteria optimisation and parametric design have recently been demonstrated by Holzer et al. using a variety of software and customised tools. This was a major focus area of his PhD research while embedded with Arup Sydney and Melbourne. (Holzer et al., 2007, Holzer, 2009, Holzer et al., 2011)

The aim for striving toward multi-criteria optimisation and parameter driven flexible design is well summarised by the following statement:

Performance oriented design aims to make "*form and function less of a dualism and more of a synergy that aspires to integral design solutions and an alternative model for sustainability*" (Menges and Hensel, 2008) p7

Unfortunately the resources and skills were not available for the envisioned multi-criteria 'optimisation', during its various stages the projects were barely able to achieve single input optimisation, despite my best efforts. Yet in spite of this inability to demonstrate multi-criteria optimisation much has been achieved and demonstrated, in relation to development of design strategies for construction 3D printing, testing and development of strategies for the use a suite of digital tools, testing and prototyping and developing a synthesis between the aspirations of man (the client), technology (D-shape, digital tools) and nature (the natural environment and design aspirations).

Many of the ideas that I have tested in this project are further refinements of ideas and strategies that I first developed and applied to the Freefab project (case study 1). The scope and extent of this project has provided a rich testing ground for this developing the original concept.

5.1.3. Rocks and the Development of a Design Language

As discussed, in the introduction, this project represents a fortuitous combination of interests, the client's brief seeking a harmonious combination of landscape and building, the site with its breathtakingly beautiful landscape and my love of rock the particular type of rock formations found on the site and a deep interest in finding expression of this in architecture.

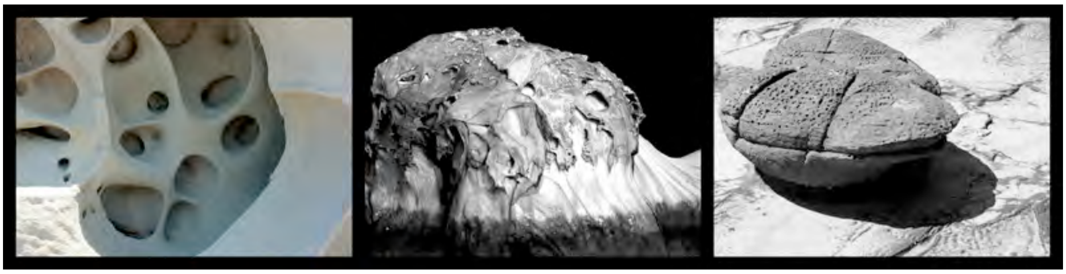

Figure 97 – Selected rock photographs from the East Coast of Australia. Photos James Gardiner

I have been actively photographing rock formations since 2002 (Figure 97) and personally find some rock formations to be more aesthetically inspiring than many of the renowned buildings that I have visited around the world. My sensibilities as an architect however remain strangely aligned with certain modernist principles, for truth and transparency in the expression of buildings, through which 'ornament' could often be justified. Modernist 'ornament' was most often achieved by revealing structure, means of construction, services and materials (Moussavi and Kubo, 2006). In addition to this modernist leaning, I have a distinct interest toward enriching this architectural expression through engagement of 'performance oriented design' (refer definition of terms 1.5).

Figure 98 – Rocks on the Villa Roccia site. Photos James Gardiner

Analysis of rock formations in the Porto Rotondo area (refer image Figure 98) was necessary, for me, to develop an understanding of the erosion typologies present in the area. This understanding informed both the development of the initial architectural language developed for the design of the Villa Roccia and for the design of the rock erosion simulation for the project. The terminology used for topographic rock features varies widely according to author and discipline, although some commonly used geological terms for erosion features include pit, groove, flute, sill, fin and cavern (Bridges et al., 2004, Turkington and Paradise, 2005). All of these features have been identified in the Porto Rotondo area. The term commonly used for eroded rocks is 'ventifact' (Turkington and Paradise, 2005). Sub-classifications also exist: clusters of pits and or caverns are called Tafoni. A series of diagrams refer, image (Figure 99), identifies these features and clusters for the purpose of developing a 'Roccia'[117] architectural language. The following terms that comprise my rock feature language borrow both from architectural language and geological literature including: boulder, seam, cave, screen, aperture, sill, flute, crease, fin, rib, bump and pit.

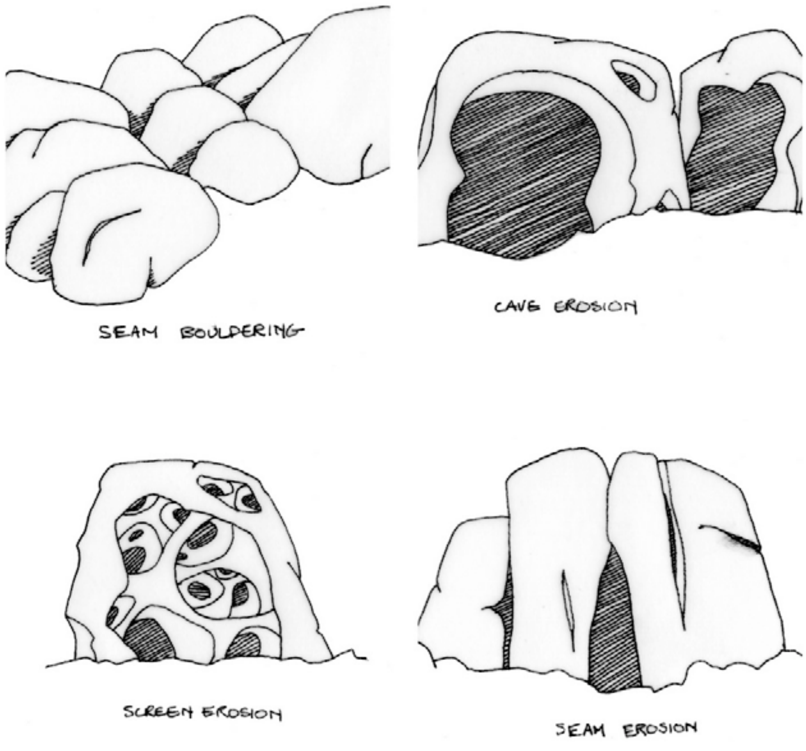

Figure 99 - Diagrams of local rock features. Image by James Gardiner 2009

[117] Roccia – Italian meaning rock

The sketch design perspective, refer image (Figure 100), includes most of the elements described in the rock feature architectural language listed above. Bouldering is used to refer to the development of the building as a series of 'boulders' within the landscape, which define separate spaces within the Villa. Vertical and horizontal 'seams' are used to define the construction sub-assemblies that collectively create the boulders while also creating 'apertures' (windows, doors and skylights). Caves define deep recesses in the structure, such as large overhangs and openings. 'Screens' are used to define collections of apertures, while using 'fins' to create shading on the exterior and structural ribs internally. 'sills', 'flutes' and 'creases' are used to define sharp changes in geometry within the boulders. Pits, bumps and ribs are surface texture elements are will be applied for wind attenuation externally, for acoustic purposes internally and other undefined purposes. The feature listed above form the basis of the architectural 'Roccia' language for the Villa.

Figure 100 – Sketch design perspective of the Villa Roccia. Image by James Gardiner

The predominant rock type in this area is granite which has been estimated to have been formed 300 Million years ago (Ferrara et al., 1978). The erosion of the granolithic rock formations in this region is well advanced and responsible for the formation of highly sculptural forms broadly called 'ventifacts'. The cause of the erosion is still being debated in current literature. The most commonly attributed cause for the creation of these rock formations in Sardinia is through 'salt weathering' (Evelpidou et al., Huinink et al., 2004).

"*Salts are widely recognized as an important cause of weathering of both rock formations and historical objects…..When a rock dries, salts are transported with* *water to spots where water evaporates. Salts crystallize at these spots and damage the structure of the material.*" (Huinink et al., 2004) p1225

Other causes such as Aeolian Erosion may also be responsible for this effect, as similar formations are found in areas without significant presence of salt minerals (Bridges et al., 2004, Turkington and Paradise, 2005).

The Aeolian erosion "*process involves the shearing and turbulent action of near surface winds that remove regolith* (loose rock particles) *and poorly cohesive sediments, forming features such as moats, wind tails and lag deposits*" (Bridges et al., 2004) p199

There appears to be very little simulation of the effect of 'salt weathering' or Aeolian erosion effects, except in a number of cases where physical wind tunnel tests have been performed (Bridges et al., 2004, Gill and Shao, 2004). Examples of digital simulation of Aeolian erosion and 'salt weathering' have not been located, although digitally modelled erosion was modelled in the 1999 film 'The Mummy' by Stephen Sommers, although this Hollywood simulation is likely to have been subject to very little scientific rigour.

There is clearly an opportunity to simulate Aeolian erosion using digital CAD based simulation methods. Such simulation could assist in the creation of a response to the local environment and topography, weather effects on the site such as wind and rain, while accommodating and responding to construction methods, creation of openings, expression of joints and volumes. Integration of such factors could be used to create a responsive design and aesthetically interesting design response. Preliminary attempts to simulate Aeolian erosion are discussed in reference to the Villa Assembly later in this chapter.

5.1.4. Bones as a Precedent for Structure

A similar ongoing field of research in my practice, which has been influential in shaping the design of the Villa is bones. The 'life' of bones is an incredibly complex and dynamic affair. This study of the bones has revealed the how bones function within the body and respond to forces acting on them by constantly destroying and rebuilding themselves.

"*Bone has a varied arrangement of material structures at many length scales which work in concert to perform diverse mechanical, biological and chemical functions; such as structural support, protection and storage of healing cells, and mineral ion homeostasis.*" (Rho et al., 1998) p92

Interest for the purposes of this project is limited to the macro-structural[118] properties of bones, including the way that different structural configurations are used in the interior cavities of bone to create a range of physical and mechanical properties, the way bones combine (compressive) mineral structures and (tensile) collagen filaments to create extraordinary strength and how these properties (including their aesthetic manifestation) can be used within an emerging freeform construction that is enabled by particular construction 3D printing fabrication techniques.

The book 'Job's body' (Juhan, 1987) gives a number of remarkable insights into bone and its various functions

"*The mineral content and architectural properties of these dried remains are similar to those of marble. Their solid resistance to compressive forces is very impressive indeed, given their relatively light weight: The ends of the thigh bone will withstand between eighteen hundred and twenty five hundred pounds of pressure*" (Juhan, 1987)[119].

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[118] Those structures that can be seen with the naked eye.

[119] 2500 pounds of pressure equals approximately 1100 Kg in Metric

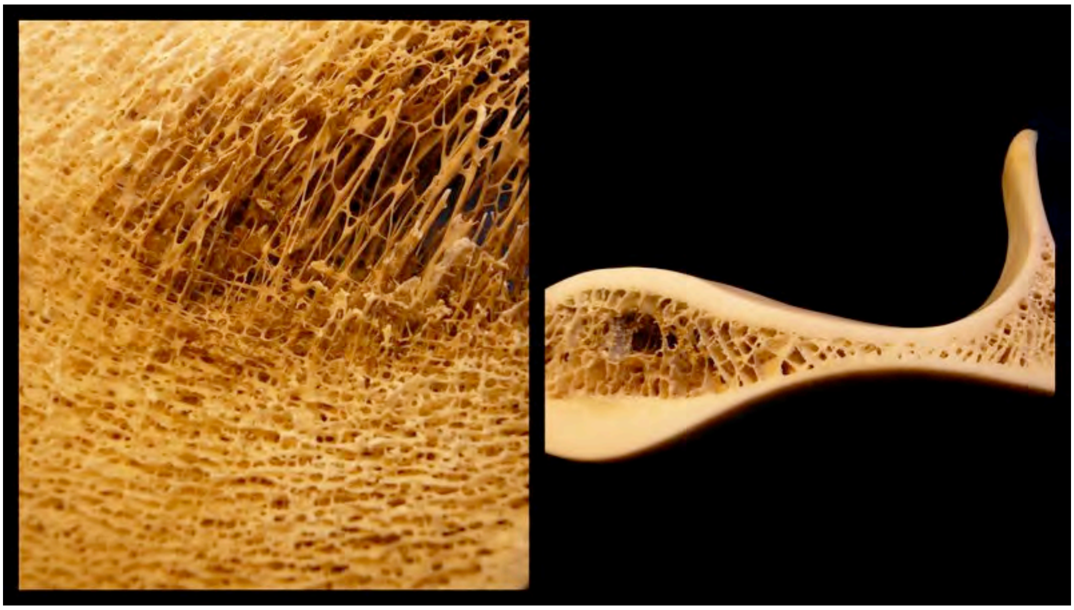

Figure 101 - Bone specimens revealing internal 'trabeculae' structure. Photos and specimens by James Gardiner

In strength to weight ratio bones are very efficient, largely due to the combination of cortical ‘solid structure‘ with trabecular ‘lightweight structures’(Rho et al., 1998). Such internal structures would be virtually impossible and hugely wasteful to create using subtractive or formative construction techniques[120] (refer images Figure 101).

The interesting counterpoint to the argument of the inherent strength of dried bone is eloquently described in the following statement by the same author

“*but this remainder* (dried bone) *is really only the skeleton of a skeleton: it is a brittle white substance that has little in common with the remarkable properties of bone*” (Juhan, 1987).

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[120] Wasteful in terms of: the quantity of formwork required with formative technique or quantity of material removed with a subtractive technique.

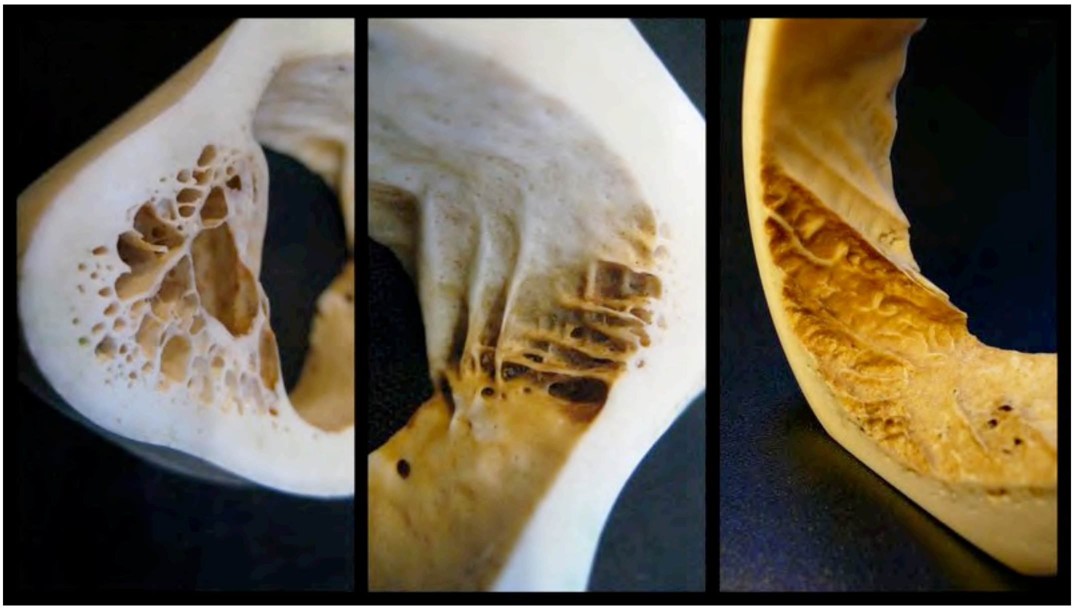

Figure 102 - Bovine thighbone specimens reveal the transformation of bone structure from joint to shaft, trabeculae following stress lines agglomerates into dense struts and then disappears into the bone walls. Photo and bone specimens by James Gardiner

Living bone has in addition to this mineral structure the reinforcement of connective collagen fibrils, largely arranged along the tension stress lines that the bone is subject to. The collagen fibrils within living bone add a high level of tensile strength to a structure that performs very well in compression (Juhan, 1987). In this way bones can be seen as an excellent inspiration for the design and responsive potential of Construction 3D printing techniques.

"*From the engineers point of view* (the dried bone) *it is a diagram showing all the compression lines, but by no means all the tension lines of the construction: it shows all the struts but few of the ties" and goes further to say of live bone "but in life that fabric of struts is surrounded and interwoven with a complicated system of ties*" (Thompson and Bonner, 1961)

The medical profession currently uses scaffolds to assist in the replacement of sections of bone damaged on the battlefield from the Iraq and Afghanistan conflicts (Meredith, 2009). 3D printed porous ceramic scaffolds designed specifically to fit the patient are currently being tested (3D_Creation_Lab, 2011). The benefit of such implants is both in the speed in which the scaffold can be fabricated, based on patient 3D scan data of the effected area, but also in the ability to create a geometrically exact replacement of the bone lost.

The D-Shape technique has a proven capability to create highly complex geometries at construction scale (refer to image Figure 22), the possibility of creating structures with similar strength to weight ratios to bone is also potentially possible.

Just as within bone, it is possible to include tensile materials within construction 3D printing structures that follow stress paths acting on the building, in the form of post-tension steel cable reinforcement. Construction 3D printing techniques, especially D-Shape™, can fabricate the internal conduits within fabricated structures, which can accommodate these tensile materials. It is envisaged that an optimised building compressive structure, could follow the model of bones with trabeculae following and cross bracing along stress lines. Tensile cables could be incorporated to act in a similar way to collagen fibres within bone.

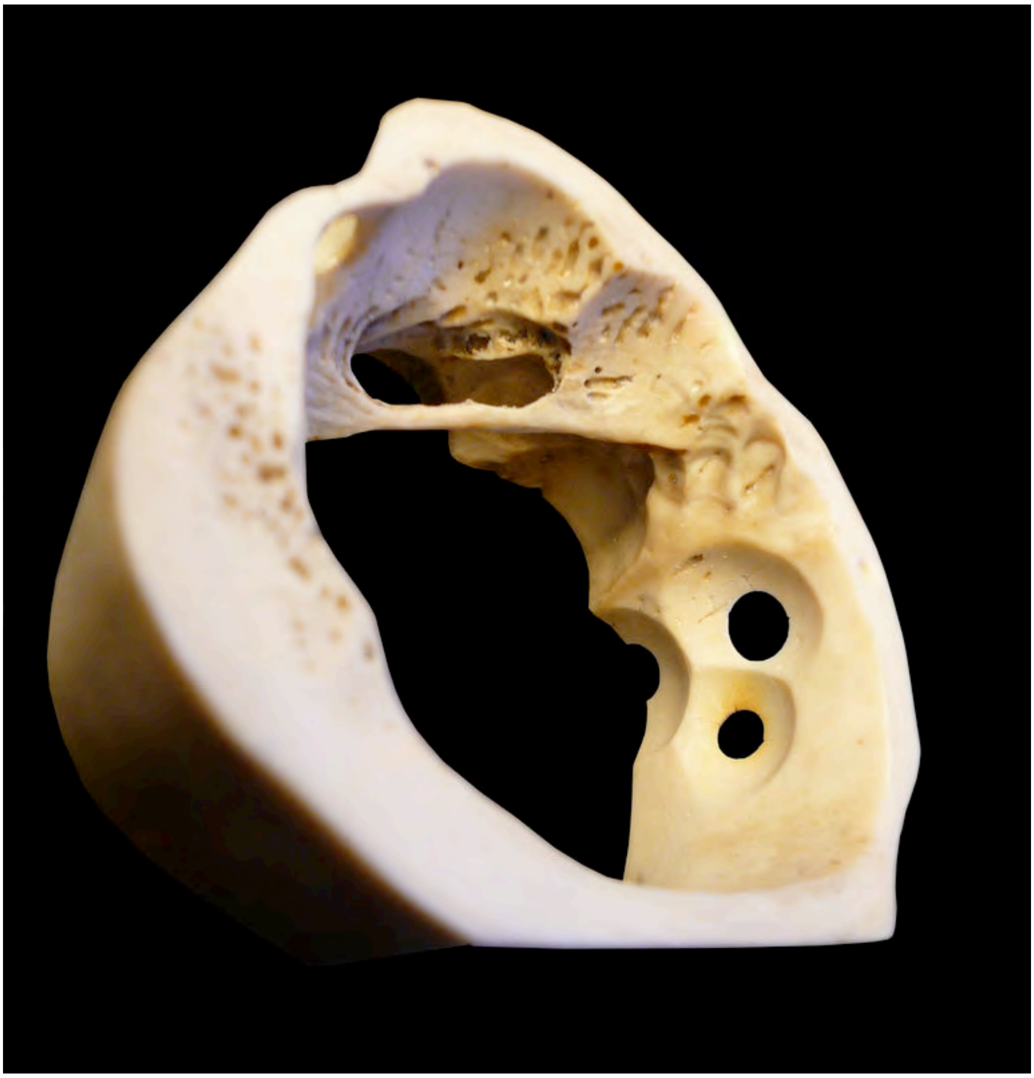

Figure 103 - Section of a cow thighbone sculpted to represent possible construction shells for the Villa Roccia. Photo and sculpted bone specimen by James Gardiner

In the case of the Villa Roccia construction a new factor needed to be considered. Due to fabrication size restrictions at D-Shape™, the monocoque shell off-site fabrication method developed for the Freefab project could only be used in special circumstances where a high degree of rigidity was required. Therefore the majority of the assembly had to be designed for panelisation rather than a mix of modular and panelised construction. The stiffening of joined panels therefore becomes of increased importance, without the stiffening attributes of the monocoque shells. Dowels could be used, as they were proposed for the Freefab project, to bridge panel joints locally. Additional stiffness through compression would be achieved through the use of post-tensioned reinforcement, working in a similar way to the way collagen fibres span from bones into ligaments and then the collagen from the ligament spans into the next bone, ensuring a continuous thread of fibres holding the structure together (Juhan, 1987) (refer image Figure 104). The provision of dowel sleaves, as designed for the Freefab project, and post tension reinforcement conduits would be integrated into the digital design of the panels and fabricated directly using the D-Shape™ technique.

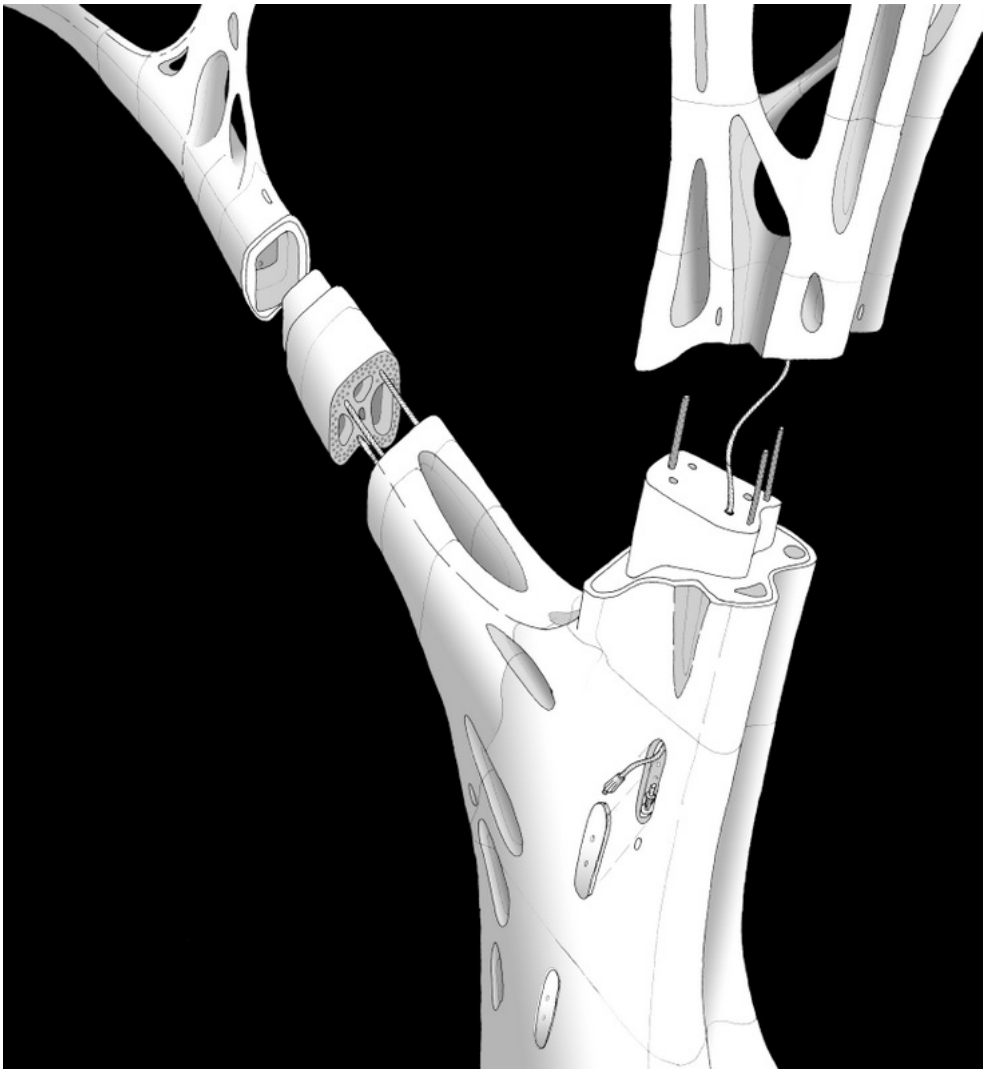

Figure 104 – Early design sketch for the breakdown of a column mortise and tenon jointed sections, with dowel and post-tension reinforcement. Image by James Gardiner.

Although we can begin to emulate some of the responsive functions of bones, it will be a long time before we can create truly responsive buildings that can change as loads and stresses change. Bones have the ability to continually erode and/or build themselves in response to the stresses to which they are subject, through the function of Osteoclasts and Osteoblasts. Such possibilities for a living architecture that could respond actively to change of use and forces acting on the building would be truly revolutionary within the built environment.

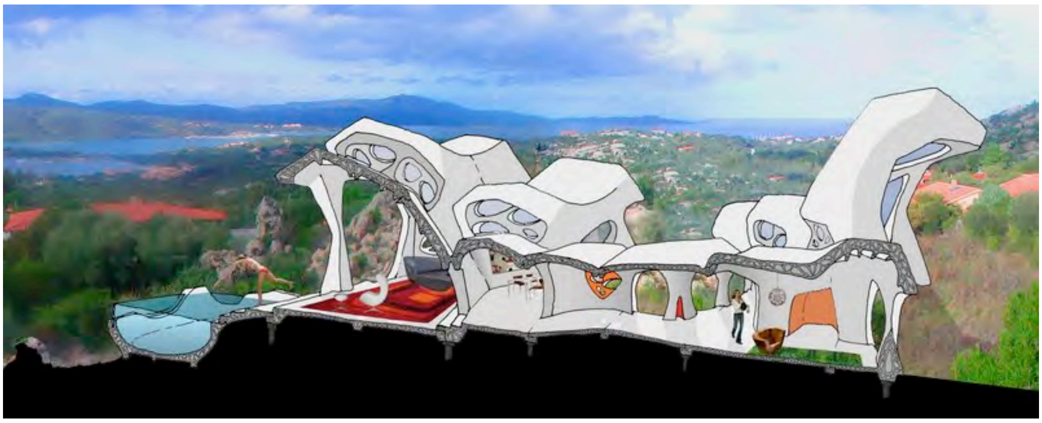

Figure 105 - Cutaway Section perspective of the Villa Roccia. Image by James Gardiner

5.1.5. Developing Strategies for Off-site fabrication

The design for the Villa was conceived under the premise that the building would be fabricated off-site, this prerequisite from D-Shape™ followed my own inclinations as a specialist in the field of off-site fabrication and construction 3D printing. D-Shape™ had experienced difficulties in the past, with in-the-field fabrication due requirements for curing and machine operational efficiency[121].

The design of elements at the outset followed a similar the methodology developed for the Freefab Tower (chapter 4.1), with the predominant use of panels rather than 'shells' as discussed above. Changes began to creep in as information about D-Shapes fabrication constraints and requirements was worked through. The sectional perspective drawings (Figure 105 and Figure 106), illustrate the preliminary methodologies developed to deal with the requirement for modularisation and reinforcement. The response to these requirements is based on extensive international research of off-site fabrication within the construction

[121] Bases on discussions with Enrico Dini throughout 2009.

and parallel industries (discussed in the preceding 3.5) and with broad discussions with Enrico Dini of D-Shape.

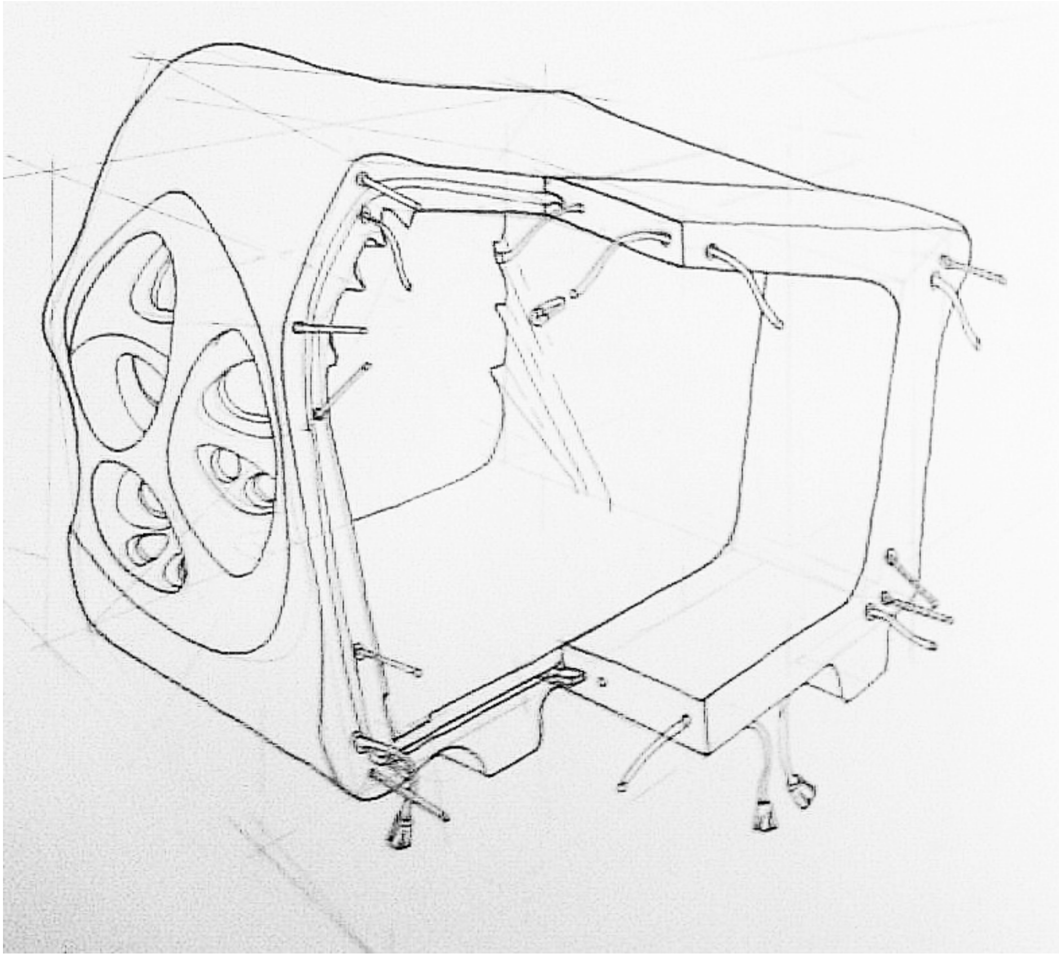

Figure 106 – Early Villa Roccia construction assembly cutaway section, showing monocoque shells rather than panels. Sketch by James Gardiner

The longitudinal section drawing through the Villa (Figure 105), illustrates a series of major sub-assemblies, the exoskeleton of the building. The sub-assemblies are expressed as individual ‘boulder’ elements. This both allows a clear reading of the building as a series of individual volumes, for example the major living room space on the left is clearly a different volume to the dining room that is next to it. This approach both satisfies my preference for clear expression of function (as discussed earlier in this chapter), while adopting off-site fabrication methods, building up sub-assemblies to create large volumes, which are consolidated to create the final building.

The sectional perspective (Figure 105) illustrates a higher level of detail for the breakdown of a sub-assembly into a series of panels. The construction process of a ship, described to me on visit at the DSME shipyard in South Korea in 2006 was: ‘part - block - mega block - ship’. The same strategy is applied to the construction of the Villa Roccia. This expression describes the gradual agglomeration of parts into larger assemblies, through discreet stages to form the whole. There are many advantages to using the off-site approach as detailed in (chapter 3.5.1) for this project these are: working within the current fabrication constraints of D-Shape™, preassembly and fit-out of elements off-site to take advantage of skilled labour and off-site quality control and taking advantage of factory production for a remote location.

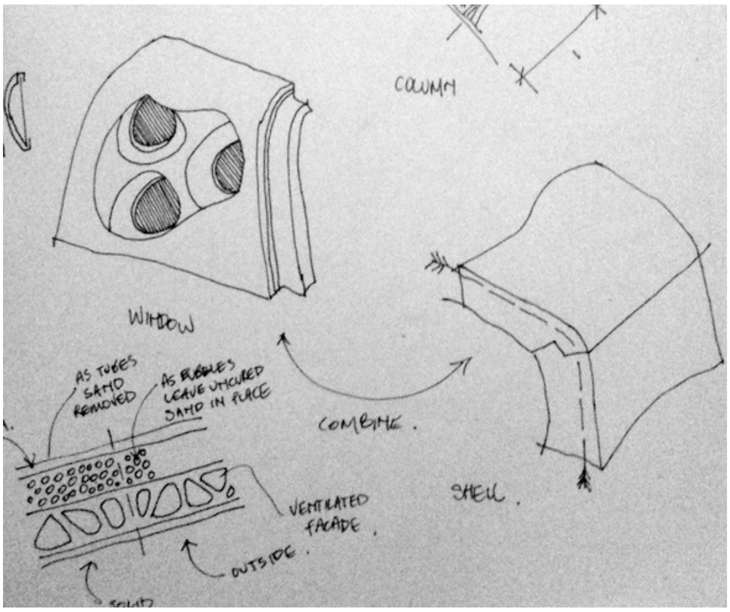

Figure 107 - Early development sketches focusing on panelisation and internal wall structure. Sketch by James Gardiner

5.1.6. Conclusion Villa Roccia design

The above description of the design of the Villa Roccia represents the first steps toward realising a building using Construction 3D printing techniques globally. The design of the Villa has been generated from a response to a study of rock formations to generate an architectural language, as well as research into the formation and properties of living bones, which are well known for their strength to weight ratio and geometric responsiveness to forces acting on them. Strategies have been advanced beyond those developed for the Freefab project, for the off-site fabrication, panelisation and detailing of the villa. The principals developed for the Villa Roccia project are explored in detail in the next two projects that focussed on the detailed design and construction of the villa.

The development of the language for the Villa Roccia design relied largely, in the sketch design phase, on the visual interpretation of the Sardinian rock formations, my physical study of bone structures and a the literature review of rock erosion and bone structures. This research was synthesised into a language, which incorporates requirements for the off-site fabrication of the elements using the D-Shape Construction 3D printing technique. This language has been applied to the design of the Villa Roccia (Figure 100) and is further applied and explored in the Roccia Assembly to follow (chapter 5.3).

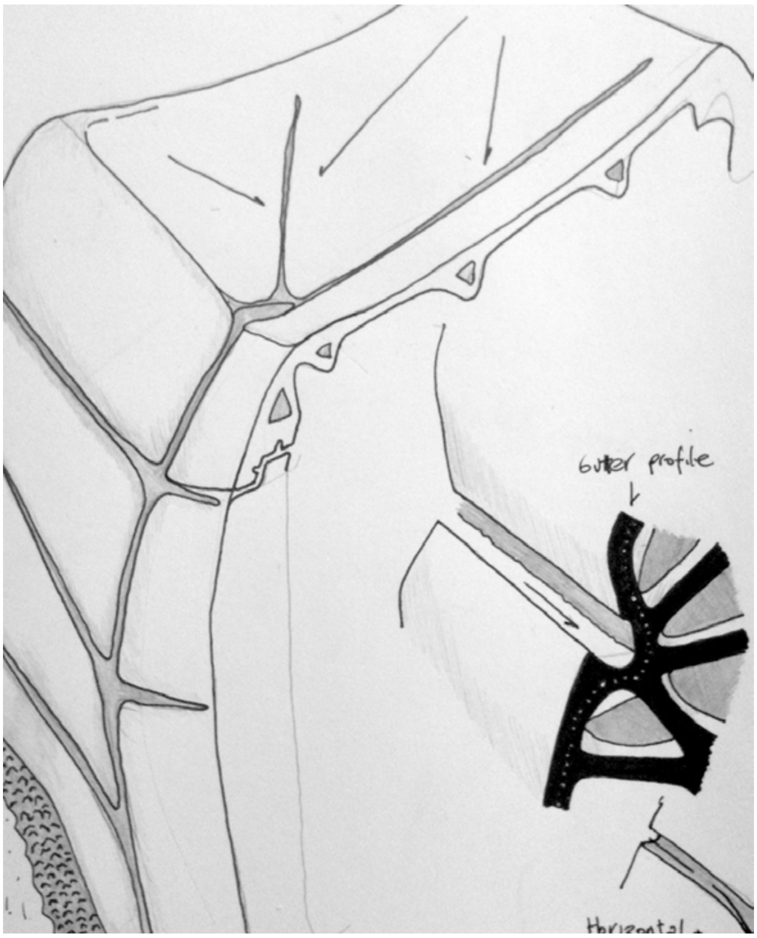

Figure 108 - Sketch development of water shedding method for the panels. Draining water away from the joints. Image by James Gardiner

5.2. Roccia Column Prototype

The Roccia Column prototype, for the Villa Roccia, was a test project initiated after the sketch design of the Villa Roccia was completed. The prototype column was used to assess the applicability of methodologies developed since 2004, as well as new methodologies developed specifically for the Villa Roccia project, essentially putting theory into practice to learn from the results. The column explores the opportunities and limitations of construction 3D printing, while adopting the use of parametric software for its design.

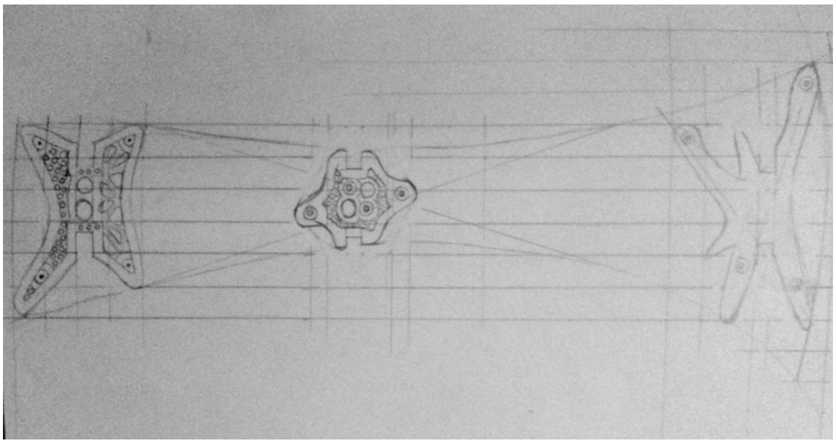

Figure 109 - Sketch for the method of generating the column from a series of profiles. Image by James Gardiner

The primary methods explored within this project were the following;

- The generation of geometry that responded to the capabilities and limitations of the D-Shape technique (such as minimum printable detail and wall thicknesses)

- Testing the use of parametric software for the development of the construction geometry, for the generation of a flexible model with detailed element joints that could be shifted and update as the envelope changes.

- Reduction of weight and materials required through the use of internal structural geometries.

- The integration of post-tensioned structural reinforcement, which could be installed after the column was fabricated.

5.2.1. Design and Digital Tools for the Roccia Column Prototype

The project described here is a fairly simple parametric column. One goal was to explore how repetitive elements could be generated parametrically that would reduce the need to model each instance separately, potentially allowing more time to be spent n the development of a smart adaptable system and less time on repetitive modelling procedures. At the time my experience of parametric Digital design tools was extremely limited, after some fiddling around with Generative Components™ and Digital project™ I decided to go with Grasshopper™ a plugin for rhino™ as this program appeared to be eminently suitable for the task and easy to use.

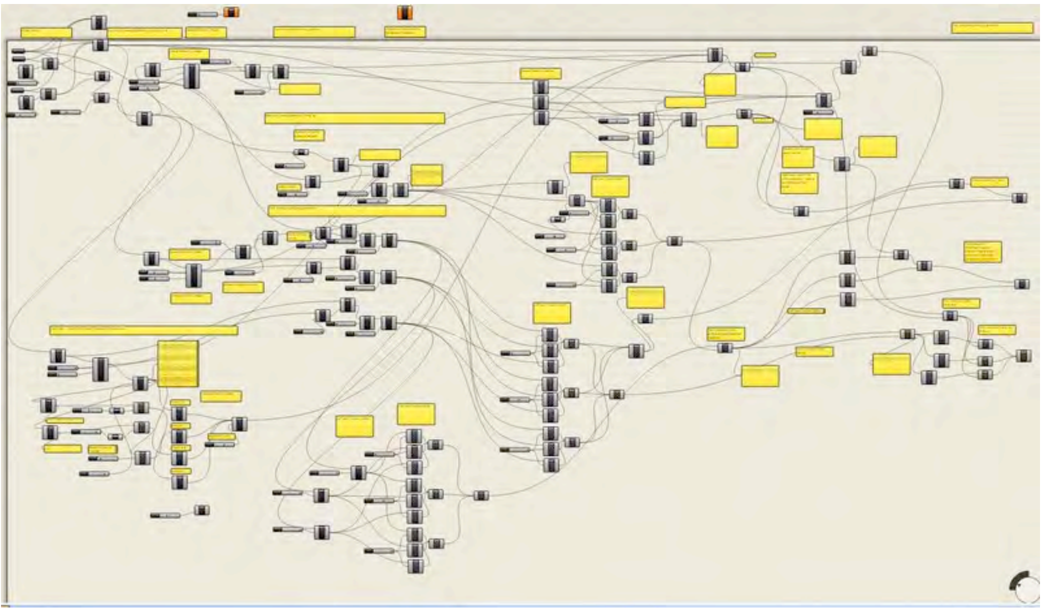

Figure 110 - Grasshopper™ definition of the parametric column. Image by James Gardiner

The following is a description of the set-up of the grasshopper parametric model (refer image Figure 110): first a point in space was generated, a second point above the first point was then generated with its height governed with a numerical slider, relative to the first point. A line was generated from these points, this line was then divided into increments, and points generated at the divisions, these points on the vertical line were each assigned a two-dimensional polygon, with numerical sliders governing the number of polygon sides and the radius of the polygon. The shapes of these polygons were then relaxed via a numerical slider to create an organic profile (refer Figure 110 & Figure 111). These profiles were then lofted together to create the external envelope of the column. The internal envelope of the column was generated by off-setting the polygons toward the centre by 30mm, this was based on the minimum preferred thickness and element size established with D-Shape™[122]. These profiles were then also lofted to create the internal envelope of the column. The two envelopes were then individually capped, with the internal envelope then booleaned (extracted) from the external envelope to create a hollow column.

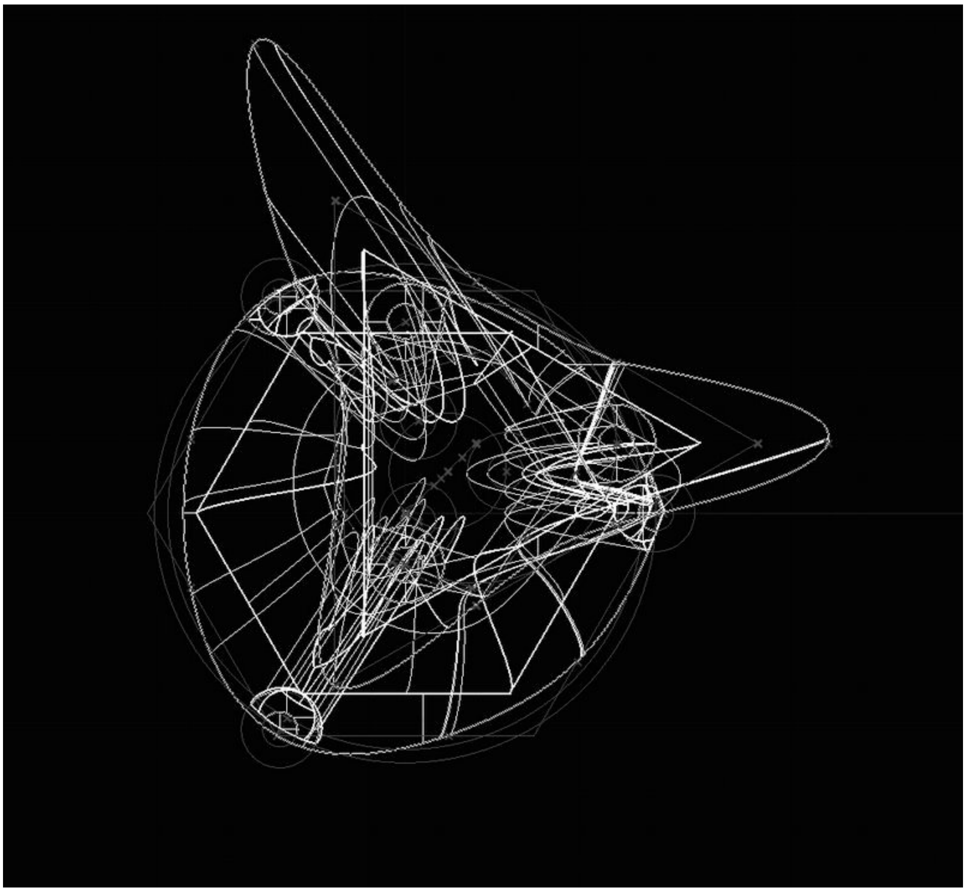

Figure 111 - Wireframe view of grasshopper setup geometry for the prototype Column, note the generating simple polygon geometries and the relaxed geometries created from them.

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[122] In this instance I encountered an inexplicable problem with offsetting the relaxed profiles by 30mm in grasshopper, the original polygons were eventually used instead as no solution to the problem could be found at the time.

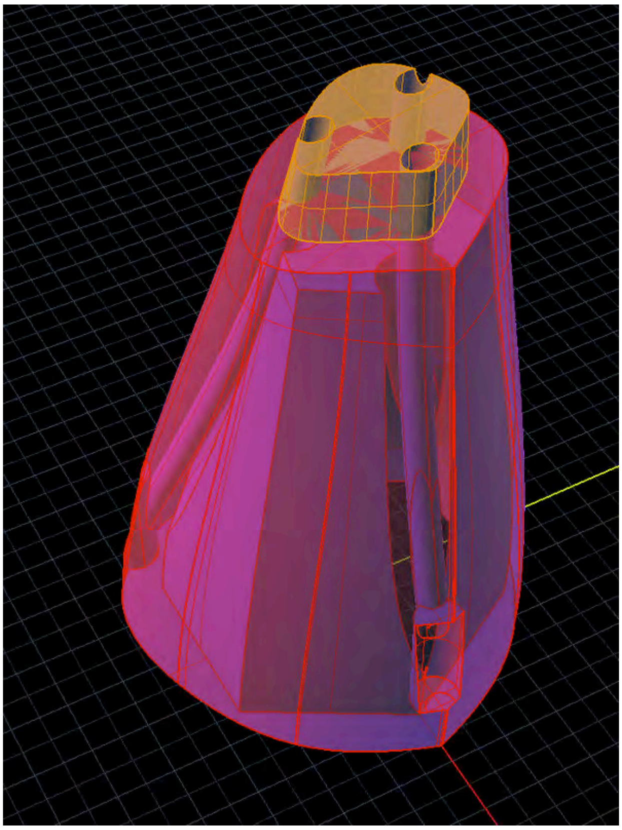

Figure 112 - Column base with internal post-tensioning conduits and mortise and tenon joint to join to column top.

Internal conduits for post-tension cable reinforcement were then generated, starting from a pocket 100mm above the base of the column and terminating through the top, which would normally be the junction between column and roof or wall panel. The conduits were given a 30mm wall thickness, as was the minimum wall thickness recommended. As these cables[123] were designed to be tensioned from the base of the column, the pocket created at the base of the column accommodates the anchorage which would be later be concealed with a cover plate. The image (Figure 112) shows the bottom half of the column, with the pockets, the solid geometries of the conduit walls were first booleaned out of the hollow column geometry and then a copy of the conduit walls was booleaned into hollow column geometry.

[123] The correct terminology is for the post-tension cable is ‘tendon’.

The column, at the time of the modelling, was designed for fabrication in two halves, each approximately 1.5 meters in height. An important test was to generate a flexible parametric model that could be cut at variable heights with a specific joint profile, in this case the mortise and tenon joint. When this joint was created a number of issues arose; wall thicknesses of the column elements and the location of the conduits needed to be closely managed[124]. The necessary management strategy that was required to be described parametrically proved to be beyond my skills and time constraints precluded me from following Alice down the rabbit hole (so to speak). I instead decided in this case to model this joint manually in Rhino with the 'baked'[125] grasshopper geometry. Hence the parametric column was parametric only to a specific stage, this breaking of the parametric model to manage an issue ended up becoming a liability when I was later asked to increase the size of the column.

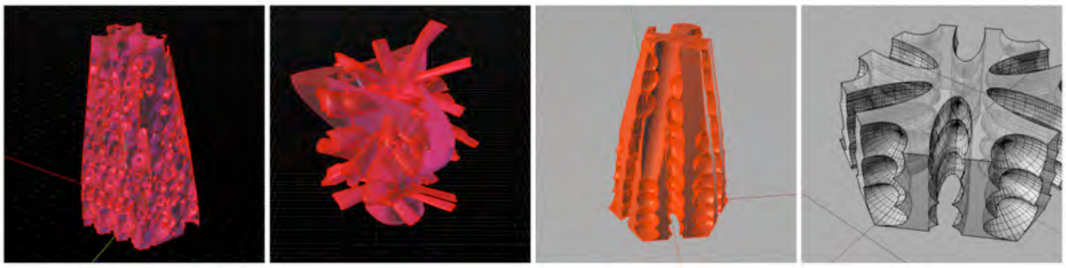

Figure 113 - Internal geometries tested - random voids, random branching, regular voids and large voids. Models by James Gardiner

The next stage of modelling was the generation of the internal geometry to fill the column void in order to allow a reduction in materials used and weight of the overall column structure, while providing maximum strength. A number of

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[124] Wall thicknesses as noted above had to be a minimum of 30mm thick, with a gap of 15mm between the elements to provide tolerance for the accuracy of the D-Shape™ technique. The conduits also needed to sit within the tenon, so that water could not enter the conduit through the joint in the column.

[125] The Term 'baked' is used to indicate the action between Grasshopper™ and Rhino™ where the live parametric model geometry is output as a non parametric surface model for further manipulation with Rhino™ editing tools.

geometries were investigated (refer images Figure 113); with two internal geometries eventually used, one for the base and another for the top of the column. These geometries were generated using Rhino™ rather than Grasshopper™ parametric modelling tools: the top internal structure was a light branching geometry and the heavier lower internal structure a for the base of the column was a solid ellipsoid subtracted geometry for carrying the greater load (refer image Figure 113).

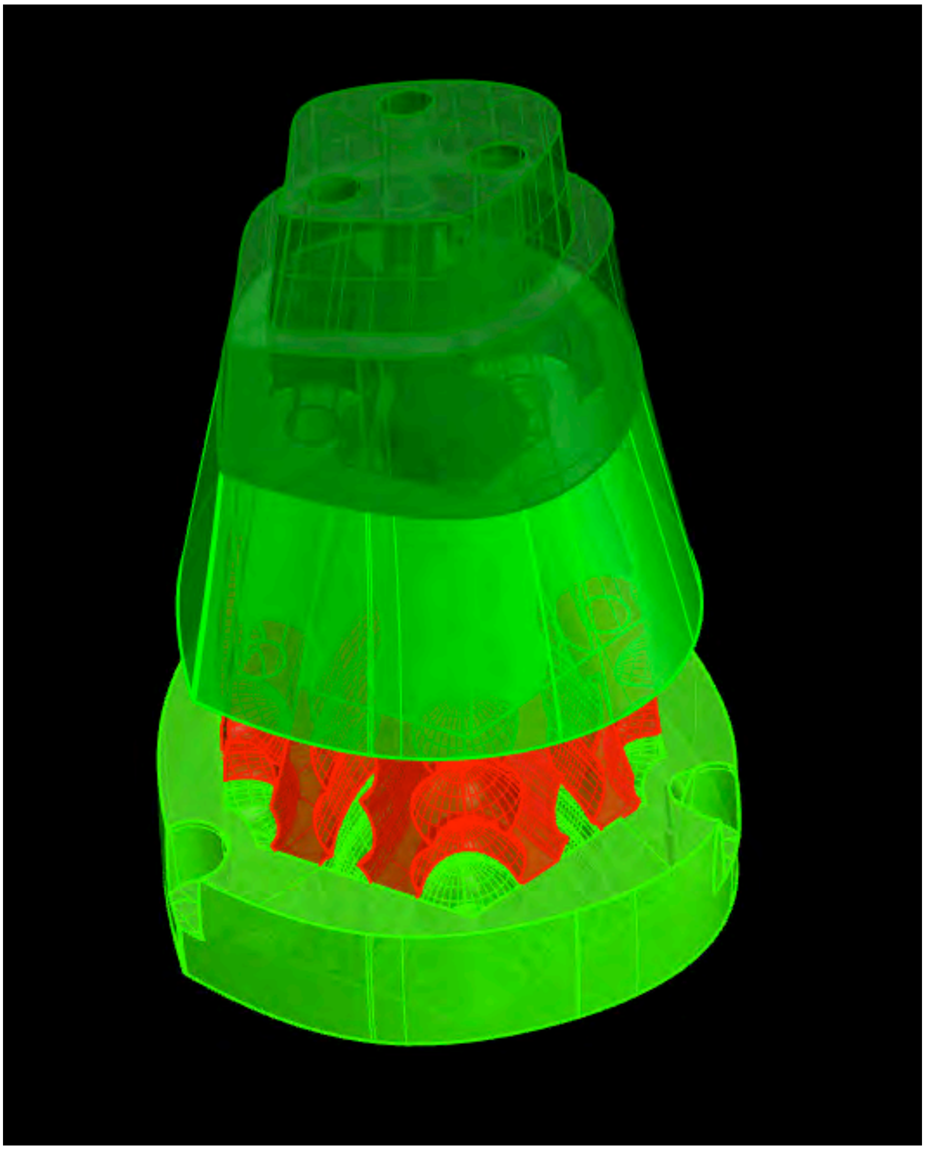

Figure 114 - cutaway view of the base of Prototype Column showing subtractive ellipsoid internal geometry

The design and modelling of the column was first completed in Melbourne, and then emailed to D-Shape for fabrication in Italy. The fabrication of the column was intended to be largely complete prior to my visit to Italy; which coincided with conference travel and the first Villa Roccia site visit in Sardinia in July 2009. This visit was initially intended to be a short stopover, to watch the end of the fabrication and witness the assembly. When I arrived the column had not yet been started and wanting to ensure the column would be fabricated I decided to stay on and get my hands dirty.

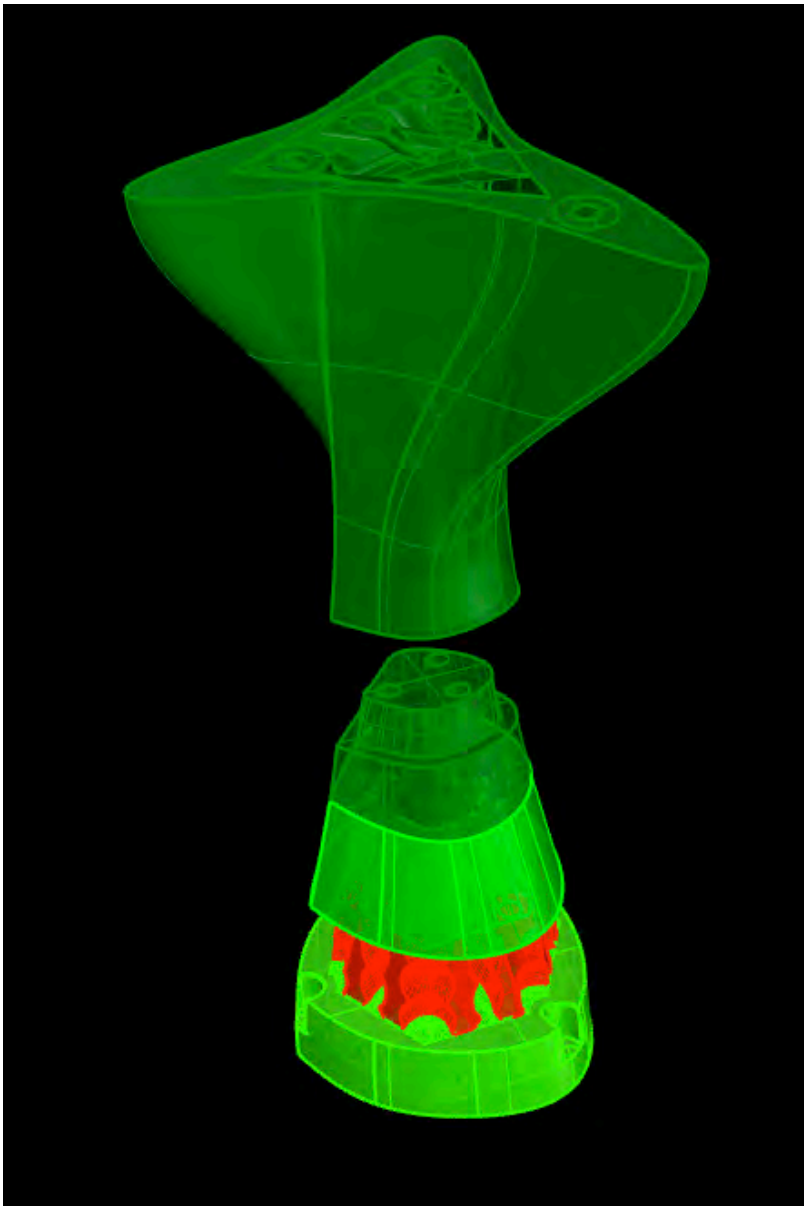

Figure 115 - Parametric column, ghosted and exploded view reveals the mortise and tenon joint between the upper and lower sections and the two types of internal used; random branching geometry in the upper section and geometrically arranged ellipsoid sphere voids removed from internal solid geometry.

Figure 116 - James Gardiner topping up the back of the sand bed after 1 ‘print’ pass. Note: the gaps left within the ‘print’ will be filled in by the returning pass.

5.2.2. Fabrication of the Roccia Column

The strategy for the fabrication of column changed from splitting the column in half to slicing it into 14 pieces, each approximately 250mm in height. The column was to be then assembled into the two pieces for transportation. Slicing up the column into smaller pieces for fabrication made sense when I realised that the D-Shape™ Construction 3D printing technique, at the time in 2009, was far less automated than I had once thought from afar in Melbourne. Instead of fabricating two pieces 1500mm high or approx 700mm deep if the objects were laid on their side (150 or 75 layers), it was much more efficient to split the column into 250mm slices, then pack these into two print runs of a total of 50 layers. Each 10mm layer of sand across the fabrication bed of approximately 5m x 5m required approximately 14 buckets of sand, which had to be moved by hand and deposited at one end of the fabrication bed (Figure 116). This sand also needed to be sifted and mixed with additives prior to commencing what was called the ‘print’.[126]

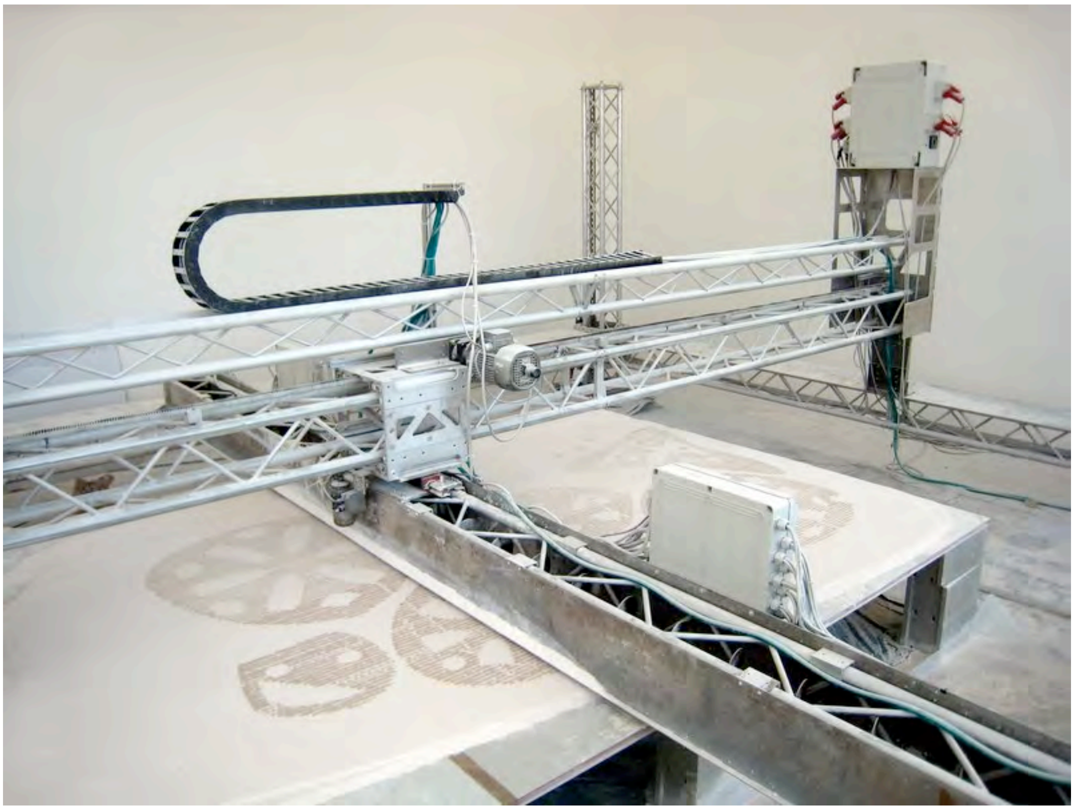

Figure 117 - The D-Shape machine printing the column

The first model of the D-Shape™ Construction 3D printing machine, which we were working with, consisted of four corner posts with a suspended rectangular frame that crawls up their legs (refer image Figure 117). This frame has a cross bar suspended through the middle of it which acts as the guide for the printer head arm, which holds 200 adapted industrial printing nozzles. As the fabrication begins, the rectangular frame crawls up the posts in 5mm increments and locks into position for the next layer. Sand was loaded by hand at the far end of the bed and the print arm moved across the bed to spread the sand with its flat leading face. Once the new layer of sand is level, the print arm moves forward across the

[126] The two ‘prints’ required approximately 12.5m3 of sand to be moved in buckets, weighing approximately 20 tonnes. We all had very sore backs by the time we finished.

sand bed and sprays out the inorganic binder, in rows 20mm apart (refer Figure 116), then the print arm shifts left to right 10mm and returns across the sand bed filling in the gaps in the last print. This process was then repeated until the end of the job was completed.

Figure 118 - Commencing sand removal after the 'print' has cured overnight.

Once the job was complete, the curing parts were left for approximately 24 hours before removal of the unbonded sand commenced (refer image Figure 118). The removal of the sand was also to be done by hand: first with a shovel and wheel barrow, then using trowels, brushes and eventually a vacuum cleaner to remove hard to access sand within the objects. The sides of the objects were, in some cases, scraped with a shovel to remove the layer of partly bonded material, resulting in a smoother finish. The process of printing at this time was, at best, difficult; due to the lack of automated feeding system, frequent clogging of the print nozzles (which delayed printing and reduced the quality of the fabricated objects), mechanical controller malfunctions due to overload and no adequate sand removal system. The surface finish of the fabricated objects was rough, but also quite distinctive and interesting, which conjured up parallels with the expressive nature of off-form timber patterning in concrete. Parts of the column such as the mortise and tenon sections were unusable due to print nozzle malfunctions (refer image Figure 119). After all of our efforts these parts did not get reprinted and so the column was never assembled. However the upshot was that we all learnt a great deal and I got to know the D-Shape™ fabrication technique thoroughly.

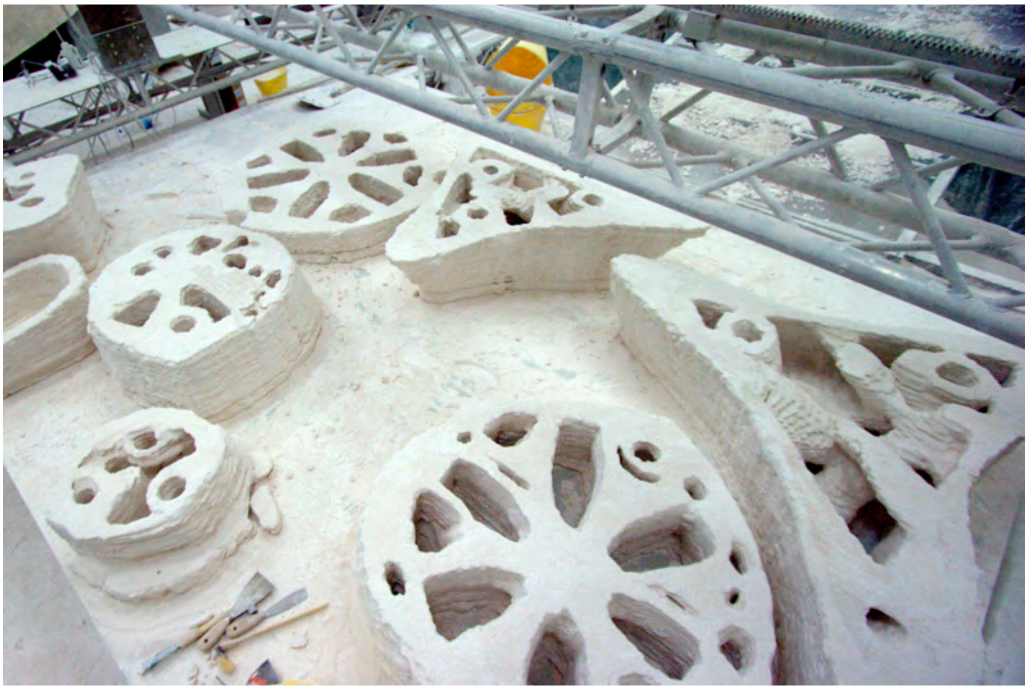

Figure 119 - Parametric column sections on the ‘print’ bed, revealed after removal of unbonded sand mix. Note object bottom left is cracked, another part further up on the left was also unusable.

5.2.3. Conclusion Roccia Column

The fabrication of the prototype column, although by no means an easy feat, tested and confirmed the use of methods that the project set out to test. This project confirms the applicability of scaled up additive fabrication techniques and digital tools (parametric design and solid modelling) originally developed for the parallel industries. These tools are today being increasingly used by leading architects and designers (Kolarevic, 2003) for projects that use predominantly formative and subtractive methods of construction (Buswell et al., 2007b), in this project these tools have been demonstrated to be applicable for the design of structures using Construction 3D printing, an additive construction technique.

Grasshopper™ was used to generate the envelope of the column and the internal conduits for post tension reinforcement. Simple flexible geometries were generated and then relaxed and lofted to develop the column profile, through the use of Grasshopper™ parametric software, this parametric capability allowed for a high level of manipulation of the column properties; height, girth and shape without the need to design each section profile. Although the parametric software worked well for the generation of the column geometry, it was found to be too difficult to deal with the intersection between the mortise and tenon joint, post tension conduits and the need to ensure that the minimum column structure thickness was maintained. The parametric definition of the column stopped at this point in the creation of the model and from this point the remainder of the column was modelled manually. This resulted in problems later when the client wanted to enlarge the column, as the model could no longer be modified easily, hence defeating the purpose of parametrically defining the column at the outset. Given more time and greater user experience with the software, it probably would have been easy to define these requirements parametrically and to generate an acceptable result.

Figure 120 – Photographic detail of printed column section, showing random branching internal geometry and post tensioning conduits.

The parametric model was frozen once the overall column geometry and detail was complete, in order to complete tasks that were difficult to achieve parametrically; namely the creation of the mortise and tenon joint (with its various tolerances and boolean operations required) and the creation of the internal geometries for the column. Grasshopper™ was found to have particular difficulty with compound boolean operations. These tasks were completed using solid modelling within Rhino™[127], the boolean operations still proved to be very difficult but eventually produced the results intended. The freezing of the parametric geometry should be avoided wherever possible because unforseen changes later in the project can result in the need to remodel significant portions of the project.

Two different three-dimensional internal geometries were tested in the column, one branching and another produced through subtractive means. These two geometries allowed a reduction of materials required[128], while maintaining adequate structural strength[129].

Internal parametric conduits, linked to the geometry of the column, were integrated for post-tensioned steel cable reinforcement, allowing the column to be fabricated in pieces and later assembled to form a rigid column (refer image Figure 121). The conduits were successfully created using the D-Shape™ technique and would be serviceable for use with post-tension reinforcement[130]. Such internal conduits would be difficult and costly to create using subtractive

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[127] Rhino is not a true solid modelling tool, but instead works with enclosed objects, this often results in unenclosed geometries and difficulty with boolean operations.

[128] Stone columns are generally created from solid sections of stone, concrete columns are also generally solid. Therefore by removing material from the centre of the column a reduction of materials used has been achieved.

[129] The greatest structural test for prefabricated or precast synthetic stone elements is generally considered to be in their handling and transport rather than when they are eventually installed in situ.

[130] Serviceability refers to the conduits being largely dimensionally accurate, free from obstructions and smooth enough to thread post-tensioning cables through.

techniques; the internal geometries created would have been difficult and costly to create using both subtractive and formative techniques, due to the complexity of creating formwork using formative techniques and issues of accessibility for subtractive tooling.

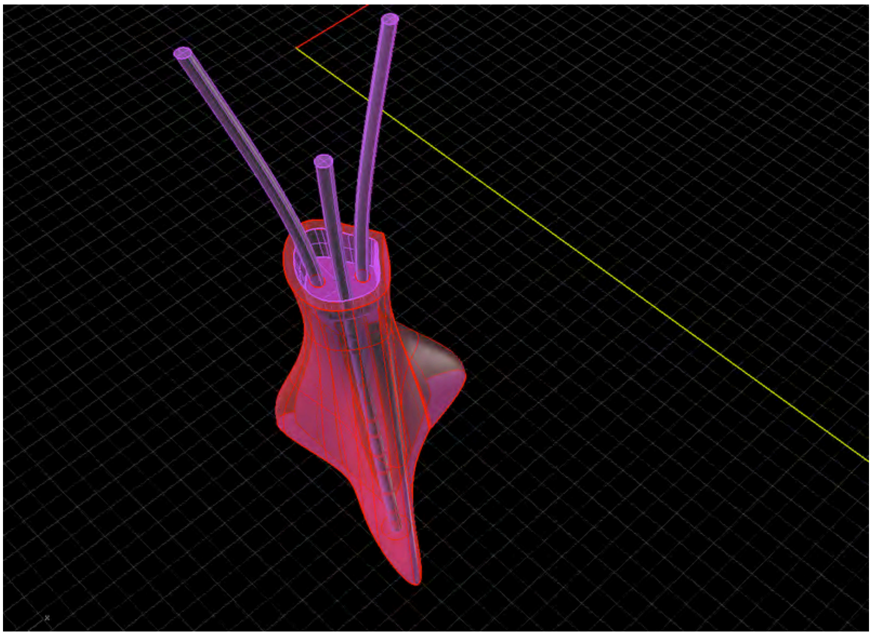

Figure 121 - The top of the column (upside down) with the generated post tension conduits, to be booleaned from the column 'solid' geometry. Image James Gardiner

Figure 122 - James Gardiner (left) and Enrico Dini (right), discussing a print layer issue with the Roccia prototype column August 2009. Photo James Gardiner

The fabrication of the column was not successful in respect to the column being assembled and tested with post tension reinforcement. This was a factor of the requirement to reprint the middle two sections of the column[131] which had not been printed properly due to nozzle malfunctions and a loss of interest from D-Shape™ to complete this task once I had left. Fabrication of the column did however provide good evidence of the capabilities of the D-Shape™ technique through the creation of the freeform column with complex internal geometries which reduced the total material required, the fabrication internal conduits for reinforcement and demonstrated the suitability of the software tested to respond to the limitation and capabilities of the D-Shape technique.

[131] These two sections included the mortise and the tenon elements of the joint.

5.3. Roccia Assembly

This Roccia Assembly project, which is a sub-project of the Villa Roccia project, was commissioned by Dini Engineering[132] in January 2010. This project which will be referred to here as the ‘assembly project’, the ‘Roccia Assembly’ or ‘assembly’, forms the second prototyping phase of the Villa Roccia project. The Roccia Assembly was initially scheduled to be exhibited at the ‘Luxury and Yachts’ fair[133] and later at the ‘Working Prototypes’ Exhibition[134]. The fabrication of the Roccia Assembly has since been cancelled, although the design was delivered within the agreed time frame and to the established specification. The assembly was intended for transport to the Villa Roccia site in Porto Rotondo after the exhibitions: to form the first section of the house. The purpose of the assembly was to test at full construction scale the methodologies to be applied to the Villa Roccia project, while taking the opportunity to exhibit our project in the interim.

Four major subject areas are explored within the project

- Design: Applying the Villa Roccia a design language through critical engagement with the design space in concert with the use of digital and optimisation tools.

- Digital design tools: identification, testing and creation of a ‘digital definition’ (refer index of terms 1.5) using a combination of the following parametric tools, polygons and sub-divs, space filling structure and optimisation and/or generative tools.
- Off-site fabrication and assembly: Breaking the design down for fabrication using construction 3D printing.

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[132] The engineering arm of D-Shape

[133] Luxury and Yachts Fare Verona, Italy February 2010

[134] Working Prototypes rapid manufacturing exhibition at DHUB in Barcelona May 2010

- Detailing: Developing and applying an architectural detailing strategy for construction 3D printing
- Fabrication of the assembly and critical analysis of the fabricated outcome

This commission of this sub-project for the Villa Roccia Assembly was the result of sending the hand drawn perspective (Figure 123) to Enrico as a means to begin the discussion about how to construct the Villa Roccia that I had designed. Enrico was very excited by the image and later decided to fabricate this assembly to show at the Luxury and Yachts fair.

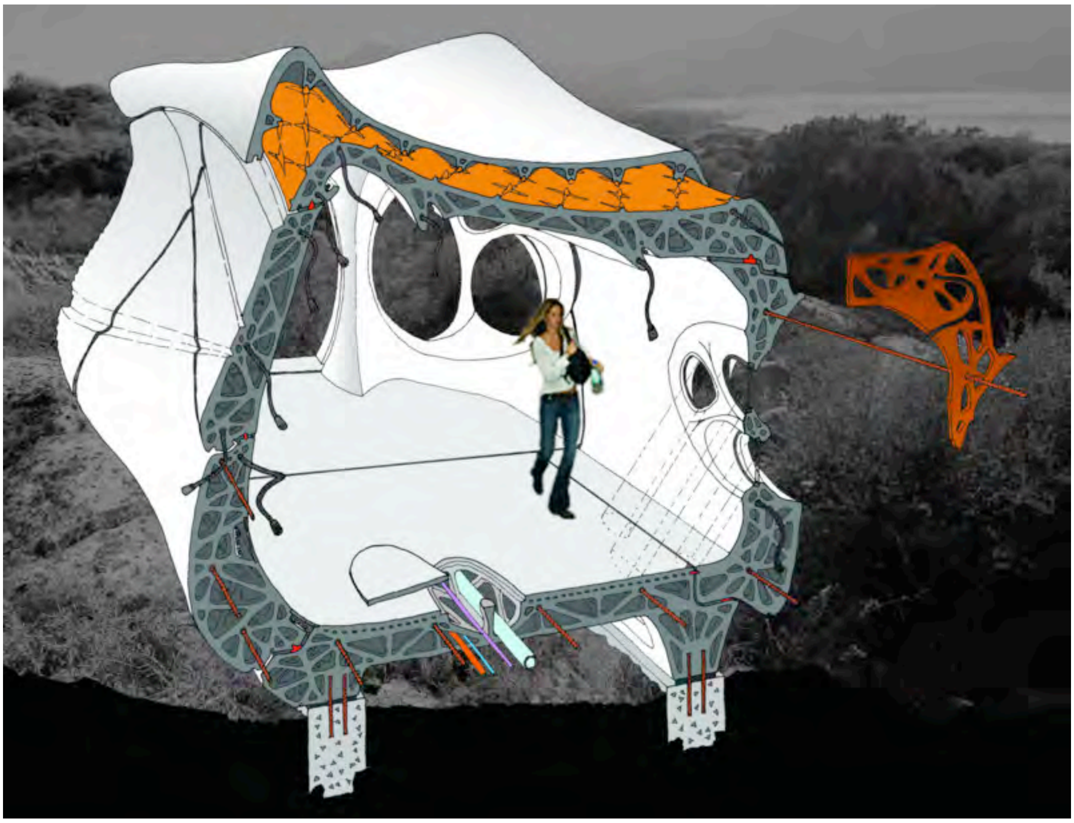

Figure 123 - Villa Roccia construction assembly cutaway section perspective. James Gardiner

This project is a culmination in digital form of my research since 2004, as presented in earlier chapters. This breadth of this research includes extensive literature review and analysis of subjects including: off-site fabrication, digital design tools, additive fabrication and design implemented by the construction and parallel industries. Interviews and site visits by me of over 80 companies globally to investigate the state of the art use of off-site fabrication techniques and digital design tools. Additional topics have been researched and explored for the Villa Roccia project including architectural design and building precedents within Sardinia relating to rock inspired buildings. An ongoing physical examination of the structure of bones has been made (by cutting up and examining different fresh and dry bone types). Local and Sardinian eroded rock formations have also been studied in the field and photographically documented in order to become familiar with their forms, this has culminated in the development on a rock inspired architectural design language.

5.3.1. Roccia Assembly Project Development

The Roccia Assembly project began with testing on a range of projects with a broad range of digital design tools, extensive site visits to construction and parallel industries fabrication facilities in 11 countries worldwide, development of methodologies for application to Construction 3D printing and embedded practice, testing and prototyping at the D-Shape fabrication facility in Italy.

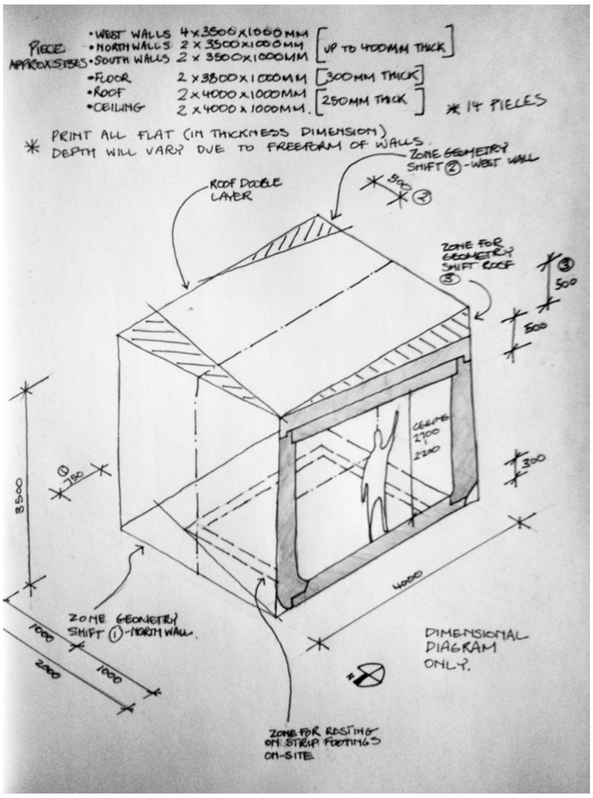

Figure 124 - Diagram of proposed Roccia Assembly dimensions and panel breakdown – approved by D-Shape™ . Image by James Gardiner

Although the categorisations of aspects explored have been outlined above, each aspect directly informed the other throughout the design of the project. It would therefore be onerous to separate discussion of these aspects into separate topics. The design for the assembly was directly based on the drawing described in reference to the Villa Roccia project (Figure 124).

5.3.2. Digital Design of the Villa Roccia Assembly

The formal design of the assembly geometry focused on emulating the effects of a range of criteria that create natural erosion of rock formations, while responding to additional architectural criteria: spatial requirements, such as provision of views, solar aspect, rain shedding, structure, weatherproofing, the fabrication of individual panels using the D-Shape technique and assembly of the panels in sub-assemblies and ‘blocks’ on-site.

The simulation of rock erosion, especially erosion that produces ventifacts and tafoni is by no means a simple matter. As noted in (chapter 5.1), there has been little simulation of salt weathering or aeolian erosion, most likely because there is still little consensus on the specific causes of erosion causing ventifacts or tafoni (Huinink et al., 2004, Turkington and Paradise, 2005). Aeolian erosion was selected for simulation, as this effect is widely considered to be a cause of erosion that can contribute to ventifacts and tafoni erosion effects. Aeolian erosion is also conceivably much simpler to simulate than salt weathering; using the dynamics/particle effects engine within Maya™ software tool.

In an attempt to form a responsive architectural design based on erosion effects, a number of digital tools were tested to attempt try to simulate these affects rather than merely interpret these in a formal aesthetic manner. A number of initial experiments were made to determine whether Maya™ could simulate aeolian erosion and also model rainwater flow. The Maya™ aeolian erosion and rain fall water flow tests had to be eventually abandoned for the current project, due to time constraints, with few notable results. Hopefully with more time, expertise and funding this path of research can be reinvigorated.

Experiments with Topostruct™, topology structural optimisation software tool, for the optimisation of the assembly structure proved to be more successful[135], with the development of a final 'optimised' geometry that could be used to indicate the forces acting on the structure as well as developing unexpected structural geometries that could be utilised to contribute to the overall design.

The design is considered from the basis of a combination of inputs including; computer based optimisation models, the 'Roccia language' and empirical design. The design sought to respond to multiple inputs and parameters rather than to optimise a single aspect such as structure, moving toward: a *'multi parameter effectiveness rather than single parameter optimisation and efficiency……(and) must from the start of the design process include both the logics of how material constructions are made and the way they interact with environmental conditions and stimuli.'* (Menges and Hensel, 2008)

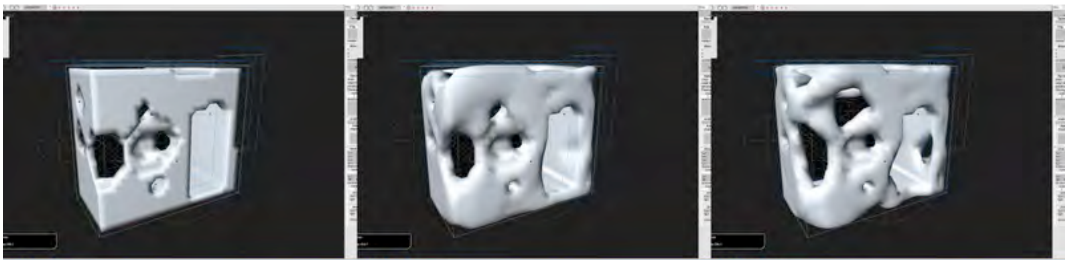

Figure 125– Topostruct™ topological structural optimisation of Roccia Assembly envelope. Image by James Gardiner

Within the Topostruct™ program a simple rectilinear envelope was defined with the similar proportions to the planned Roccia Assembly.. Window and doors recesses were located within the envelope; these were defined as density regions with 0% density (refer image Figure 125). Initially the density regions for the openings were defined as squares and rectangles but left traces of these geometries in the optimised outcome. Spheres were later substituted as they, did not leave such traces and were closer to the tafoni effects formed by Aeolian

[135] This is the first structural optimisation program that has yielded workable results repeatably.

erosion and salt weathering. Support regions[136] were applied to the model geometry as well as material self-weight (based on D-Shape material data). Although the forces applied in the Topostruct™ program are uniform constant loads, some creative licence was used with the application of two very low wind loadings. These loadings were calculated from the maximum annual wind velocities for the site and applied to the geometry according the proposed orientation of the Roccia Assembly when later placed on site. On completion of the optimisation process the resulting geometry was exported from Topostruct then imported into Rhino™. The geometry was then sliced within rhino™ into vertical, horizontal and diagonal contours at 200mm intervals to produce sets of polyline geometry to work from in the 3D modelling programs used (refer image Figure 126).

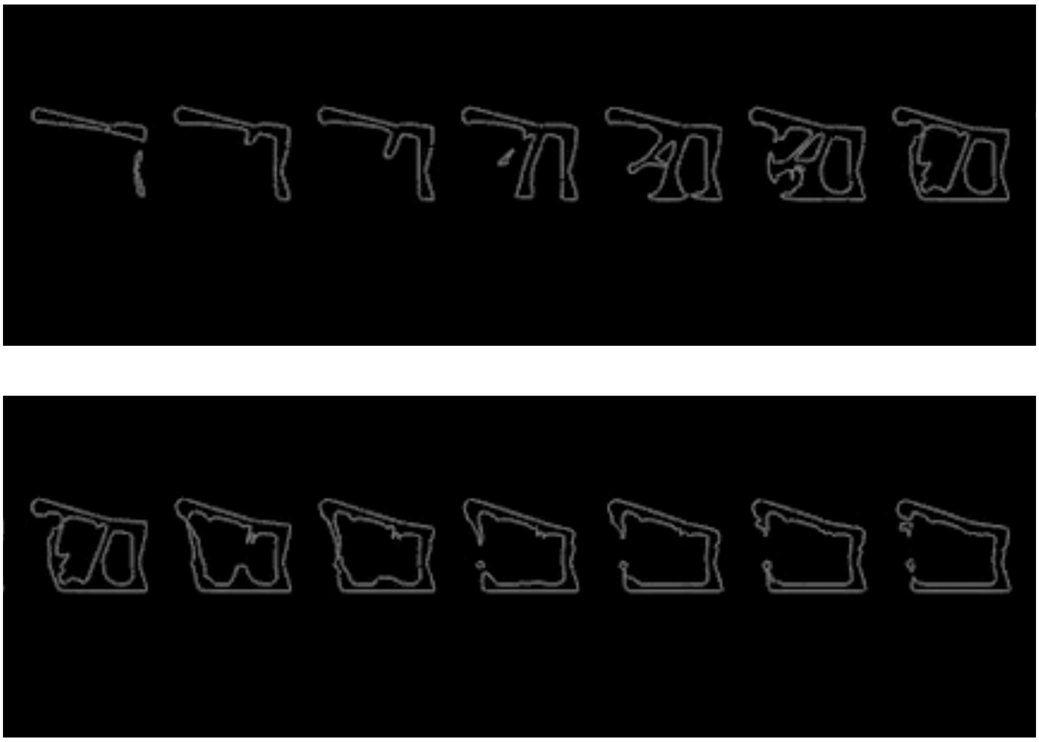

Figure 126 – Geometry slice contouring from Topostruct. Image James Gardiner

[136] Support regions are points where the load is transferred to, such as to footings.

The intention from the outset of the project was to develop CAD modelling methodologies that could later be used on the Villa Roccia project. Alina McConnochie (a student that I had previously tutored at UTS) led the CAD modelling for this project, under my direction. She conducted many of the CAD tasks from the program functionality testing phase through to the breaking up the geometry into highly accurate panels. This functionality testing is common practice within the AEC industry[137], prior to adopting CAD programs for specific projects. This testing was used to ascertain an appropriate set of CAD programs to be used for the project, by testing a number of critical functions that would need to be carried out through the suite of software packages.

I focussed initially on translating the Topostruct™ optimised model into Maya™ and refining this to create the initial Cad geometry for the assembly. This geometry was then refined by Alina under my direction. Once the panels had been completed by Alina, I completed the project, which included shelling of the panels (giving them an external wall thickness, creating the internal geometry for the panels and output to .stl format ready for construction 3D printing by D-

The following were identified as the most important aspects to test for the project

- Interoperability between programs, particularly maintaining curvature of the geometry.
- Accurate lofting of 2D joint details along the geometry surface, this lofting created poly-surfaces which could be converted into solids and 'booleaned'[138] from the base geometry to create the panels with interlocking joints.
- Quality of 3D curvature

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[137] A number of Architects, engineers and fabricators interviews interviewed during the DDAA research project identified trialling of software, in a number of different ways on trial and/or live projects, as common practice prior to adopting software into the office.

[138] Boolean - removal of one solid geometry from another refer index of terms (chapter 1.5).

- Flexibility of the model geometry, for the development of second-order[139] geometry/details within the overall shape, in response to particular project criteria (such as windows and structural ribs).

It was initially considered that the primary modelling tool should be an architectural parametric CAD program, based on projects with equivalent complexity[140] and positive experiences from using grasshopper™ for the Roccia column prototype, discussed above. Tests were made using Generative Components™(GC™) a parametric Digital design tool program and significant issues were encountered. This was largely due to the master geometry not having being developed from a parametric rule set (i.e. generated outside of Generative Components™). In this case prior structural topological optimisation of the design envelope had been performed using Topostruct™ prior to starting with Generative Components™. Such topological optimisation is not available within Generative Components™ and the results were not transferrable into a ‘rule set’ that Generative Components™ could work with[141].

Initially we had tried to take contour slices of the Topostruct™ optimised geometry, so that these curves could be imported into GC™ The quality of curvature resulting from lofting contour geometry, which was deemed important to maintain continued flexibility, did not create seamless 3D curvature geometry. Fluidity of the geometry cannot be easily achieved when lofting 2D line

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[139] Terms such as ‘course’, ‘medium’ and ‘fine’ refer to levels of detail within the geometry and are used to denote the following, course level defines the macro geometry: the overall shape of the assembly. Medium level order refers to details such as doors, windows, ribs and other details that were added to the course detail geometry geometry. Fine denotes details such as joint profiles, textures and other items of fine detail within buildings.

[140] Sagrada Familia in Barcelona detailed design is performed using parametric software Digital Project™and can generate and function well with very complex geometries (Burry 2007).

[141] Structural and agent based optimisation has been used in concert with Generative Components™, by companies such as Arup on the rectangular pitch stadium (Holzer 2009), although this is usually based on structural component optimisation rather than topology optimisation of monolithic shapes.

geometries along curves in one direction. This process of lofting tended to lose detail in the translation from object, to contours, to lofted object. In the case of this particular project, this fluidity was particularly important to achieve the desired outcomes, as mentioned above.

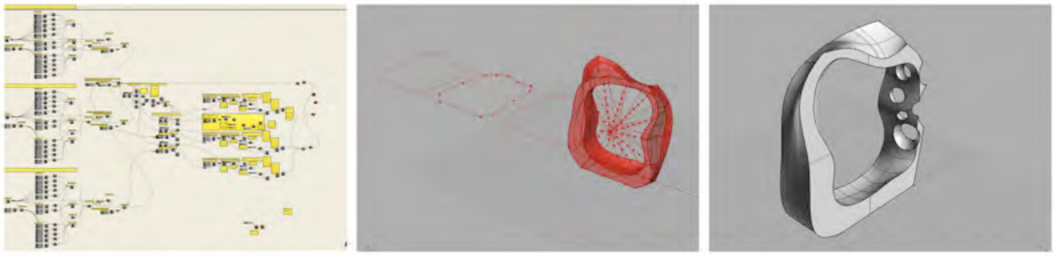

Figure 127 - Grasshopper(tm) experiments for the parametric definition of Villa Roccia shells. Image by James Gardiner

Additional issues were also encountered with Generative Components™ that hampered the effectiveness of parametric software on the project, a major issue encountered was the implementation of 2D joint detail geometries (to be applied both vertically and horizontally). These 2D details formed the 'splitting geometries' that separated the master geometry into individual panels and created water shedding/proofing joints. In a large number of cases when lofting the 2D joint details through the tight curves of the master geometry, the resulting 'split' geometry created self-intersections and other anomalies that could not be used without substantial individual remodelling of the problematic intersections. The development of scripts within generative components™ could have possibly been used to overcome many of these issues, but project time constraints were not conducive to this course of action.

In addition to the problems created by lofting the splitting geometries, other factors also had to be taken into account for the joints, which necessitated individualised assessment of each joint and junction to ensure minimal conflicts and maximum build-ability of the individual panels. The design of the shape was not based on a set of rules or formulas and therefore the use of parametric software for the project was not deemed appropriate.

Maya™ was instead used, focusing on the use of polygon solids for the creation of the course detail geometry and medium detail geometry for the assembly. The implementation of polygon solids for the generation of the geometry, allowed a high level of flexibility within the model, by first defining a small number of 'splits' or subdivisions at the outset to the boundary rectangle (which defined the maximum agreed[142] assembly volume, 4m wide, 2.5m deep, 3.5m high). The geometry was gradually built up through manipulation of the vertices and edges of the polygon, while continuing to add subdivisions to create the localised detail required. The outcome of this software evaluation phase was the decision to use Topostruct™, Maya™, Rhino™ as the suite of software packages[143].

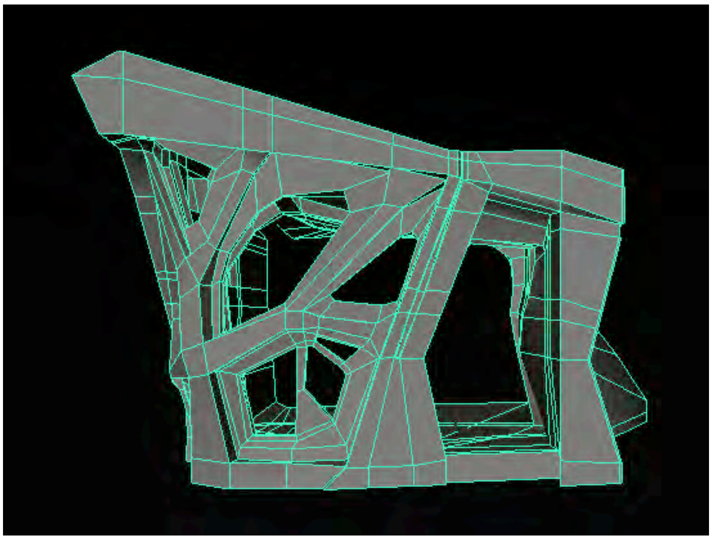

Figure 128 - Maya polygon model of the Roccia Assembly. Image James Gardiner

The exported geometry generated within Topostruct™ and contoured within Rhino™ and then imported into Maya™. This geometry was used as an initial guide for the manipulation of the control elements of a simple divided polygon to

[142] A diagram of the proposed assembly and panel breakdown was sent to D-Shape at the outset of the project and formed the basis of negotiations for the size of the overall assembly and number of panels to be fabricated.

[143] Netfabb™ selective space structures ™package was also added to this list of programs as the project progressed.

generate the course and medium detail geometry, which approximated the initial Topostruct geometry and followed the flow of loads through the structure.

Manipulation of the geometry was then made to the editable polygon to accentuate the aesthetically dynamic form (refer image Figure 128), create adequate falls for rainfall drainage, define window and door openings and to work with the proposed panelisation of the geometry. The manipulation of the geometry to work with the panelisation was made to ensure that panel joints did not run through window openings, to avoid the flow of water near the joints and to reduce delicate projecting elements.

Once the overall geometry had been modelled to an acceptable level, the polygon was converted into a dub-division surface (sub-div), which allowed for continued manipulation of the underlying polygon geometry, while adding the fine level of detail to further refine the geometry, by sharpening and softening edges, adding creases etcetera. The sub-div surface feature within Maya™ digital design tool allows for fine tweaking of the surface with tools such as ‘crease’ and ‘pinch’, allowing for a greater level of refinement beyond that which could be achieved using the editable polygon model.

As Maya™ was initially developed as an animation software, there are inherent limitations within the software for working in a dimensionally controlled manner, in contrast to most Architectural software including Rhino™, which allow for all operations to be performed by specific dimensional increments and reasonable ease of examination of geometry by measurement. There was therefore a continuous requirement to export the geometry to Rhino™ for checking, by contouring and cutting sections, to ensure minimum and maximum panel thicknesses were being achieved. In some cases modified contour polylines were exported back into Maya™ for modification of the model (refer image Figure 129). This created an import/export circular workflow, moving from one program to another based on the tasks that could take be most effectively performed by each software package.

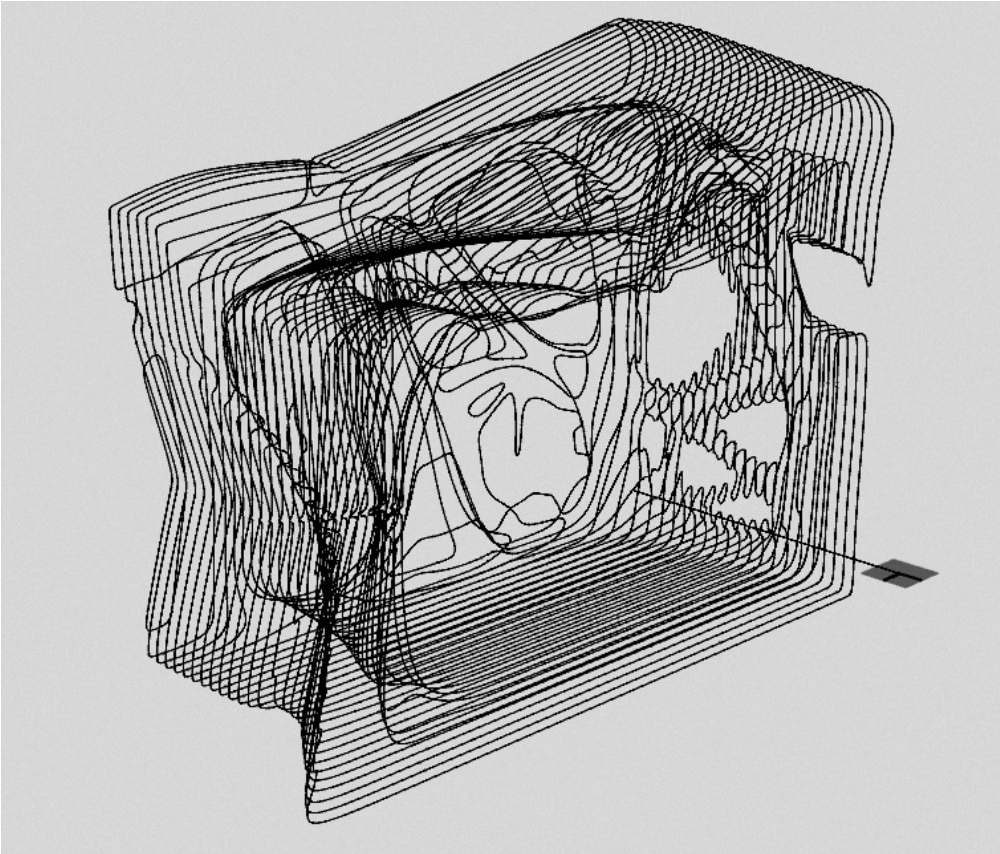

Figure 129 - The Maya model exported to Rhino to be contour sliced to check minimum dimensions. Image by James Gardiner

5.3.3. Digital design and detailing for construction 3D printing off-site fabrication

When the geometry reached the desired outcome, the model was ‘frozen’ from further manipulation and ‘Nurbs’ type surface were exported to Rhino™ for detail manipulation. The second main stage of model development then began; splitting the master geometry into separate panels. The creation of splitting surfaces within Rhino™, were used to effectively split the master geometry into panels. Similar issues were encountered to those experienced in Generative Components™, although these issues were more easily managed within Rhino™ than Generative Components™ as the surfaces could be more easily modified without the constraints of being generated parametrically.

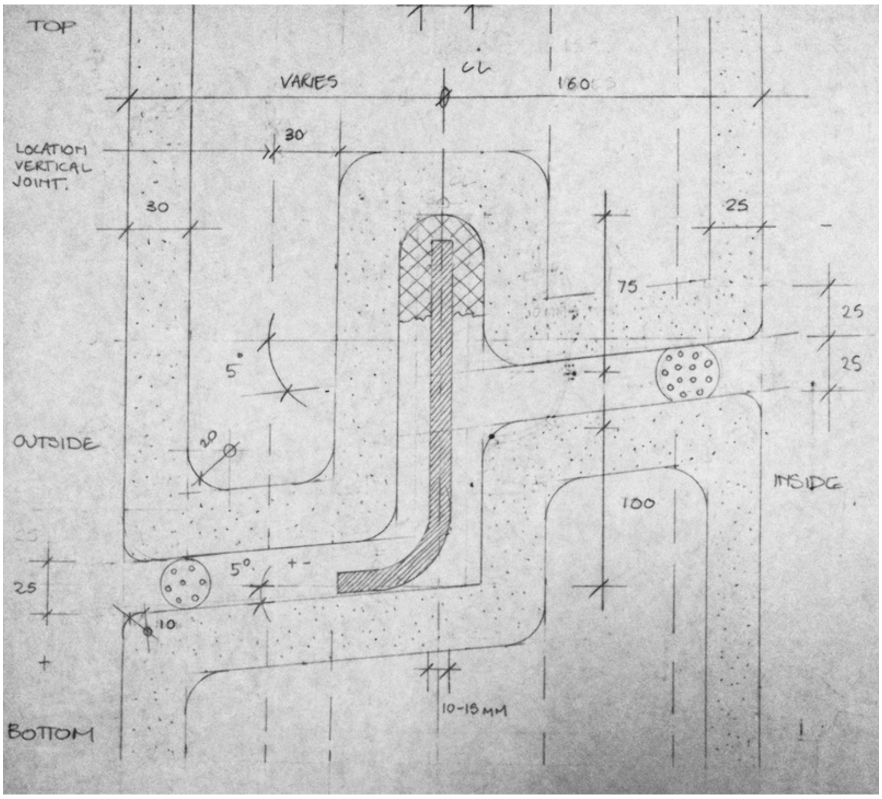

Figure 130 - 2D sketch detail of vertical ‘rain screen’ panel joint used to create the ‘splitting geometry’. Drawing by James Gardiner

The details, refer image (Figure 130), which form the basis of the splitting geometry for vertical and horizontal joints, are a hybridization of ‘open drained’ joints (C.I.A, 1983), which are predominantly used for higher specification precast concrete cladding panels within the Australian precast industry[144], such as high-rise buildings. ‘Butt’ jointing details are the predominant precast panel joint type in Australia due to being simpler to fabricate, but rely on polymer sealants for waterproofing. ‘Open drained’ precast concrete panels utilise integrated joint up stands and baffle grooves formed into the panel and achieve waterproofing through the use of baffles, flashings and air seals, rather than primarily relying on sealants and glues.

[144] Knowledge of precast concrete detailing is based on direct involvement on previous projects with Lacoste + Stevenson, numerous visits to precast factories in Australia (DDAA research project) and overseas (funded by the Byera Hadley and Jack Greenland Travelling scholarships).

The preference for gasket joints for the Villa Roccia and assembly projects is based on the increased reliability of these joints as a long term waterproofing measure (even in the unlikely event of baffles or air seals failing[145]), the requirement for disassembly and reassembly of the assembly project and the preference to reduce the use of sealants and glues within the projects. The use of sealants and glues within buildings requires regular checking and maintenance and residual sealants left on disassembled panels contaminates materials for recycling, due to the difficulty of removing these adhesives (as discussed in the Freefab case study 1).

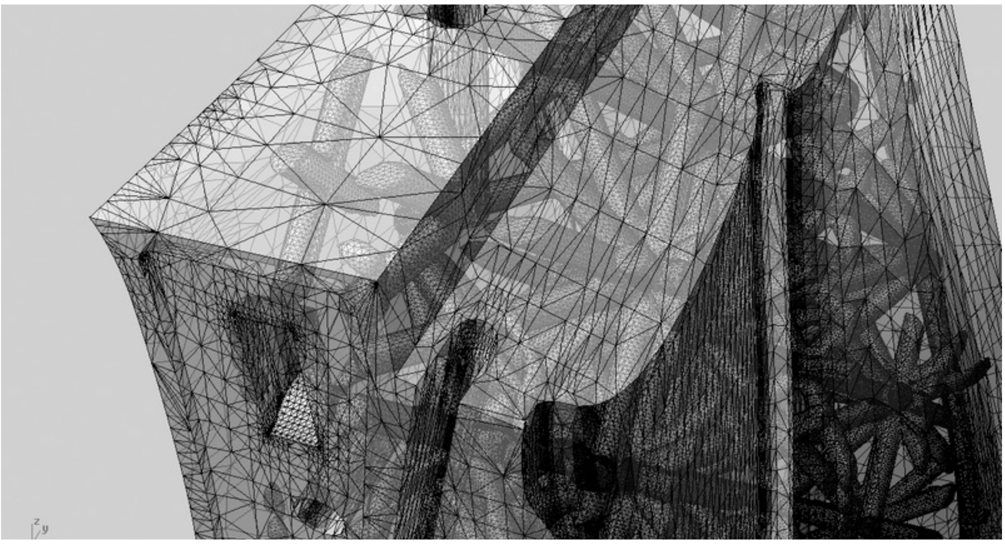

Figure 131 - Ghosted wireframe image of one of the panels before splitting. You can see the internal structure. Image James Gardiner

In addition to the division of the panels for fabrication purposes, the majority of panels required splitting through the middle, creating an internal and external panel. This panel splitting requirement was a direct response to the issue of removing the un-catalysed sand from within each of the panels, as removal of uncatalyzed sand, when working on the prototype column, in a number of cases

[145] Baffles and air seals are not exposed to UV or direct weathering so should last far longer than sealants.

was observed to be very difficult when access was restricted due to tight geometry.

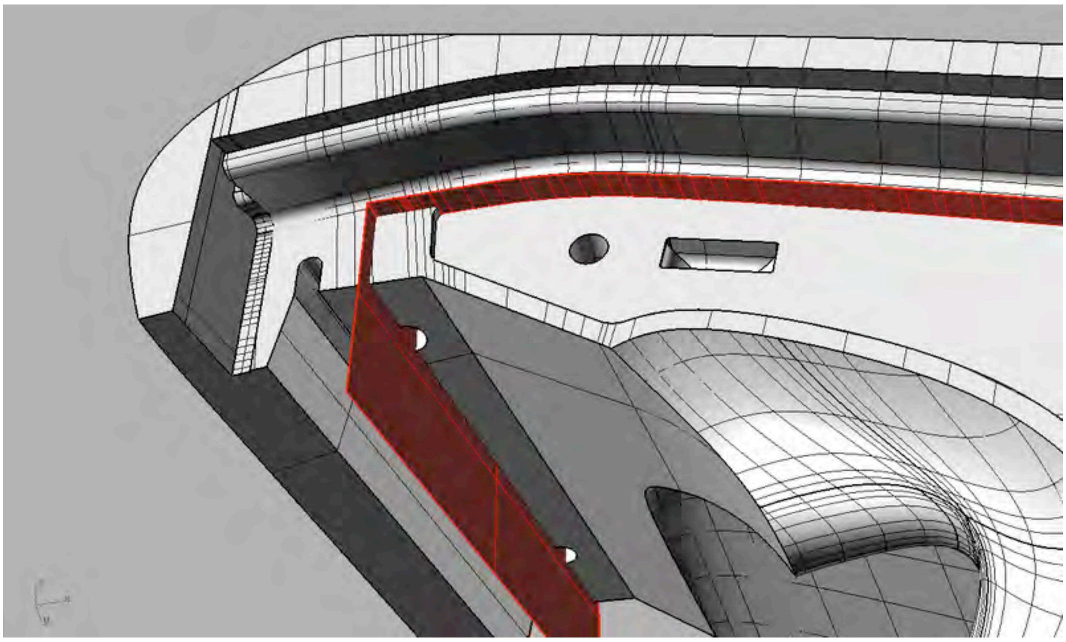

Figure 132 – Roof panel for the Roccia Assembly, showing non-standard specifically detailed joints. Circular dowel rebates, rectangular lifting rebates, plate stirrup rebates are located in the central part of the image under the splitting geometry surface. The internal/external panel splitting geometry, is indicated by the red planar surface that runs from the far left of the image to the left and then folds down, leaving its edge exposed.

The splitting geometry, a surface used to split the panels into inside and outside pieces, runs on the inside of the (refer image Figure 132) hybridised ‘open drained’ precast joints, is lofted from 2D polylines along a prescribed curve at the joint location. The resulting splitting surfaces are then joined and edges capped to create a solid splitting geometry, this splitting geometry is used to cut or split the master solid geometry into separate panels. The lofted surfaces needed to be vigilantly managed after creation to ensure accurate translation of the intended geometry, especially around tight curves in the master geometry. Issues with the splitting geometry were numerous and this process needed to be micro managed. I believe that this level of management would be very difficult to define parametrically. With individual details required for mitred joints for an individual corner, modification of dimensions within the splitting geometry dimensions to allow for structural dowel placement and for terminations between a number of splitting geometry details, refer image (Figure 132). Alina McConnochie excelled in her attention to detail during this phase of the design and detail development.

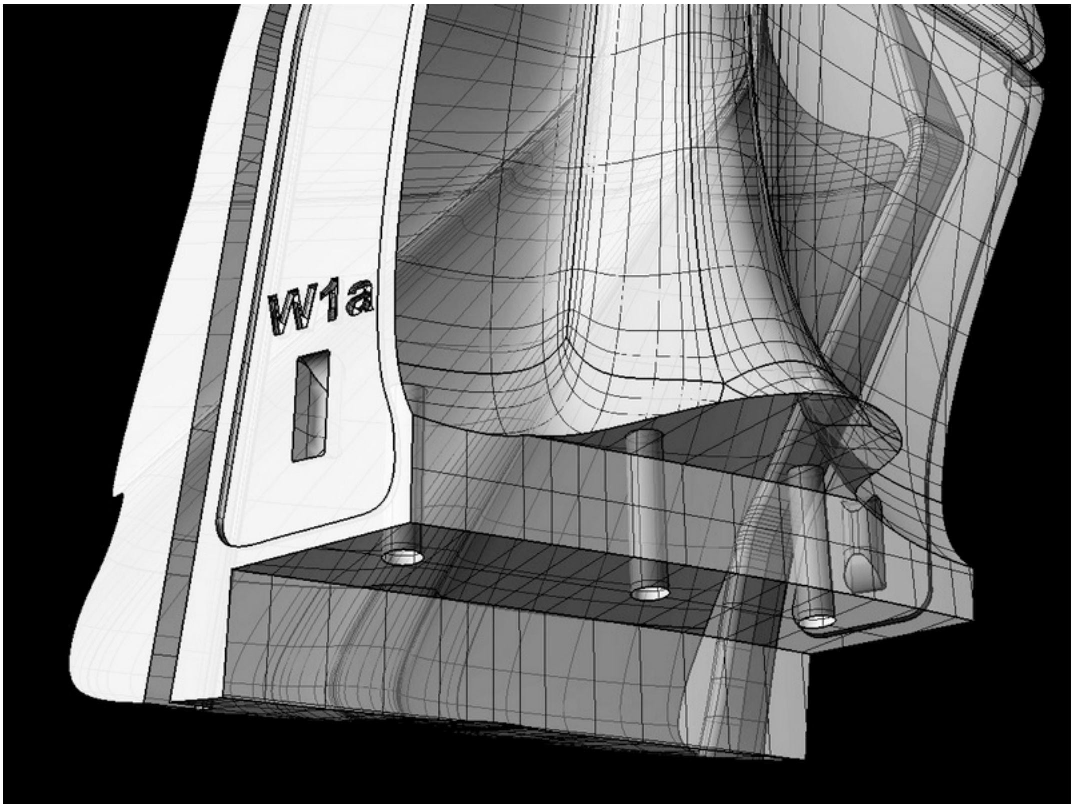

Figure 133 - Roccia assembly panel showing ‘rain screen’ horizontal and vertical joints and rebates, dowel and lifting panel rebates and panel numbering.

Additional detail items were added to the panels during this second stage of modelling within Rhino™, which included structural elements, panel numbering and lifting rebates (Figure 133). In reference to the structural elements incorporated into the panels, dowel rebates were added to vertical joints between panels (it would be physically impossible to fit a panel with both horizontal and vertical dowels). The dowels were designed to hold the panels together both during assembly and once the assembly is completed, in a similar way to assembling an IKEA™ bookcase. These elements are best described as sleaves for the dowels into which they are fitted; these were solid modelled into the panels, to allow for fitting of the dowels prior to assembly.

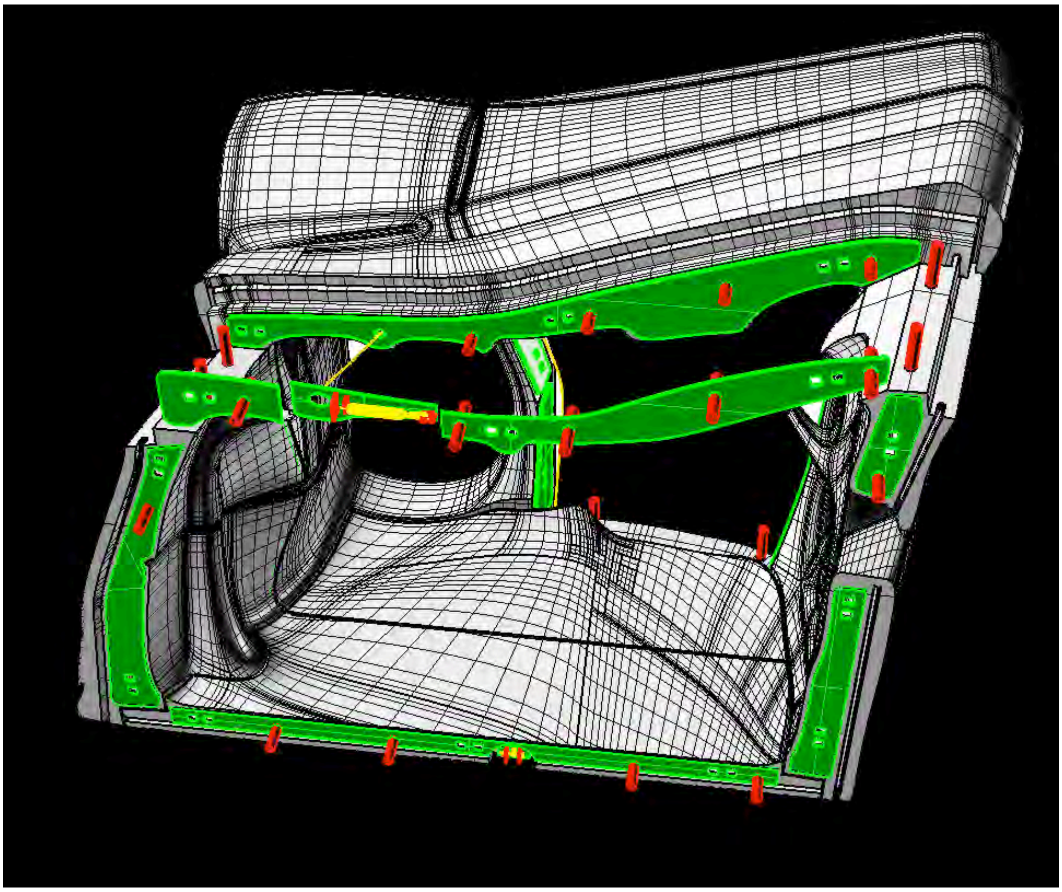

Figure 134 - The Roccia Assembly showing one roof panel removed while leaving thedowels, steel plate stirrups and post tension reinforcement. Image by James Gardiner

Post-tension reinforcement conduits were incorporated into the assembly project geometry to thread through and tie the panels together. The image (Figure 134) shows the line of post-tension reinforcement: the fine yellow line of post-tension reinforcement runs from the top left yellow tensioning plate, through the roof panels and down through the end panel and back through the floor to be terminated at the bottom. The tensioning of the panels acts to increase rigidity of the assembly by tensioning the panels together into a homogeneous assembly. Between each vertical joint, on each of the panels joined, rebates were added for steel plates, which act as Stirrup reinforcement, through which the post tension reinforcement is threaded, refer image (Figure 135)[146].

The integration of such a large number of elements into the non-uniform master geometry precluded any form of automation or scripting to be used in the placement of these elements. Each of the dowels, plates, reinforcement cables and lifting rebates had to be placed in reference to the other, while taking into account the appropriateness of its location within the panel for fabrication, structural stability and transportation.

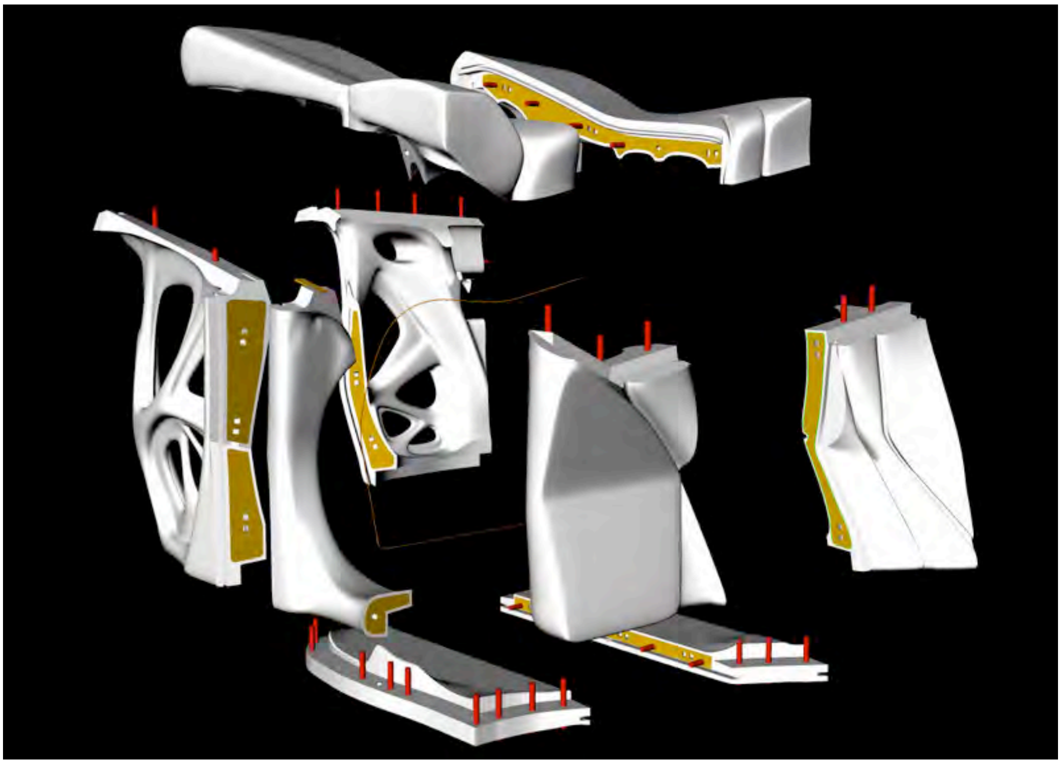

Figure 135 - Exploded perspective of assembly panels including dowels, steel plate ‘stirrups’ and post tension reinforcement cable.

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[146] The principles of this design were discussed with Richard Hough, David Moorehead and Mathew Clarke from Arup Sydney on the 13th of January 2010. They generously agreed to meet with me, though they were not engaged on the project. After showing them the scheme and discussing the principles of the structural mechanical and tensioned fixings, they agreed that the principles applied to the assembly were sound. Without funding to engage an engineer, I just needed to at least check that the principle applied were sound prior to sending the files off for fabrication.

The question of whether any form of software based automation, such as parametric or scripted operations, can be achieved on such non-uniform assemblies appears to be unlikely, taking into account the number of factors that must be addressed by the CAD operator/designer. Further investigation of such automation methodologies to reduce designer input will be investigated on the Villa Roccia project, where time constraints should be more generous and the burden of a much greater number of individual interventions will be much higher, making investigation of possible methodologies more rewarding.

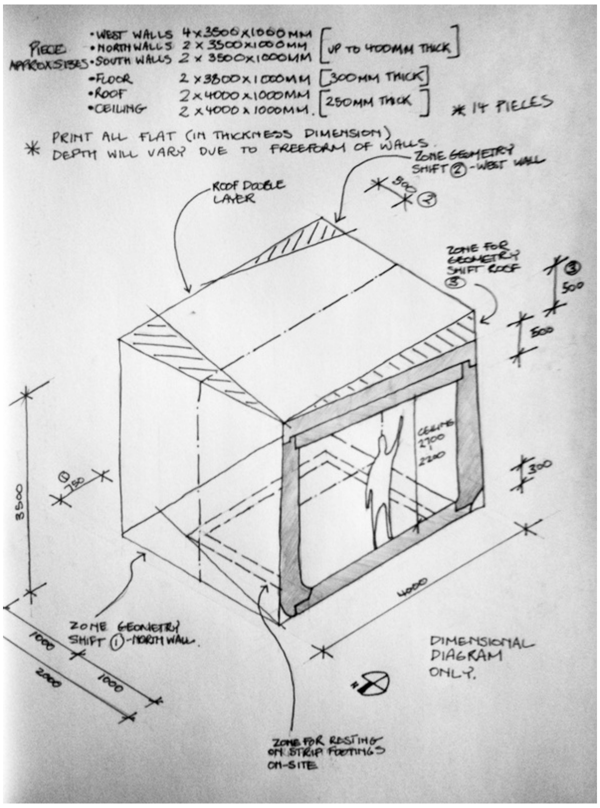

Figure 136 - Diagram of proposed Roccia Assembly dimensions and panel breakdown – approved by D-Shape™ . Image by James Gardiner

The size of the panels was another factor considered from the outset of the project, refer image (Figure 136) discussed above, with the initial calculated weight of the assembly approximating 10 tonnes and D-Shape fabrication constraints generally being limited to 3.5m(x) in length, 2.5m(y) wide and 1m(z) in height. Each panel, with exception of the roof panels, which needed to span up to 4m, was designed to fit within these fabrication constraints lying flat on the printer bed so that the thickness of the panel is printed in the Z-axis. The size of the panels for transportation by truck from the D-Shape fabrication facility in Tuscany to the exhibition site was therefore not an issue; as the D-Shape fabrication constraints were far tighter than those for transportation.

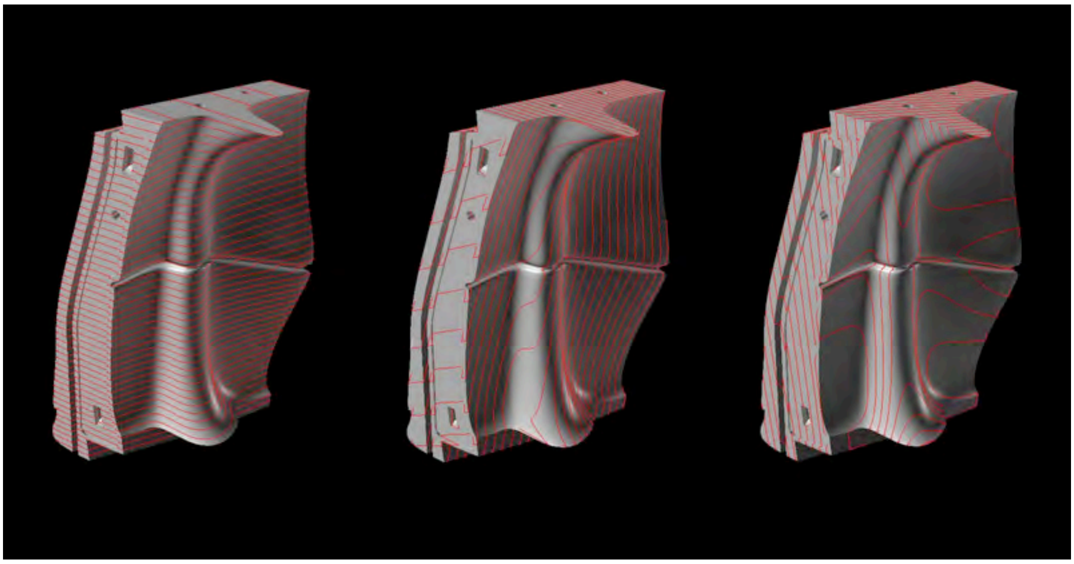

Figure 137 - Contouring the panels to communicate issues for c3p. The direction the panel is fabricated on is important. Image by James Gardiner

One issue that was identified fairly early during the project, was the question of in which direction should the panels be printed. The image above (Figure 137) indicates how the panels would be sliced and printed in layers by the D-Shape™ depending on which way the panels are printed. The first image on the left shows the slicing if the panel were fabricated upright (with the contours sitting quite closely together), the second image indicates how the panel is sliced if the panel were fabricated on its side and the third image shows the panel slicing if it were fabricated flat. Although fabricating the panels flat is preferred by D-Shape™ because this reduces the number of layers to be printed, is probably the least desirable option for the maintaining the curvature of the panel.

This, observation of the D-Shape™ print output, is based on experience from the Roccia Prototype column print (Figure 138). As each slice becomes an approximation of the curvature of the shape. This is easily demonstrated by doing the contouring exercise above and then lofting the curves together, the smoothness of the curve will be lost to a certain extent. The stepping is compounded in printing because the lines are not joined together, instead each sliced profile sits atop of the last one, potentially leaving a slightly stepped profile. This stepping becomes accentuated when the contours sit apart from each other as they do in the image on the right.

Figure 138 - One of the Roccia Prototype column sections as printed. Note the internal stepping where the curve is not in the direction being printed. Photo James Gardiner

Significant issues were encountered with the use of boolean operations on the project with the use of Rhino™. With the complexity of surfaces and mesh objects causing significant anomalies with all types of boolean operations within the Rhino™™: such as program crashes and incorrect results from proven operations tested with simpler geometries. The likely cause of many of these issues is that Rhino™ is a surface modelling program ‘solids are created anytime a surface or polysurface is completely closed' (McNeel and Associates, 2005) rather than a true solid modelling software such as Solidworks™ or Solidedge[147].

Semi-automated repair and rebuilding functions were carried out repeatedly on the geometry intended to be booleaned. In some cases the boolean operations proceeded and created the intended results, but in many cases the boolean operation produced an inexplicable result or could not be completed. Sometimes a particular boolean operation within Rhino™ would add and on other occasions the same operation would subtract despite being intended to do only one of those functions. Netfabb professional™ was used as an alternative to Rhino™ when such problems occurred. The Netfabb professional software had few issues in performing the same boolean operations with .stl files imported from Rhino™, although occasionally mesh repair operations were required prior to the boolean operation taking place within Netfabb™.

An unexpected, but major, undertaking within the project was the creation of internal geometry for the panels. The internal geometry was intended to add structural strength to the panels, while reducing as far as possible the materials used and weight of the panels. Initially a two part internal structure was designed within Rhino™. This dual internal structure was developed in reference to the need to stiffen the internal largely flat and thin panels. Due to the thin profile of the internal split panels solid ribs needed to be incorporated into these panels to ensure that they would not crack when lifted. A finer lattice structure could be used on the thicker outer split panel to ensure structural integrity of the panels (especially during lifting and transportation). The outer panels were generally more freeform for which an open lattice structure could be utilized. The lattice structure was designed to have struts projecting at approximately 45^0 increments radiating out from the central node in all directions, these struts were to be configured to intersect with the ribs structure at the intersections of the panels.

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[147] Both Solidworks™ and Solid edge™ have been developed for use in industrial design industry

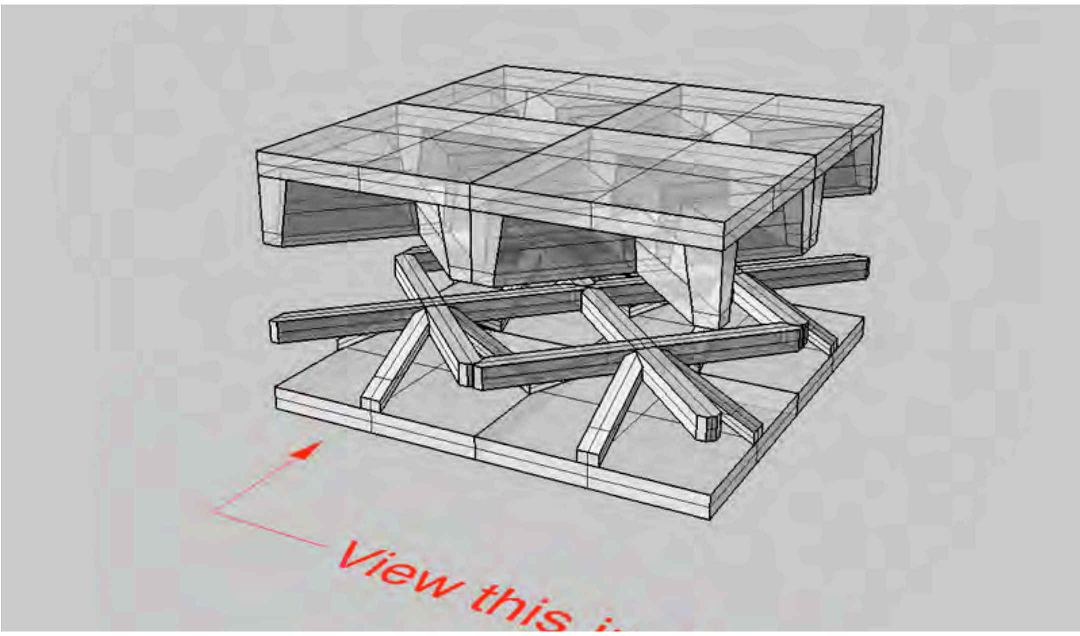

Figure 139 – Original design for panel internal geometry. Sent to D-Shape

After D-Shape™ had made several trials at incorporating this structure, using Solidedge™, (refer imageFigure 139) on a relatively simple flat floor panel it was considered that the software was creating too many issues to proceed with using it for this task. Issues that were encountered were; difficulties with ‘shelling’ the panel to create a uniform 25mm wall thickness relative to the outer faces, Solidedge™ was creating solid geometry with major holes in it[148], these non-solid geometries then created problems for creating the .stl files required for printing.[149]

The program Netfabb™ Professional™ Selective Space Structures™ software was used as an alternative to Solidedge™ to perform the necessary ‘shelling’[150] operations and to generate the internal geometry required. This software was designed specifically for the rapid prototyping industry for the generation of

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[148] I would have thought this would be impossible with a ‘solid modelling’ program.

[149] It is unknown whether these issues were generated by the user or an inherent issue with the software program.

[150] Shelling – as mentioned in the above footnote, is the creation of an offset to a surface with a nominal thickness and edge conditions that create a closed geometry between the offset and shelled surfaces.

complex repetitious geometry. Issues were also encountered using the Netfabb™ professional™ software and the Selective Space Structures™ utility, although these were largely resolved with the assistance of the software vendors[151]. These issues included problems with the calculation of construction elements; which were resolved by scaling down the elements by a factor of 100. After this change of scale the problems were largely resolved. The Netfabb Professional™ program, as explained to me by the vendors, was designed to calculate objects down to measurements of micrometers and therefore had difficulty in calculating objects larger than $2m^3$. There were also difficulties in the creation of two separate internal geometries, generated to meet at the intersection between the panels. After discussion with the Netfabb team a compromise solution was adopted by using one single lattice structure and splitting it rather than a combination of the two geometries discussed above (refer image Figure 140).

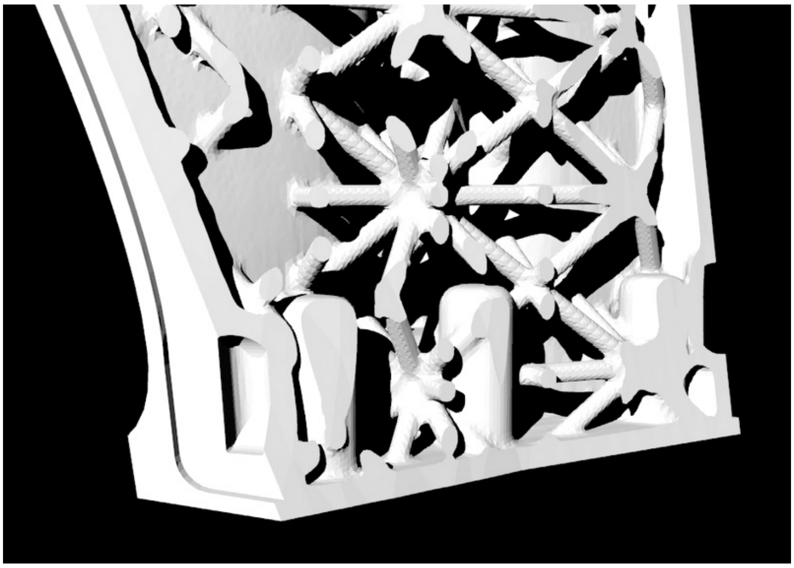

Figure 140 right – Internal geometry, generated using Netfabb Professional™ software, which was used to generate a single lattice geometry. Note the partial lattice on the left hand side of the panel. The incomplete lattice structure in this location would provide no structural support to the panel until after the two halves of the panel are united.

The panels in this instance were instead filled with the single internal geometry (refer image Figure 140) and then split using a splitting geometry surface created

[151] Netfabb™ generously supplied a trial version of their software which was used for this project.

in Rhino™ and then this surface was booleaned from the panel splitting it in two, using the Netfabb professional™. In certain cases this splitting of the panel ad internal geometry resulted in the internal geometry contributing little or no additional structure to the panels in specific locations. The image (refer Figure 140) reveals the struts of the internal geometry not meeting to form a stable structure. As a remediation measure for areas of perceived low structural integrity ribs were added to the panels within the Rhino™ software and booleaned in Netfabb™.

This resulted in a small number of less than ideal internal geometries that in some cases did not perform their structural stiffening function until the panels were joined (and the lattice structure was re-united) (refer imageFigure 141).

Figure 141 - Split panel showing internal geometry, rebates for plate stirrups & lifting and dowel slots

The outcome of the decision to use Netfabb Professional™ software did not result in the generation of the initially proposed geometry. The software did however produce results that were acceptable within the time constraints of the project. The major obstacle to generating the proposed geometry was that the splitting surface, used to separate the panels into inner and outer panels, could not be used as the generator for the orientation or the centre/starting points for the generated geometries. Netfabb™ has also stated by email in January 2009 that they were developing capabilities within the program that could perform the task of generating geometries that follow and are generated in reference to such non-rectilinear geometry. The creation of the internal structures would have been possible using parametric software, although the processing power required to work with the thousands of meshed elements could have posed a problem.

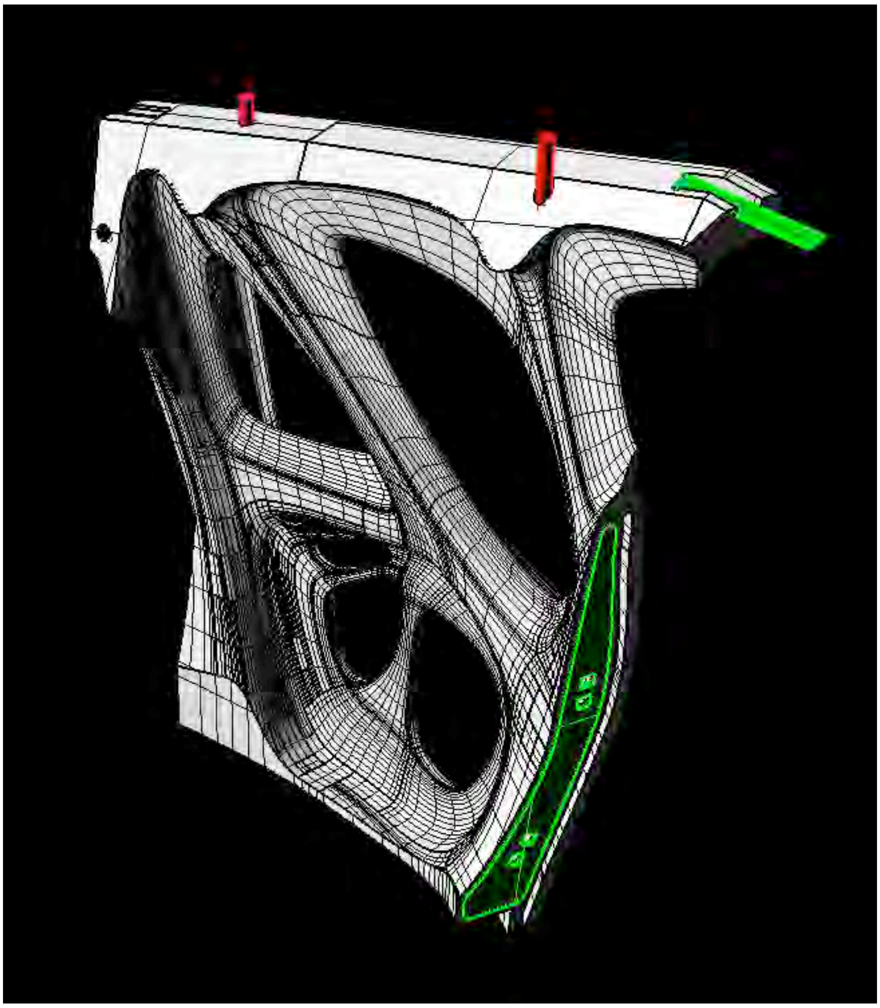

Figure 142 - Complex panel that could not be split, has instead sand removal voids under the metal plate stirrups

Some panels with windows and fine detail could not be split into two panels, in this case a number of access points were created in the panel to allow for the extraction of the sand by blowing or vacuuming (Figure 142).

Each individual software package used for the project had limitations that could not be resolved within that software environment, within the project time constraints. These limitations were addressed in most cases by shifting between software packages to take advantage of capabilities of the alternative software program. No single software package alone had the capabilities to perform all of the tasks required to complete this project and hence a workflow methodology was developed that shifted between software depending on the tasks required. For future projects of a similar nature testing of alternative solid geometry software, such as Solidworks™, should be undertaken to take advantage of true solid modelling and integrated parametric capabilities.

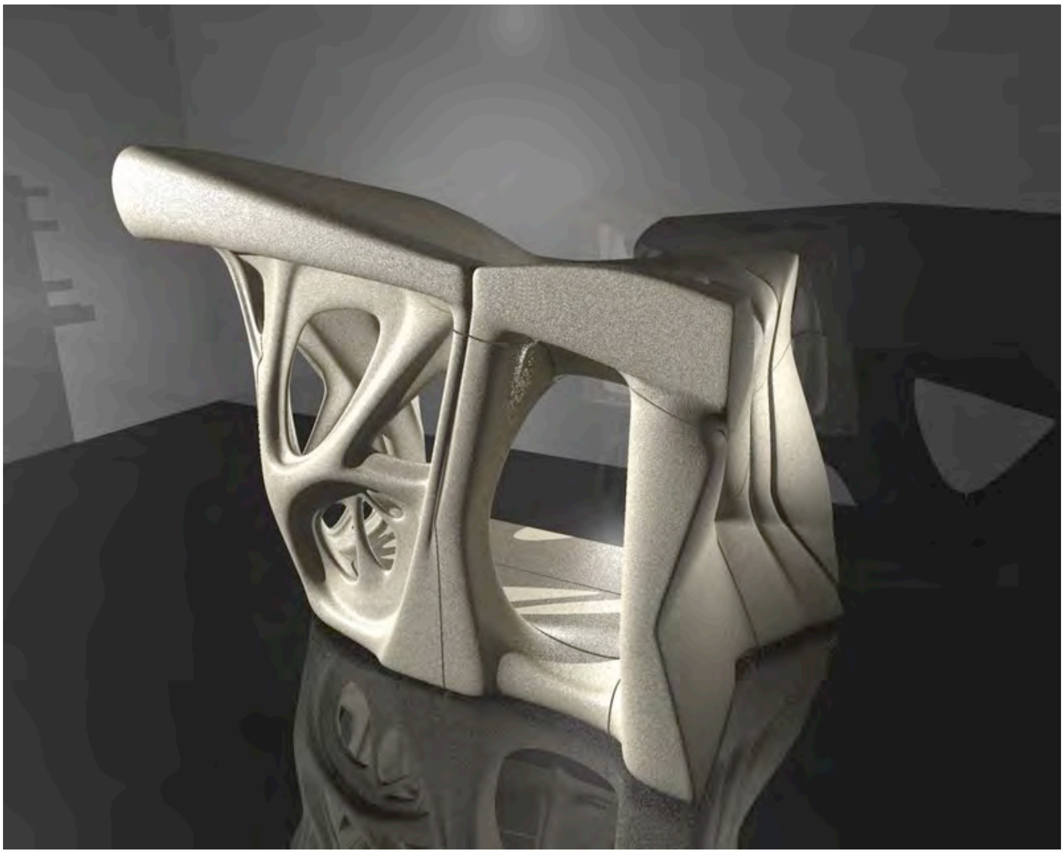

Figure 143 - Rendering of Roccia Assembly. Image by James Gardiner 2010

Almost all of the of the software used within this project was surface modelling rather than solid modelling software and thus presented problems with the creation of robust solid geometry required for output for printing and with ‘boolean’ operations discussed above. The use of parametric software for the modelling proved to be inappropriate on this project case due to a number of factors. Firstly the master geometry was not generated from a rule set that could be calculated, within the means of the project, within the parametric software used. Therefore management of the geometry was outside the strengths of parametrically based operations. The second factor that hampered the use of parametric software on the project was specificity of details, which needed to be managed individually, due to the large number of factors under consideration. This need for specific management of individual details reduced the effectiveness of the automation possible through the application parameter based operations. Writing scripts or designing specific operations for each operation would have been too time consuming for such a small project, although this may be appropriate for larger projects.

Figure 144 - Roccia Assembly rendering. Image by Alina Mcconnochie.

5.3.4. Conclusion Roccia Assembly

The Roccia Assembly project pushed deep into uncharted territory for the design at construction scale of large-scale elements to be fabricated using Construction 3D printing and the D-Shape technique. Methodologies were developed for the creation of geometry suitable for fabrication using the D-Shape technique, that responded to a multiplicity of requirements; including maximum panel sizes for printing and transportation, minimum detail and wall thicknesses achievable using the D-Shape technique, structural integration of three types of reinforcement and fixings, reduction of materials while maintaining panel structural integrity, integration of weatherproof joints, rainwater shedding and considerations of on site assembly while working with the Roccia design language and within the framework for the design of the Villa.

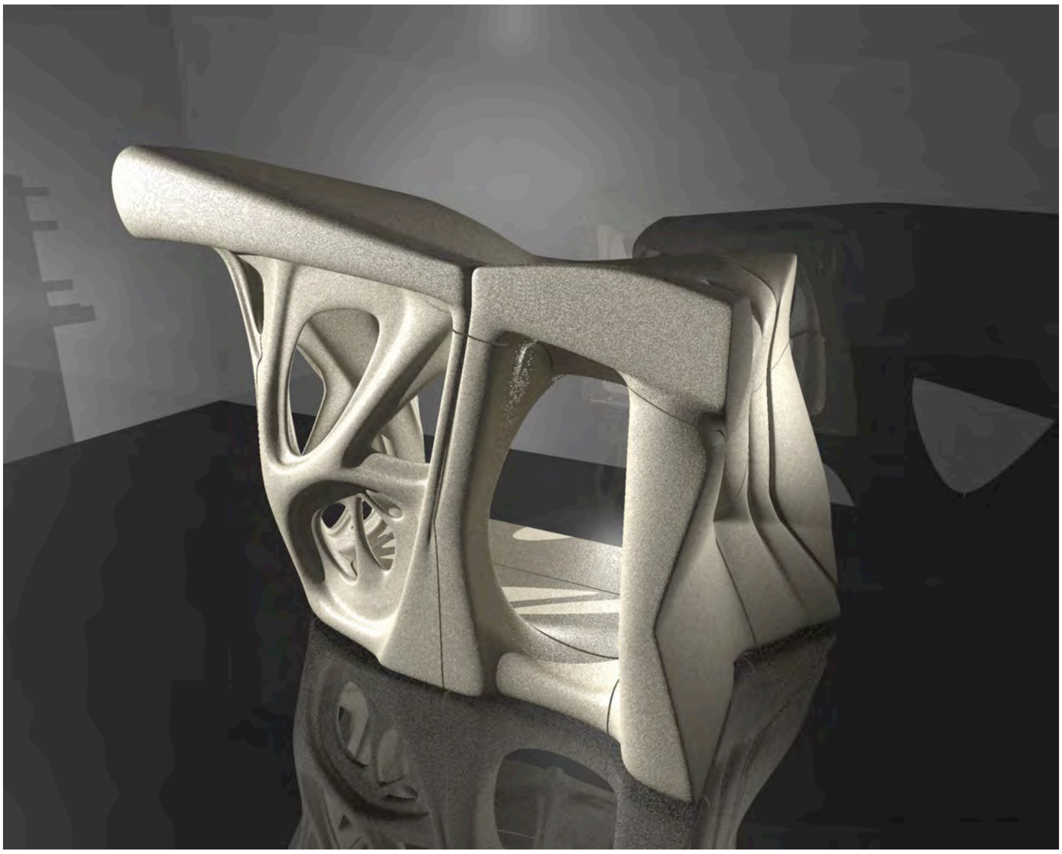

Figure 145 - Roccia Assembly rendering. Image by James Gardiner

A relatively efficient suite of software packages was identified and used after a period of testing had been carried out to ascertain the best set of programs for the project. This exercise was highly valuable because the programs that we thought would be ideal for this type of project proved to be unusable for what we were trying to achieve. Parametric modelling software although initially favoured for the project was ruled out, mainly due to the fact that the primary geometry was generated from a rule set that could not be integrated, negating much of its functionality.

The software packages used for the project included Maya™ for modelling the main envelope geometry. Rhino™ was used for modelling detail, creating joint profiles, creating the splitting geometry used to split the panels from the master geometry, boolean operations to remove geometry for dowel sleaves, post tension reinforcement conduits, lifting rebates and for checking the master geometry while being modelled in Maya™. Topostruct™ was use for the creation of the initial optimised geometry based on the sketch of the construction assembly cutaway section perspective (refer image Figure 123). Netfabb™ was used for boolean operations and for generating .stl files for D-Shape™ and Netfabb™ Selective Space Structures™ was used for the generation of the internal panel geometry.

Figure 146 (a) Bone sculpture indicating adaptation of bone structural concepts to the Villa Roccia project. (b) Photo of rock erosion. Sculpture and photos by James Gardiner.

Generative Components™ was tested for the development of the Villa Roccia project geometry and detail. Issues were experienced with this project due to the fact that the envelope was not generated parametrically; this fact I think presented difficulties because the envelope did not have any generating parameters. This made it difficult as new operations could not interact with the master geometry parameters. The second issue was that the detailing of the model again needed to be micro-managed due to the complexity of the geometry and the complexity of the joints that we were trying to break the envelope down with. The parameters were difficult to define for this project, as there were a number of single instances of different problems, rendering the use of parametric definition as a solution to these problems a cumbersome way of dealing with the issue. Had this project been much bigger, perhaps at the scale of the Gehry Disney Concert hall, it probably would have been worth parametrically dealing with the joints in this way, as there would have been many instances of each problem and too time consuming to deal with each of them individually.

The Roccia Assembly geometry was developed within Maya first as a detailed polygon model then tweaked using 'sub-divs', with a circular workflow established with Rhino™ for the checking of tolerances. Once this primary project geometry was complete the design was frozen and exported to Rhino where the geometry was broken down into panels with profiled joints, integration for reinforcement and filled with an internal structural geometry to reduce weight while retaining panel strength. Three types of reinforcement were used including dowels, stirrup plates and post tension cable reinforcement. The panels were filled internally with a structural lattice to allow for a reduction of materials required for the panels and a reduction in panel weight. This resulted in the need to split the panels along their length to ensure access for unbonded sand removal.

The splitting of the panels, a boolean operation, and generation of the internal geometry was completed using Netfabb™ Selective Space Structures™. This process was one of the most challenging tasks of the project, firstly due to the difficulty in generating the splitting geometry, that avoided cutting through the joint edge profiles and secondly because the boolean operations within Rhino were highly problematic.

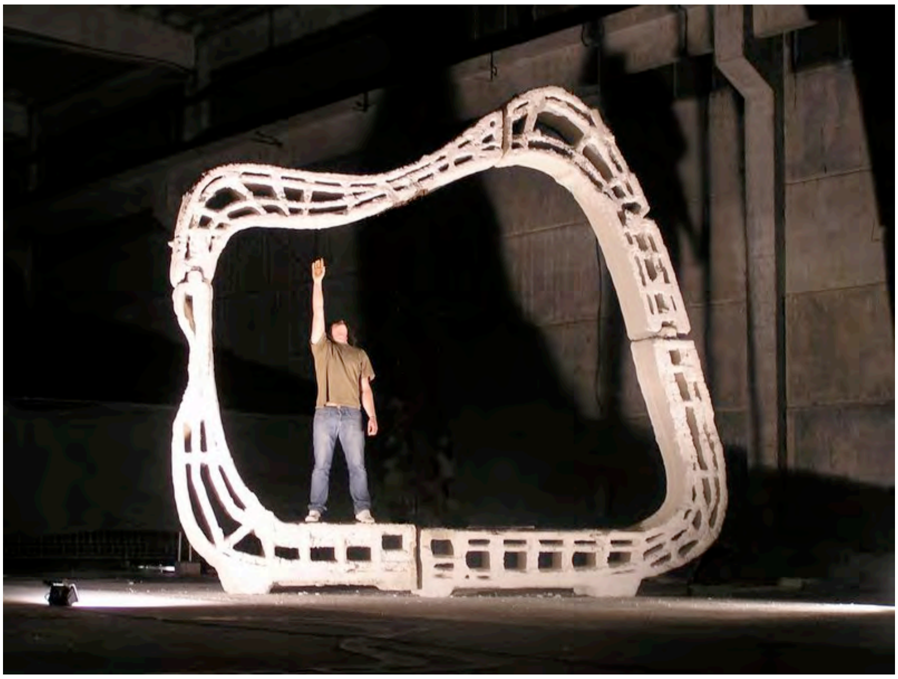

Figure 147 - D-Shape fabricated assembly loosely based on the assembly cutaway section perspective (refer image Figure 123).

Despite the fact that the project files[152] were delivered within the agreed timeframe the project was not fabricated by D-Shape™. A number of factors seemed to have contributed to D-Shape™ not fabricating the Roccia assembly; safety was one issue as demonstrated by the exhibition organisers requiring assurances from D-Shape™ that the assembly would be structurally safe. During earlier discussions with Arup Sydney in January 2010 the engineers had suggested physically loading the fabricated assembly to prove its structural stability, as quantifying the structural stability through engineering calculations would have been difficult due to a lack of independently generated material testing data.

[152] Project files included all panels, in .stl format, ready for fabrication without post processing and reinforcing stirrup plate cutting profiles for plasma cutting.

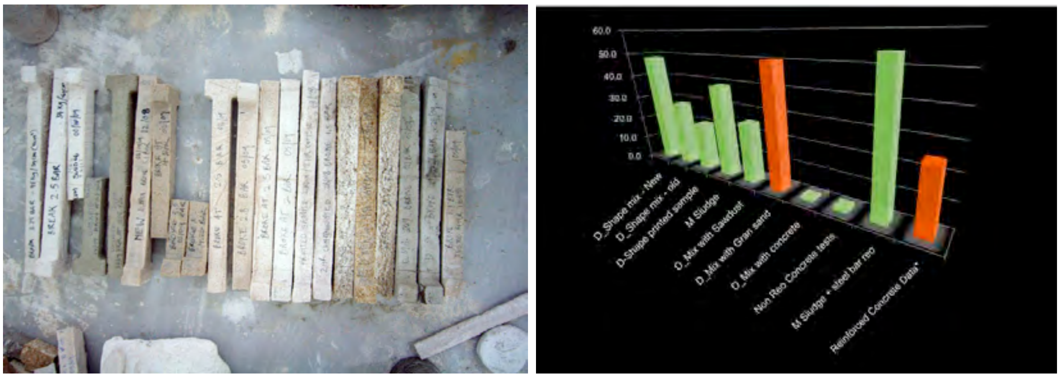

Figure 148 (a) James Gardiner made an extensive series of material samples and tested these during his time at D-Shape™ in 2009, independent testing was required to confirm these results. (b) Collated testing data for D-Shape. Testing, data and images by James Gardiner

Another issue was that D-Shape™ appear to have either thought that the project would not be delivered on time or would be unbuildable, unfortunately this was not communicated with me at the time and thus mediation of perceived issues was not carried out. D-Shape™ subsequently designed their own version of the assembly, which they fabricated without informing me (refer image Figure 147).

Unfortunately it is difficult to know whether the project could have been fabricated successfully at the time using the first generation D-Shape™ machine. It is clear from the image (Figure 147) that there were issues with fabrication tolerances that may have caused issues with the Roccia Assembly had it been fabricated. On reflection I believe this was probably the main motivation for D-Shape™ designing and fabricating a far simpler version instead.

The project did however explore the design territory of construction 3D printing (especially the D-Shape™ machine) and contributed significantly to developing methods to take advantage of the potential of these techniques. A level of highly detailed resolution was applied to the creation of the 'digital definition' which forms the equivalent of a documentation package in contemporary construction. Such resolution has not been previously applied to any project to be fabricated with Construction 3D printing and therefore this project has no precedent nor had it been equalled in 2011 at the time of writing this exegesis. Many strategies, methods and tools have been borrowed from the parallel and the construction industry: these have been critically re-evaluated for construction 3D printing and in many cases applied anew with consideration of a new set of Construction 3D printing constraints.

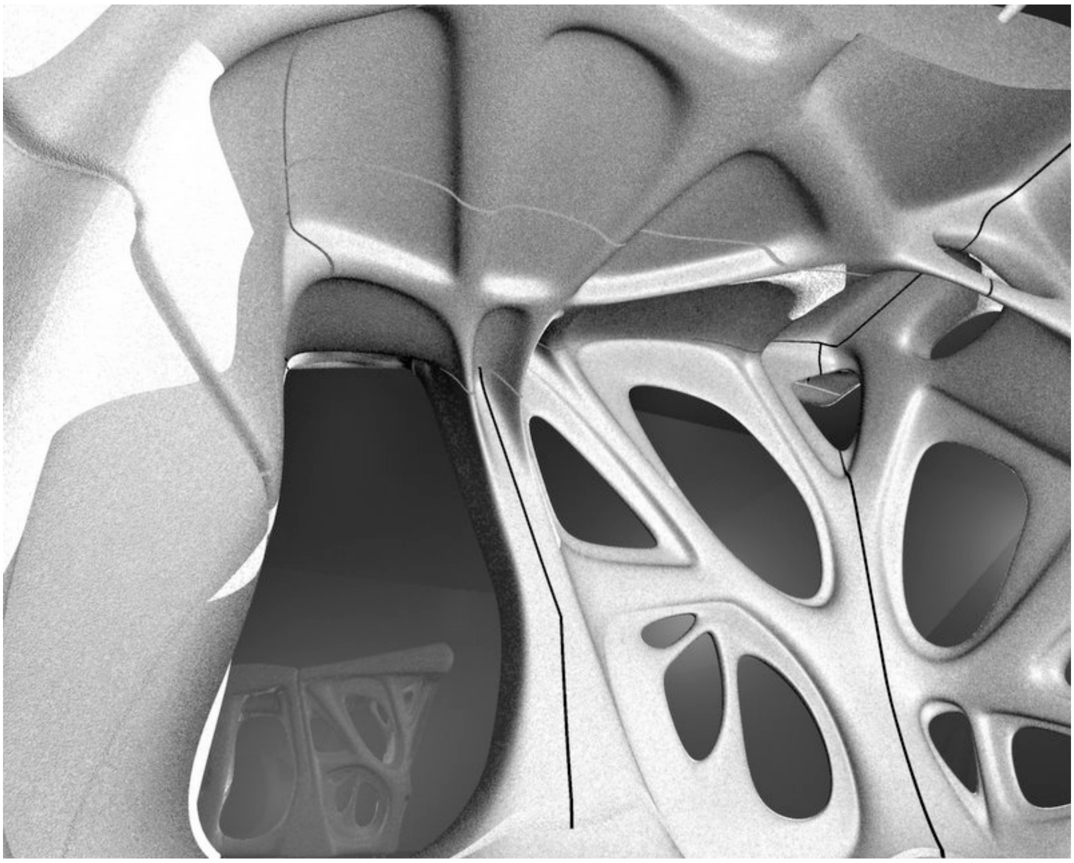

Figure 149 - Internal rendered perspective of the Roccia Assembly. Image by James Gardiner

Four of the five main objectives of this project have been achieved on this project: The objective that has not been achieved is fabrication and assembly of the Roccia Assembly, as unfortunate as it is, what we can learn from this is that the D-Shape™ technique was perhaps not quite ready for the task at the time and that communication could improve.

The other four objectives have been fulfilled however: The architectural language developed for the Villa Roccia has been implemented and applied with a high level of resolution. The result, I believe, is beautiful and does justice to the earlier design perspectives approved by the client. This Roccia design language and its application could still improve, especially through further testing and implementation of multi-criteria optimisation and/or simulation tools. I look forward to developing this further in construction of the Villa Roccia or on another project that has similar aspirations.

A suite of digital tools has been identified and used on this project, although this process has been incredibly difficult, the result in the form of the digital definition generated both achieves the desired result and is fit for the purpose for which it was intended - fabrication. A high level of architectural detail and resolution has also been applied to this project, which has created a wealth of knowledge to be further developed in future projects by me or by others.

5.4. Villa Roccia Conclusion

The villa Roccia project commenced in 2009 and came into existence through my contact with D-Shape™. The commission for the Villa Roccia project, located on the Costa Smeralda in Sardinia, came in existence through Enrico Dini, of D-Shape™, who had been in contact with a client who wanted a rock house. My interest in rock formations and the clients desire for a rock house were united and development of the design of the villa soon followed.

The sketch design phase occurred early in 2009, the design and fabrication of the Roccia column prototype followed shortly after with fabrication largely occurring in August of that same year. The Roccia Assembly was commissioned in 2010, to be exhibited in Europe and was also intended to serve as a second prototype and part of the final house.

This research has identified both the Sardinian tradition of building into and occupying natural rock artefacts and a more recent architectural tradition of designing rock inspired houses. The methods and practices of Gaudí however, have contributed more to the design of the Villa Roccia. These practices of Gaudí’s have been identified as the following: identifying and responding to forces, the development of a design system, design for fabrication, working collaboratively with fabricators and working toward the synthesis of man, technology and nature. All are present within the Roccia projects presented in this case study chapter.

The development of the Roccia design language was developed as part of the development of the design for the Villa Roccia and was based on my dual interest in the efficient and beautiful structures of bones and my study of both Sydney and the Costa Smeralda eroded rock formations. The development of the design language was based on literature review on bones and rock erosion, the visual study of rock formations and the physical study of bones. The designs for the Villa Roccia and the Roccia assembly are a demonstration of the application of this language and its interpretation in form.

With the design of the Villa and later the design for the Roccia assembly, the shell and panel methodology of the Freefab tower, was transformed into a predominantly panel based system, in response to the workings of the D-Shape™ technique. This panel system was developed to incorporate medium and fine levels of detail articulation: through the strategies used for panelisation, the articulation of windows, the design of waterproof joints and reinforcement methods.

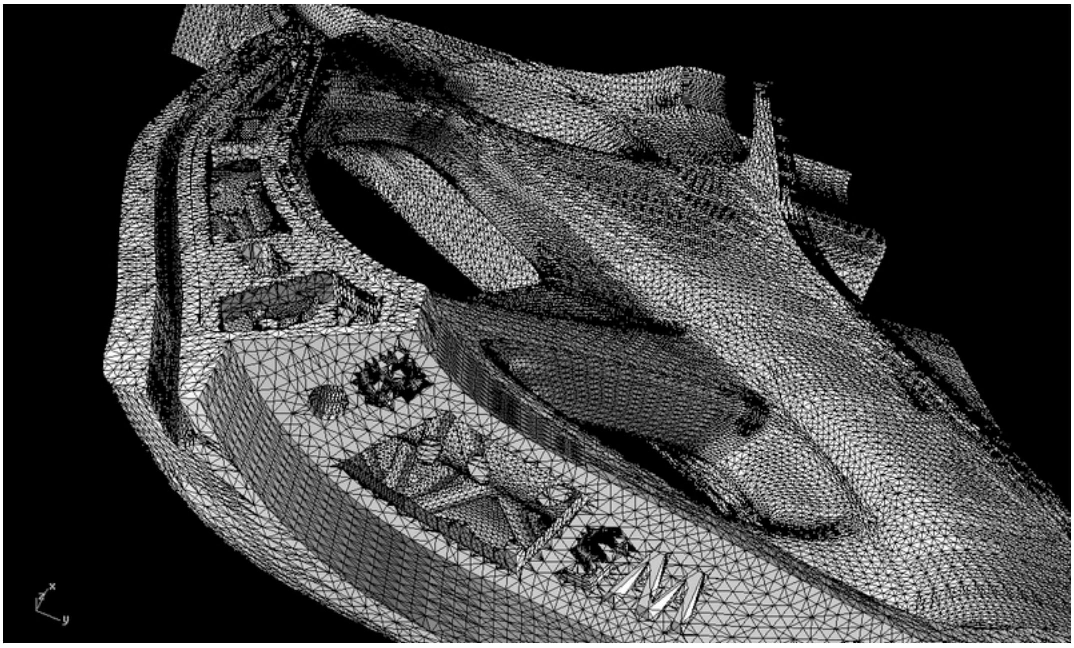

Figure 150 - View of one of the window panels that could not be split in two for fabrication. These panels have access holes that allow for unbonded sand to be remove. Image by James Gardiner

A suite of digital design tools was used for the generation of the digital definition of the Roccia Column prototype and the Roccia assembly. Parametric digital design tools were tested and used on the Roccia Column and the Roccia assembly projects, these tools were found to have been of limited use to the projects. The issues identified with the parametric software tools were attributed to the need to micro-manage joints: in the column at the mortise and tenon joint and on the Roccia assembly for each of the panels. The programs can be considered to have been of limited use on the project because of the size of the projects. If the scale of the projects had been much larger, the issues experienced would have likely been worth solving parametrically.

Simulation of rock erosion was attempted using Maya™ but had to be abandoned due to time constraints. Topostruct™ topographic Structural optimisation software was use to generate the external envelope that responded to the forces estimated to be acting on the structure. The resulting envelope was used as a guide to the forces acting on the assembly which was later remodelled in Maya™.

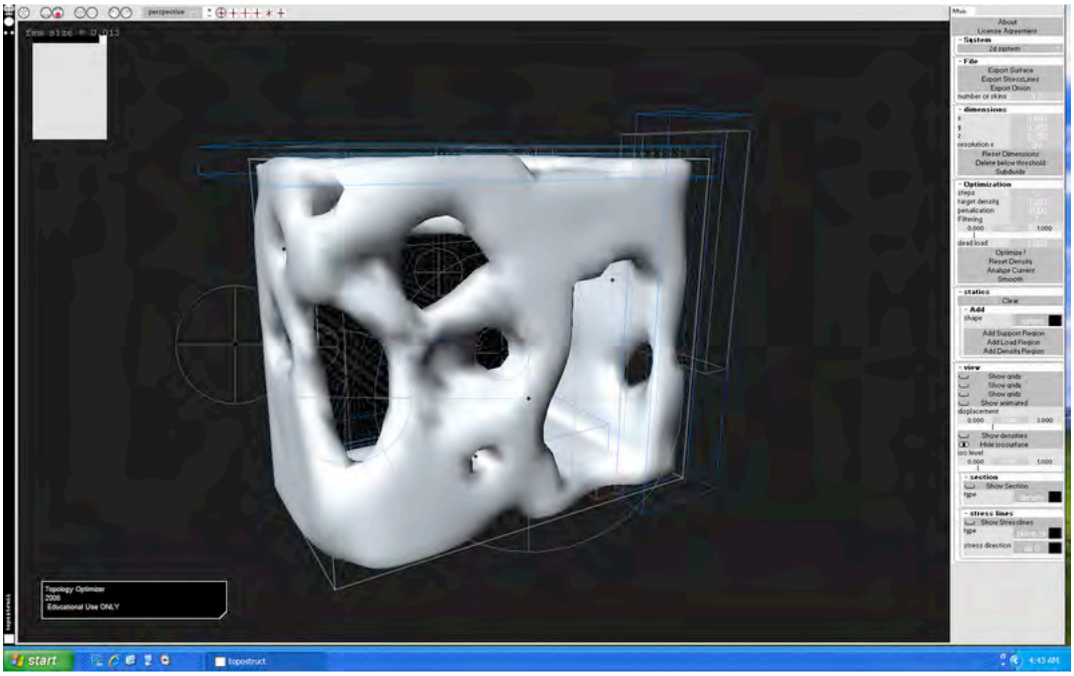

Figure 151 - Topostruct™ structural optimisation of the external envelope. Image by James Gardine

The use of Maya™ on the Roccia assembly was successful due to the relative ease in which the Roccia language could be developed in the design of the Roccia assembly envelope. The use of editable polygons enabled the progressive tweaking of the external envelope through a number of scales of refinement. With

Maya™ used primarily to generate the course and medium levels of detail within the external envelope: the form and its articulation with windows, ribs and sills. Rhino™ was used to add the architectural detail, being a more dimensionally accurate tool than Maya™. Rhino™ was used to generate the cutting planes and joint profiles for the creation of the panels that broke down the envelope into elements that could be fabricated by D-Shape. Rhino™ proved to be a highly dexterous tool for these operations, whereas others tested such as Generative Components™ had been more problematic in their execution of these tasks.

Netfabb™ fulfilled the function of the generation of the internal geometries for the Roccia assembly, which can be likened to the creation of trabeculae within bone. This internal geometry allowed for the removal of much of the material within the panels, which made them lighter and potentially more thermally efficient due to internal voids. This task had been attempted with Solidedge and had been unsuccessful, perhaps due to dexterity of the user. The Netfabb program did however generate some issues, the two planned internal geometries had to be reduced to one, because there was no method to control the meeting of these geometries at their intersection, a single internal geometry was substituted for the panels which resulted in less than ideal structures on some panels.

Issues with boolean operations both within the Roccia column and Roccia assembly indicate that these operations are a fairly significant issues for these programs. Both Rhino™ and Netfabb™ repeatedly crashed and produced problematic unclosed geometries as a result of boolean operations. Rhino™ threw up incomprehensible results from boolean operations with addition occurring in one instance time and subtraction occurring in others while using the same command.

A number of significant potentials were identified which could have significant implications for the construction industry, designers/engineers and construction 3D printing. The potentials have been teased out through engaging directly with construction 3D printing and through the creative problem solving and visioning.

These potentials can be summarised as follows:

- Construction 3D printing has been demonstrated to have excellent potential for the creation of very complex 3d double curved geometries and fine filigree bone like structures.

- The use of optimisation software is ideally suited to construction 3D printing as additive fabrication techniques have been demonstrated to fabricate complex geometry without a cost premium. Optimisation software, especially topology structural optimisation software, generally creates geometrically complex structures that are difficult to fabricate using conventional subtractive, formative or additive construction methods. Such optimisation can be done at the three scales described in this and the next case study chapters, fine (detail), medium (articulation) and course (topology). Ideally this optimisation of the three scales would be done simultaneously.

- There is great potential for multi-criteria optimisation of structures to be fabricated using construction 3D printing techniques. As all construction 3D printing techniques fabricate using a single material at present this perceived limitation can be turned to advantage with the creation of complex structures that have been optimised for a broad number of criteria such as; strength to weight ratio, thermal performance, acoustics, sun light, wind, fabrication constraints (including joints and panel sizes)rainwater shedding/weathering.

- The digital definition file can be used to capture virtually every aspect of the constructed element and leveraged to be the central information source. The precedent of the use of the digital definition within the aerospace industry is directly applicable to design for construction 3D printing because the entire assembly must be modelled prior to fabrication and thus this information should be leveraged in a similar way to that of other industries to ensure maximum value is derived from the 3D digital definition.

- The use of scripting and parametric modelling technique are well suited to automating tasks associated with the generation of large and very complex structures, such as those ideally suited for construction 3D printing.

- Design for construction 3D printing is well suited to the development of new ‘design language’ which can be both whimsical and functional, such as the adaptation of rock erosion formations to echo the landscape and bone structures to create efficient structures.

- Construction 3D printing has been demonstrated to be well suited to off-site factory based automated construction. This is partly due to the inherent need for the construction 3D printing machines to be located within controlled environments to ensure materials a deposited and cured within ideal conditions. There is also a need to integrate post processing of the parts fabricated to ensure dimensional tolerances are met and lastly due to the suitability for production line automated manufacture.

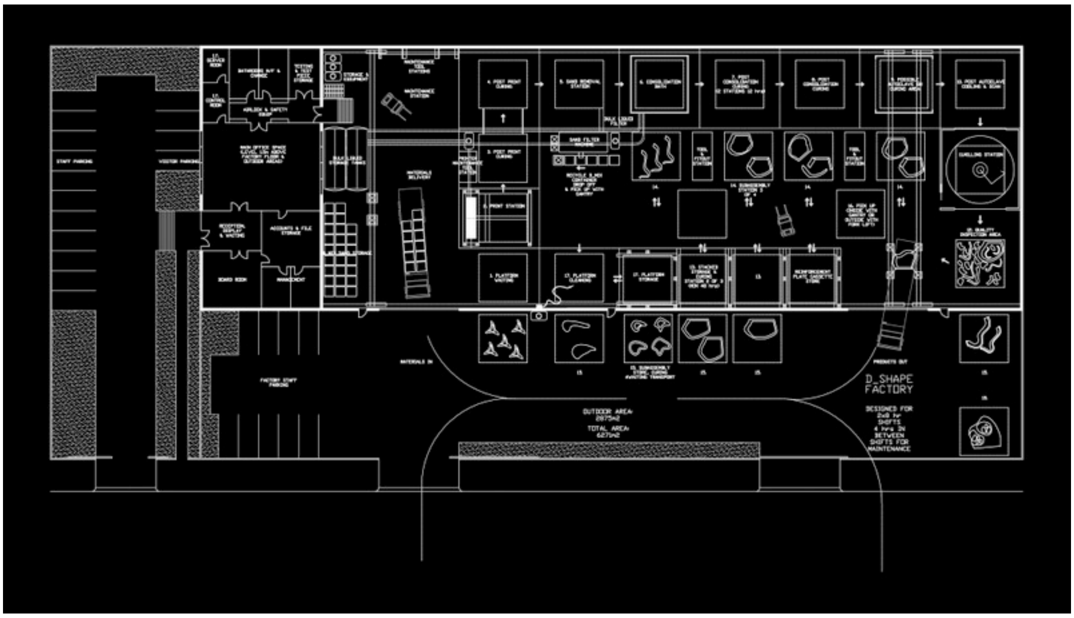

Figure 152 - Design for D-Shape automated construction 3D printing factory by James Gardiner

The Roccia column was fabricated in August 2009 by the D-Shape™ team, Marta Male-Alemany and myself. Marta Male-Alemany visited for two weeks during mid August and assisted with all aspects of fabrication with the D-Shape™ machine during that time.

The Roccia assembly was not fabricated as intended, for reasons that are still not entirely clear. Yet the Roccia assembly project can still be considered a success based on the learning outcomes from this project. The generation of the digital definitions for both the column prototype and the Roccia assembly have resulted in valuable insights relating to the interpretation and application of a design language, generation of digital definitions specifically for a construction 3D printing technique and the integrated use of a variety of digital design tools. My involvement in the fabrication of the Roccia column was instrumental in increasing my understanding of construction 3D printing and particularly the D-Shape™ technique. This project has resulted in the generation of significant knowledge in the design for construction 3D printing and especially the D-Shape™ fabrication technique, which has assisted with designs that have been tailored to the capabilities of the D-Shape™ technique.

6. (In)human Habitat: Rethinking the Constructed Reef – Project Case Study 3

The project below describes a world-first research project that investigates a potential new link between constructed reefs and construction 3D printing. This link has not been made before either in theory or practice. This case study project has investigated this potential through the design for fabrication, for construction 3D printing techniques, of a complex constructed reef. This case study explores the design territory that construction 3D printing techniques potentially make available and how this new type of constructed reef could contribute to marine environments and habitat.

This research project builds on the knowledge generated in the preceding case study projects, Freefab and in particular the Villa Roccia. The inspiration for this project evolved from working with D-Shape™ on the Villa Roccia project and the basis for the digital design working methods have been adapted directly from this project. The project is however very different from these preceding case studies. Although the project also provides habitat the nature of this habitat couldn't be more different, as you will see as the project is described below.

The case study is described in the following order; a background literature review is presented that investigates topics such as the growth and formation of coral reefs and the value of these to man and marine flora and fauna and causes of coral reef degradation and decline. A review of artificial and constructed reefs is presented, which also defines the differences between two reef types: artificial reefs and constructed reefs. A definition is then made between the three scales at work within natural and constructed reefs in reference to literature review and personal observation. An argument is presented describing the suitability of the D-Shape™ fabrication technique to the creation of constructed reefs. Concepts for the planning of constructed reefs are discussed in relation to emerging concepts of urban design relating to existing principles of urban planning with a discussion regarding the design of constructed reefs as ‘complexes’ of multi-environment topologies.

A brief introduction of the (in)human habitat project is then made which includes the motivations and the context within which the project was developed. The location for the hypothetical reef project is presented with an explanation of the sites suitability for a project of this type based on the literature review. The (in)human habitat project is then presented with a discussion of the two principles concepts that underpin the project: the reef complex as an assemblage of topologies and the ‘deep scaffold’. The design of a new type of constructed reef, is then presented, based on the principles described. This is followed by a discussion of the generation of the ‘digital definition’[153] of the constructed reef complex using digital design tools and the fabrication opportunities available through the use of construction 3D printing. The results of this process as manifested in the project design are presented and discussed through reference to images and drawings of the project.

The project is concluded with a discussion of the successes and limitations of the project, followed by the identification of potentials identified through the case study project. The recognition of the project and the opportunities that have arisen from the project are then discussed, which demonstrate the relevance of this project and the speculative mode of research.

6.1. The formation and value of Coral Reefs

This research is focused specifically on coral reefs rather than other natural reefs types that may be formed from rock, sand, biological matter etc. Coral reefs are defined as “*a marine limestone structure built by calcium-carbonate secreting organisms which, with its associated water volumes supports a diverse community*

[153] Refer to definition of digital definition in the index of terms (chapter 1.5)

of predominantly tropical affinities, at a higher density of biomass than the surrounding ocean." (Hatcher, 1997)

"Corals are actually invertebrate animals and are in the same taxonomic group as jellyfish and sea anemones. Each individual coral animal is called a polyp. Most coral polyps live in "colonies," which are groups of hundreds to thousands of genetically identical polyps formed when the original polyp grows copies of itself (the process is called budding). Corals are grouped into two types—hard corals and soft corals. Hard corals are the "reef-building" corals, and there are approximately eight hundred known species of hard coral." (Mulhall, 2008)

Figure 153 - Coral of the Great Barrier Reef. Photos by James Gardiner

Darwin pioneered the understanding of the formation, distribution and growth of coral reefs. He was the first to define the principle types of coral reefs which are; fringing reef, barrier reef and atoll (Darwin, 1842). There are a number of other micro-scale types of reefs that have been identified such as such as bank reefs, coral cays, apron reefs, ribbon reefs and ridge reefs. Darwin's theory posited that the two of the types of coral reefs, fringing reef and atoll, were the result of the subsidence of volcanos, with the fringing reef forming around the volcanic island which over 1000's of years gradually subsided until only the coral reef atoll was visible (Darwin, 1842).

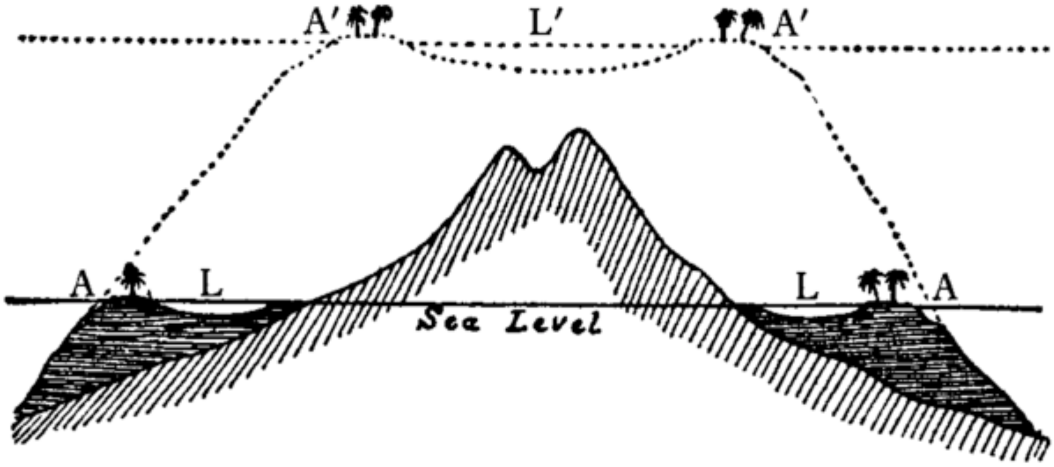

Figure 154 - Drawing from Darwin's "Structure and Distribution of Coral Reefs' Image source - http://en.wikisource.org/wiki/1911_Encyclopædia_Britannica/Coral-reefs Access date 19th August 2011

In addition to these reef types there are also reef zones, which are identified and named differently by different authors (Field et al., 2008, NOAA, 2010). The most useful categorisation of the zones, that I have found, are identified as the following: Deep fore reef, fore reef, reef crest, back crest, reef flat or lagoon zone (NOAA, 2010) (refer imageFigure 155).

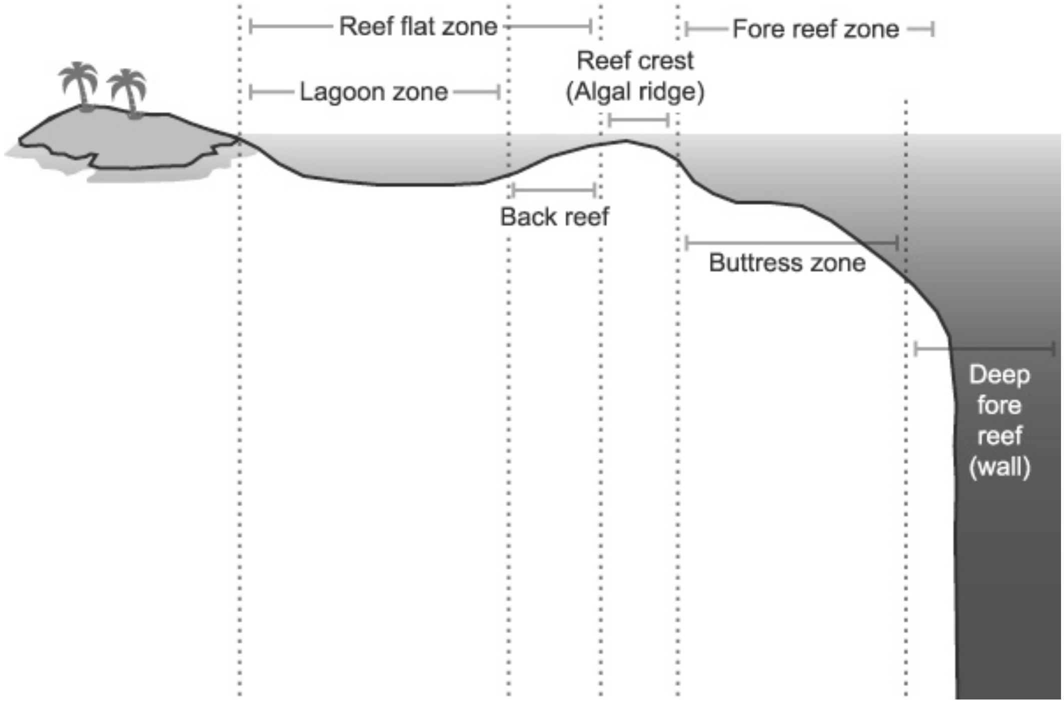

Figure 155 - Coral reef zones. Image source - http://oceanexplorer.noaa.gov/explorations/07twilightzone/background/plan/media/reef_diagram.html Access date 20th August 2011

The stony corals form coral reefs are formed can only survive within a reasonably tight band of atmospheric (be it underwater) conditions, changes in these conditions due to changes in water temperature or increases in nutrient levels from run-off can lead to coral bleaching, which is the result of loss of symbiotic algae and/or their pigments (Brown, 1997). A description of the environmental requirements of coral and thus coral reefs are as follows:

"*Most reef-forming corals prefer sea temperatures between 17 and 33°C, salinities of between 30 and 38 parts per thousand, and clear water. Light is also important, and coral growth is usually restricted to the upper 25 or 30 metres. Because of these factors, coral algal reefs are found mainly between latitudes 30°N and S on mud-free coastlines, particularly in western parts of the Pacific, Indian and Atlantic Oceans.*" (The_Dictionary_of_Physical_Geography, 2000)

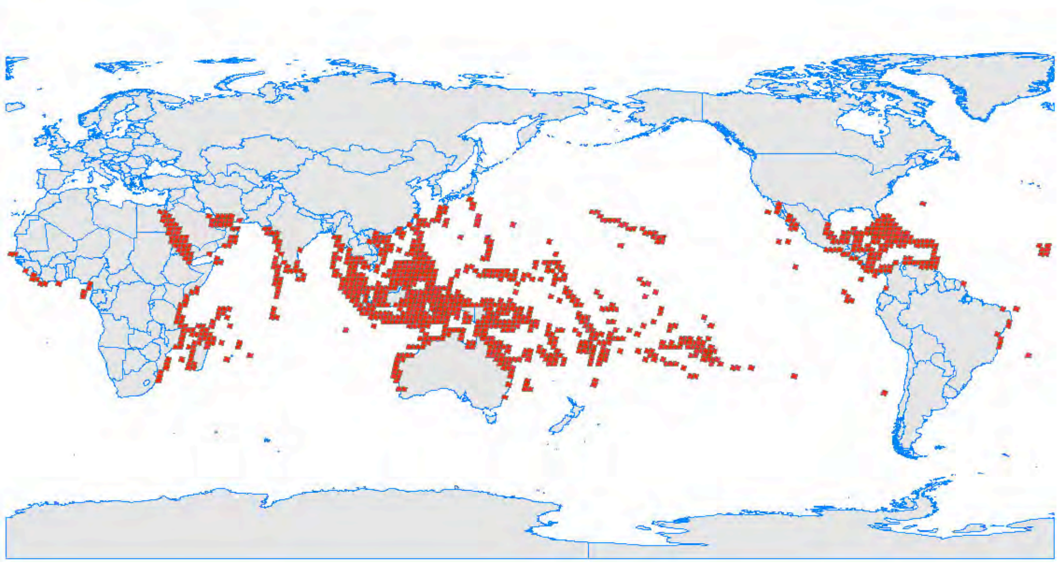

Figure 156 - Distribution of Shallow Water Coral Reefs Worldwide. Image source - http://cornellbiochem.wikispaces.com/coral+reefs#toc%20%20Coral%20Reefs-Sources

Despite coral reefs relatively small size and narrow band of distribution worldwide, coral reefs are considered to be critically important to the health of the world's oceans and marine life.

"Coral reefs are often referred to as 'the rainforests of the sea'. The comparison is fitting—despite occupying less than one percent of the ocean floor, an area about half the size of France, temperate and tropical reefs provide a home for as much as twenty-five percent of the world's marine species. Scientists are only just beginning to account for the more than one million species believed to live in coral reefs, but they know that more than four thousand species of fish alone call the reefs home. Only tropical rainforests can compete with the sheer concentration of biodiversity found in coral reefs, and rainforests occupy twenty times as much area as reefs." (Mulhall, 2008).

Coral reefs, as well a being nurseries for spawning marine life, serve many other important purposes, such as being a refuge for endangered species, protecting coastlines from damaging seas, waves and tsunami's. Coral reefs also provide approximately 10% of the worlds fish catch, are considered responsible for regenerating fish stocks and support valuable activities such as pharmaceutical research and marine recreation (Lowry et al., 2010, Mulhall, 2008).

Much research is being conducted at present regarding the reaction of coral reefs to the effects of climate change[154] (Hoegh-Guldberg, 1999). It is not within the scope of this research to address this issue, although it is hoped that this work may assist if required.

6.2. Artificial and Constructed Reef Precedents

The historic approach to creating man-made reefs has been to use waste products: scuttling ships, decommissioning oil rigs, dumping automobiles, planes, tires, concrete barriers and other waste products (Chou, 1997, Kaiser, 2006, Lowry et al., 2010) and at best placing specifically fabricated reef units (Charbonnel and Bachet, 2008, Nakamura, 1985, Bortone, 2006).

Two terms will be used within this chapter ‘artificial reefs’ and ‘constructed reefs’. The term ‘artificial reefs’ will be used to describe reefs made from waste products; such as ships, tyres and pipes. The term ‘constructed reefs’ will be used to describe elements fabricated specifically to be reefs; such as Reef Balls™ (Figure 158 a), Ecoreef™ (Figure 158 b) and the Haejoo Fish Cave™(refer image Figure 160b). The term artificial reefs can be considered to refer to a traditional approach to creating reefs, often cited as beginning at least several hundred years ago in Japan (Bohnsack and Sutherland, 1985). The term artificial reef is also widely used to refer to reefs created by accident such as the sinking of ships, which would certainly predate Japanese efforts. It is likely that the sinking of ships in marine accidents or as the result of national or regional conflicts later demonstrated a benefit from the ships presence, through increased provision of habitat for both marine flora and fauna. As awareness of the benefits of the

[154] As noted in the introduction: Human induced global warming is considered for the purposes of this research to be a proven based on the current scientific published reports (refer references above) and the status that it is given by Australian and world scientific groups (IPCC, CSIRO climate change, Climate Scientists Australia) and government/non-government related bodies (UNFCC, USGCRP, climate

accidental creation of marine habitat became apparent artificial reefs, would have begun to be used as a method to increase sea food harvests.

This segregation of terminology, by adding the term ‘constructed reefs’, in order to create a distinct grouping, separate from artificial reefs is used to help distinguish between man-made reef types. The term artificial is also considered to be a barrier within the industry with the word ‘artificial’ often being interpreted as meaning ‘fake’ rather than man made and/or custom built[155]. The term ‘constructed reefs’ has been recently used by the authors (Sheehy and Vik, 2010) to refer to constructed elements that act as reefs as a secondary function. The use of the term to mean: ‘reefs that have been specifically fabricated from new materials for the purpose of creating marine habitat’ was originated by David Lennon Director of Sustainable Oceans International and Reef Ball Australia[156].

The benefit of artificial reefs is generally to “*improve fisheries by increasing the harvest of algae, lobster, other shellfish and fishes*” (Bohnsack and Sutherland, 1985). Other purposes for the construction of man-made reefs can be summarised as the following: attraction of fish, improvement in spawning and recruitment of larvae and adolescent marine life, protection and survival of young marine life. Other functions also include reefs serving as breakwaters, controlling beach erosion, preventing trawlers from using certain areas, restricting fishermen from fishing lanes, reducing fishing pressure on other stocks and mitigating habitat loss and the provision of new or alternative locations for recreational diving (Bohnsack and Sutherland, 1985, Lowry et al., 2010).

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[155] The distinction of the word ‘artificial’ as being taken to mean ‘fake’ is based on email correspondence between David and I dated 19th August 2011. The topic of the email was on the origin of the term ‘Constructed Reefs’, another term ‘designed reefs’ was also mentioned to be in use.

[156] This opinion on the origin of the term ‘constructed reef’ is based on email correspondence between David and I dated 19th August 2011. The topic of the email was the origin of the term ‘Constructed Reefs’.

Figure 157 - Tyres used as an artificial reef. Image extracted from the paper - Lowry et al. 2010.

Some of artificial and constructed reef products, such as used tyres and plastics, have been found over time to be toxic to their environment, structurally inappropriate, inadequate to resist storm effects and damaging to environment in which they were placed (Salahuddin, 2006); in some cases requiring large scale removal of the artificial reef materials (Morley et al., 2008).

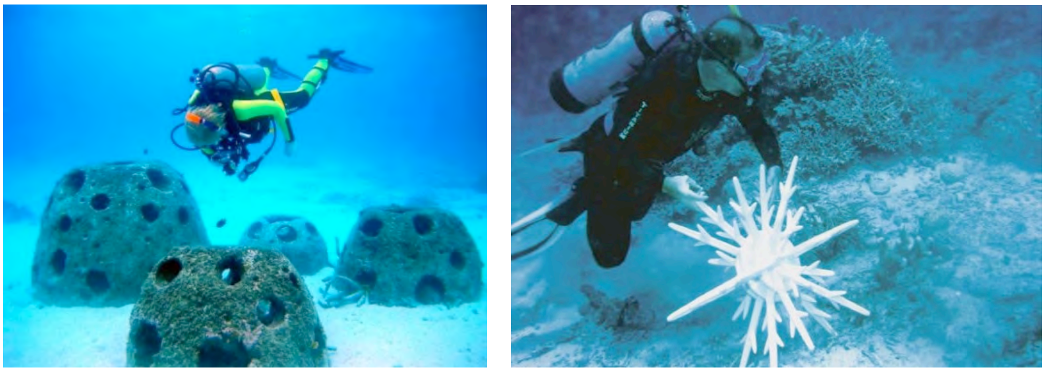

Figure 158 (a) A variety of different size Reef Balls™. Image source - http://repeatingislands.com/2010/10/29/the-montserrat-reef-project-to-enhance-marine-ecosystems/ (b) Ecoreefs ceramic 'snowflake' module. Image source http://sciencereview.berkeley.edu/articleex.php?issue=3&article=coralreefs Access date 25th March 2011

Constructed reefs today are predominantly based on modular elements, using steel, concrete, cables and other elements that are cheap to manufacture; these low-cost materials tend to be poor at emulating their topographically diverse natural cousins. This is due to the fact that constructed reef modules are in most cases highly sensitive to cost constraints[157]; this control governs how the modules are fabricated (in most cases casting or welding) and the complexity available as a factor of fabrication technique and labour. Serial and/or mass production is used for all of the main commercially available constructed reef modules including; Ecoreefs, Reef Balls, Ecosystems™ etc; this standardisation results in a limited range of products that are deployed in groups of 3 through to deployments of 100s and 1000's (Harris, 2007).

Although most commercially available modules are good at providing habitat for a variety of marine flora and fauna, they do not individually or in groups provide the level of complexity of topology[158] or spatial diversity found in natural reefs (Carr and Hixon, 1997, Perkol-Finkel et al., 2006). The researchers in describing the Rundle™ reef note:

"its ability to produce a very large growing area in a relatively small space, i.e. an area covering 5 m2 produces a growing area of 250 m2" (Hopkins, 2007) p8.

Figure 159 - Rundle Reef Module; concrete and polyethylene pipes – Image source http://www.seacult.com/pdf/reefsystems_dubai_pilot_project_report_2007_final.pdf (Hopkins, 2007)

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[157] A 'Bay Ball' Reef Ball™ costs approximately AU$200 (source Reef Balls Australia)

[158] Topology – (as per index of terms chapter 1.5) – "6. the anatomy of any specific bodily area, structure, or part". This word is used instead of topography - "3. the land forms or surface configuration of a region"

When you inspect the reef however (refer image Figure 159), it is possible to distinguish only four separate spatial types: inside the thin pipes, in between the pipe rows, in between the pipes themselves and inside the concrete central cylinder. Given the distinctions made by Carr in describing another reef project:

"*the greater vertical relief and shelter availability (number of holes) of artificial reefs did not compensate for the greater structural complexity (variety of hole sizes) and natural forage base provided by the corals and associated benthos of the natural reefs*" (Carr and Hixon, 1997) p30

The Japanese have been pioneers in reef design and research (Nakamura, 1985) and have developed many of constructed reef typologies and concepts adopted elsewhere such as in the US (Bohnsack et al., 1994) and in Europe (Charbonnel et al., 2008) and Asia (Kim, 2001). The two images below (Figure 160 a & b) are designs available from Haejoo, a Korean reef company and represent the increasing sophistication of artificial reefs. These reefs are designed for specific target species, essentially developing a monoculture for production of octopus, abalone etc. This approach highlights a narrow commercial focus rather than the development of constructed reefs to develop and compliment an ecosystem.

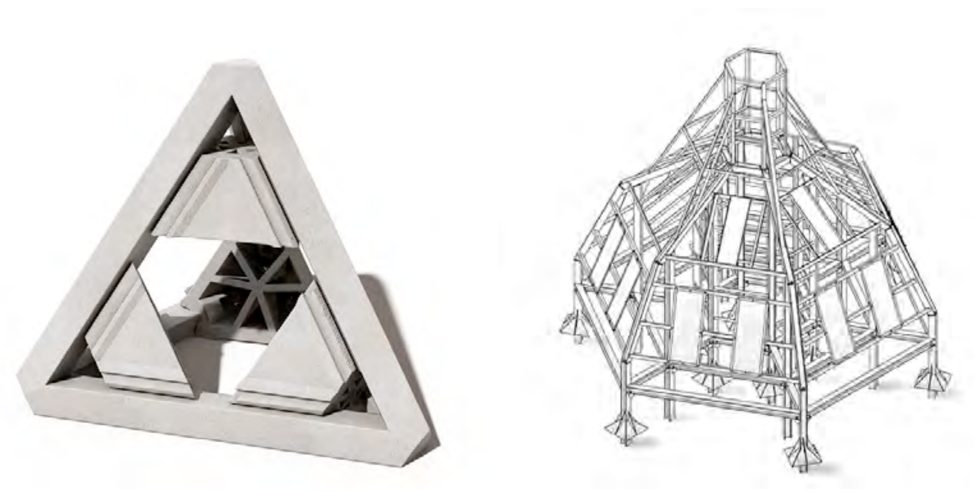

Figure 160 (a) Haejoo Marine Pyramid. Image source http://haejoo.com.au/service/modules/pyramid/
(b) Haejoo Fish Cave. Image source http://haejoo.com.au/service/modules/fishcave/ Access date 14th May 2011

Japanese research identified three specific fish types by behaviour in and around reefs, these are Type A – Fish in physical contact with the reef, Type B – Fish linked to the reef through vision and sound and Type C – Fish that hover above the reef in the middle and upper parts of the water column (created by the reef) (Nakamura, 1985).

There is an ongoing research and debate of the topic called 'fish attraction versus production' amongst academics, government agencies and other stakeholders that focuses on, as the name suggests, whether constructed reefs actually produce fish (this the main focus of the discussion) and marine fauna or whether they merely attract this fauna from elsewhere (PIRSA, 2010, Pickering and Whitmarsh, 1997, Brickhill et al., 2005, Bohnsack and Sutherland, 1985). It is not within the scope of this research to try to tackle the discussion of fish attraction versus production. Based on my discussions with experts in the field[159] and from literature review my leaning is toward production, although this is a debate outside of my field of expertise and training. For the purposes of this project it is assumed that constructed reefs, by being a destination for floating larvae and also a permanent home for some species, will both attract and produce marine fauna; and therefore the constructed reef has an ecological and environmental benefit to the marine environment and its species diversity.

6.2.1. Topology, articulation and texture

Extensive research shows that there is a direct correlation between the topology, articulation and texture in natural and constructed reefs. There are three scales or levels of detail that are important for the success of natural and constructed reefs. These scales or levels of detail are course, medium and fine, there definition cans be described as topology, articulation and texture and will be described in detail below. The discussion of levels of detail has been discussed in previous chapters

[159] Discussions with Dr Michael Lowry Senior Research Scientist, Wild Fisheries, NSW Industry and Investment on the 28th September 2010, Australia and David Lennon, Director Sustainable Oceans international 5th of November 2010 with ongoing discussion and emails through until 20th of August 2011.

(Chapters 3.2 and 5). The course level of detail, topology, relates to the shapes within a reef and is very important in determining the population density and diversity of a reef. The creation of a variety of different topographies is a critical factor in the creation of species diversity within a constructed reef (Perkol-Finkel et al., 2006, Nakamura, 1985):

Further articulating this course level of detail, within reefs, is the medium level of detail, articulation, which articulates the reef and provides further habitat specificity:

"*The reef architecture and module design determine not only the global performance of the reef (species richness, abundance, and biomass), but also the identity of the species*" (Charbonnel and Bachet, 2008)

On artificial reefs the density of fish aggregation and diversity of species has been found, to be directly related to the medium level of complexity and articulation of the reef structure (Charbonnel and Bachet, 2008, Grove et al., 1989, Carr and Hixon, 1997).

The fine level of detail, texture, is also very important and a feature in the success or failure of constructed reefs (Fitzhardinge and Bailey-Brock, 1989), which has often been overlooked when making choices about materials for constructed reef projects

"*in general, uneven surfaces with cracks, crevices and holes increase benthic diversity and biomass*" (Bohnsack and Sutherland, 1985)

The characteristics of this fine level of detail manifested in constructed and natural reefs. This fine level of surface texture is most important to marine flora and sessile (stationary) marine flora. Reef surface is particularly important to coral polyp larvae recruitment, with uneven and textured surfaces being the most appropriate for the attachment of coral polyps. Surface texture and shape are important as they determine the ease and energy required for the polyp to attach and secure itself to the reef structure through the deposition of a stony carbonate (Richmond, 1997). It is also said that small concave surfaces (depressions on the surface) assist with coral polyp recruitment[160], although reference to this capability has not been located by me in literature to date.

6.3. Site Selection and Planning of Constructed Reefs

6.3.1. Constructed Reef Planning

Figure 161 (a) Traditional suburban tract housing. Image source - http://www.city-data.com/forum/general-u-s/616577-cookie-cutter-towns-2.html Date accessed 18th August 2011 (b) Reef balls lined up in rows. Image source - Lowry et. al. 2010.

Today in the Western world the design of constructed reef complexes can be said to be, at best, equivalent in planning sophistication (Charbonnel et al., 2008, Leitao et al., 2008, Lowry et al., 2010) to 1950s era tract housing suburb design (Figure 161) and rarely goes beyond the scale and complexity of small towns. In contrast to this simplistic approach to the creation of constructed reefs, reef design and planning in Japan by the late 1980's had already reached a level of spatial arrangement, structure diversity and sophistication (Bohnsack and Sutherland, 1985, Nakamura, 1985, Grove et al., 1989) still rarely present in the west today. This thinking is beginning to change with industry experts (Lennon, 2010a) calling for a shift in the way we design and think about constructed reefs based on established urban principles (Benninger, 2001).

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[160] Based on discussion with David Lennon from Sustainable Oceans International, 20th October 2011

"*Artificial reefs are basically underwater cities and their design and planning is similar to the design and planning of our towns and cities on land*…(for example)...*artificial reefs can be designed to have neighbourhoods that include features that appeal to juveniles and exclude predators*" (Lennon, 2010a).

Lennon briefly describes how these principles are relevant to constructed reefs (Lennon, 2010a), some of which I have very briefly summarised below:

- **A balance with nature**: Nature must be able to resurge each year, biomass must be able to survive in its own ecosystem, breeding grounds for fauna must be safe, no erosion and the biomass must be maintained.

- **Appropriate technology**: the use of building materials, techniques and systems that are consistent with local contexts.

- **Efficiency**: Compact settlements along dense urban corridors, location near other productive habitats and close enough for user groups to cost effectively access them.

- **Opportunity**: Cities provide services and opportunities for residents and visitors (such as cleaning stations used by sharks and rays), have neighbourhoods that appeal to juveniles and exclude predators, provide temporary resting, spawning and foraging grounds

- **Regional integration**: A reef cannot operate in isolation and relies on the nearby constructed and natural reefs and is exposed to currents. Reefs need to be planned with the broader region in mind.

There is excellent scope to further develop these design principles and begin to establish principles for the creation of reef 'buildings', complexes and even cities that take advantage of emerging fabrication techniques. These principles can be used to inform the planning arrangement of both generic reef modules that cater to different needs of target flora and fauna groups and the design of landmark reefs (similar to landmark buildings) and high density / high value (urban) reef centres.

This project demonstrates the design of the equivalent of a landmark urban centre, the design for the constructed reef complex is considerably more complex than could be fabricated using conventional construction techniques and instead takes advantage of the freedom afforded by the D-Shape™ construction scale 3D printing technique.

Figure 162 - (a) Hunetwasser house, vienna. Image source - http://www.kaboodle.com/reviews/hundertwasserhaus-green-roof-vienna Access date – 18th August 2011 (b) (in)human habitat reef complex. Image by James Gardiner

6.3.2. Choosing a site(s) and scanning the ocean floor

Many of the worlds greatest cities, but not all, have interesting and varying topographies, such as New York, Rome, San Francisco, Buenos Aires, Constantinople and Sydney. These sites have been chosen for reasons including: proximity to food, natural resources, areas with important topography (such as rivers, harbours, on high ground etc), on transportation routes or being easily defendable (Ullman, 1941, Hurd, 1903). Similar characteristics exist for the location of natural reefs: they are usually located in ‘topographic discontinuities’ (areas with important topography) such as on the edge of a continental shelf, on the side of a ridge which produce ‘desirable oceanographic and hydrodynamic’ effects such as up-wellings, down-wellings, gyres, drifts or internal waves (Nakamura, 1985). These effects are responsible for bringing food, transporting spawning marine life and creating pathways for migratory marine life, these effects also clean the reef with their large movements of water. Other important factors responsible for the location of natural reefs and constructed reefs include the depth, distance to the shore, temperature, ocean floor bottom type and slope, proximity to other reefs (Bohnsack and Sutherland, 1985). The location of artificial reefs in the West is often not on the ‘topographic discontinuities’ but instead located in ‘flat’ or ‘gently sloping’ areas that are less difficult to place, are optimal for reef module stability (Barber et al., 2009a, Barber et al., 2009b) or are placed primarily other reasons other than optimal constructed reef location (Bohnsack and Sutherland, 1985). This is in contrast to Japan where “.... *the majority of reef sites are located at the upper part and along the perimeter of submarine topographies*” and “*the next most popular sites are a flat sea floor at a depths between 30-70m*” (Nakamura, 1985) p277

Constructed reef complexes can take advantage of topographies to enhance the function of the reef complex. Natural reefs are usually located adjacent to areas with strong currents and areas where topography dramatically changes often in contrast to the placement of constructed reefs.

“With the sonar technology available and differential GPS we can map a reef to within cm” (David Lennon, Sustainable Oceans International. Source - email 17th May 2011)

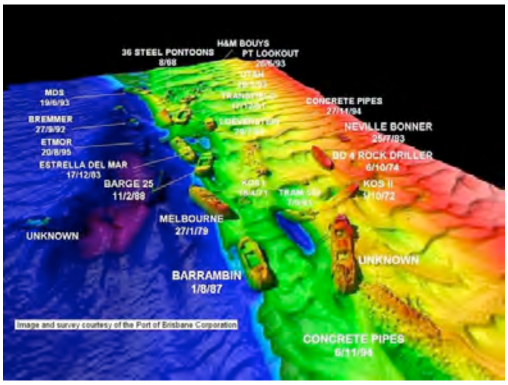

Figure 163 - Curtin Artificial Reef Sonar Side Scan for Brisbane Port. Image courtesy of Port of Brisbane Corporation.

If more topographically diverse areas are to be utilized for the location of constructed reef complexes, highly accurate site survey information needs to be available so that the constructed reef can be designed to drop into this seascape. There are a number of methods used to create accurate underwater topographical surveys; among these sonar scanning is the most widely used. David Lennon of Sustainable Oceans International stated[161] "with the sonar technology available and differential GPS we can map an area to within a cm". Such scanning techniques are widely used today within a broad spectrum of industries that use the ocean and its resources. Scanning is used within the constructed reef industry today, to select appropriate sites for proposed reefs, checking the placement of reef elements and in surveying fish stocks and densities within constructed and adjacent natural reefs. These three-dimensional scanning survey techniques will become increasingly important in the planning process, just as terrestrial scanning and modelling is becoming increasingly important for planning and design on land.

[161] Email discussing current use of oceanographic scanning by sustainable Oceans International. Received 17 May 2011

6.4. The D-Shape™ technique and constructed reefs

Figure 164 - Interconnected ring test coffee table for Freedom of Creation fabricated by D-Shape™ in 2009. Photo of Enrico Dini and I after removing unconsolidated sand from around the coffee table and lifting it onto the palette from the print bed. This piece texture looks remarkably like a natural coral structure. Photo James Gardiner

The D-Shape technology is particularly well suited to the fabrication of artificial reefs, as it has demonstrated an inherent capability to fabricate reef like structures (refer to Figure 164) at equal or greater complexities than conventional constructed reef structures (as discussed in chapter 6.2). The image (refer Figure 166) of the coffee table fabricated by D-Shape™ technique has demonstrated the capability to create objects with the three levels of detail discussed above (course, medium and fine). The first a course level of detail which defines the shape of the object (or topology of the reef), the second medium level of detail which can be observed in the ring structures (equivalent to the branching in some types of coral reefs) and the third level of detail is in fabrication of a fine level of surface texture. D-Shape™ fabricated objects, without further finishing, have a surface roughness, due partly to the printing process and the course sand granules used, this makes the technique an appropriate substrate for marine flora and fauna (including hard corals).

The capability of the D-Shape™ technique to fabricate unique structures of high complexity at a the course level of detail (topographic scale), at the med scale (articulation through branching and creation of voids) and fine level of detail (texture and surface roughness) makes this technique an ideal candidate for the fabrication of constructed reefs.

Figure 165 - D-Shape marine testing ring showing flora growth. Photos Nov & Dec 2010, April & August 2011. Images Enrico Dini.

The D-Shape material, predominantly sand bonded through a reaction between oxides and chlorides, has been shown to be appropriate as a reef substrate through testing described below. The material is likened to a limestone and is Ph neutral[162]. Two separate tests are being conducted of the D-Shape™ material, within saltwater marine environments, to test the material longevity and growth of marine flora on its surface. The first tests began in November 2010 by D-Shape™ with the placement of a ring test piece (refer images Figure 165) in the waters adjacent to Porto Santa Stefano in Tuscany on the Italian coast. The second began in January 2011 in Pittwater, Sydney Australia, which is being conducted by me.

6.5. Project Introduction

This case study project was developed as a result of the provision of seed funding provided by the Open Agenda Award open to Australian and New Zealand recent Architecture student graduates; an *"annual competition aimed at supporting a new generation of experimental Australian architecture… Open Agenda is*

[162] Based on discussions with Enrico Din between April 2009 and August 2011.

focused on developing the possibilities of design research in architecture and the built environment" (Open_Agenda, 2011)

The '(in)human habitat' project was developed over a five month period culminating in the publication of a book (Bennet et al., 2011) and an exhibition of the three projects at Customs House in Sydney and was open to the public between October 2010 through to January 2011, subsequently the exhibition was further extended until April 2011.

This project, one of three awarded, titled '(in)human habitat: rethinking the artificial reef', focussed on the potential for transformation of the design and fabrication of artificial reefs. The project stems from the following statement:

"This century will be marked by the creation of (in)human habitat, after a century of record habitat destruction. Increasingly this century man will be compelled to create environments to rebalance and sustain the ecosystems on which he so heavily relies. Approximately 10% of the world's coral reefs have been declared dead with a further 60% under serious threat from destructive fishing practices, reef mining and pollution" (Gardiner, 2011)[163]

With first-hand experience with the D-Shape™ Construction 3D printing technique from the Villa Roccia project (chapter 5) and developing skills with a broad range of three-dimensional CAD tools, allowed me to identify emerging potential within this non-architectural field. The seed for this project was planted during an extended working visit to D-Shape in 2009, to fabricate a Prototype Column for the Villa Roccia project. While removing a the unbonded sand from a series of pieces on the print bed, that had been fabricated by D-Shape™ prior to

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[163] As noted in the introduction (1.1) - Human induced global warming is considered for the purposes of this research to be a proven based on the current scientific published reports (refer references above) and the status that it is given by Australian and world scientific groups (IPCC, CSIRO climate change, Climate Scientists Australia) and government/non-government related bodies (UNFCC, USGCRP, climate commission (Australia). It is however further acknowledged that this phenomenon is still being actively debated and there are detractors of the theory.

my arrival, I came across a prototype coffee table (refer image Figure 166). I immediately recognised the potential for creating artificial reefs with the D-Shape technique.

Figure 166 – Test coffee table for Freedom of Creation, fabricated by D-Shape. This form struck me for its reef like appearance. Photos James Gardiner

6.6. Project intent

Research for this project began in 2009 with a visit to the Great Barrier Reef on my return from working with D-Shape™ in Italy 2009. This visit to the great Barrier Reef was intended as field research to gain a preliminary first hand understanding of coral reefs. Following this visit, with the potential for constructed reefs firmly in my focus, I began to study both natural reef formations through online photographic image survey and literature review on coral reefs and artificial/constructed reef precedents. This research and minor field study led to a desire to explore the potential of construction 3D printing reefs through a hypothetical design project. I became aware of the Open Agenda competition, which grants seed funding for architectural research, which I then entered and won.

The key premise of this project is that constructed reefs could greatly improve in their provision of high diversities of habitat, following the precedent of natural coral reefs. I believe from my research that natural reefs have many different layers and zones based around their topography, which from my study of constructed reef precedents is lacking in past and present constructed reefs. I also believe that to create a truly sustainable and thriving ecosystems, rather than just a fishing reef, one needs to design both the topography of the constructed reef as well as the specific habitats.

Although the presence of artificial reefs is generally considered to have an economic value, based on attraction or production of marine flora and fauna and the cost benefit of the reef to stakeholders (Bohnsack and Sutherland, 1985). The value of this project is considered to be based primarily on the ecological benefit it provides.

"*The intent of this project was the design of a reef that can emulate the diverse spaces that are required*" for a diverse range of marine flora and fauna by "*creating a deep scaffold that can form the basis for coral growth, while providing habitat for a range of marine life. Natural reefs of such complexity can take thousands (and in some cases millions) of years to grow*." (Gardiner, 2011)

6.6.1. Defining the Project principles

The project started by identifying the key attributes of coral reefs; mainly through literature review, the study of thousands of underwater photos published on the Internet and personal diving experience (I am now a licensed diver). These key attributes were identified:

Site

- Topography (providing the following characteristics within the range that is suitable for coral growth: water flow, bottom depth, water temperature, sunlight, nutrient and food levels, chemical levels, protection from storm events)

- Proximity to natural or artificial reefs (for fauna commute and migration and larvae recruitment)

Reef design

- Topology - Reef topology (to create spatial diversity and protection from strong water movements)

- Articulation - Spatial and structural complexity (to provide a range of habitats and provide protection from predators)

- Texture - Substrate (material and surface finish for sessile (stationary) organism attachment)

These elements form the basis for design development of the constructed reef. It is important to note that the reef needs to be designed for its local environment and specific species composition, as provision of structural features that are foreign to the local environment can lead to the introduction of invasive foreign species that can disturb the local species composition and eco-system (Mulhall, 2008, Perkol-Finkel et al., 2006).

Finkel et al. state "*There is a correlation between the structural complexity of the reef and its species diversity and abundance of the inhabiting fishes" and "given sufficient time, when an artificial reef and its adjacent natural reef offer similar structural features their community structures will become almost indistinguishable. However when substrates displaying different structural features are compared, be it within an artificial reef or between an artificial reef and a natural reef, taxa assemblages will differ even after more than a century.* " (Perkol-Finkel et al., 2006)

This quote, and the paper from which it is taken, describes the importance of the micro and macro topology[164] of the constructed reef and substrate in creating or

[164] Topology – "6. the anatomy of any specific bodily area, structure, or part". This word is used instead of topography - "3. the land forms or surface configuration of a region" both definitions sourced from the Collins English Dictionary – Complete and unabridged 10th edition 2009. William Collins and Sons. Accessed through www.dictionary.com March 24 2011.

enhancing coral reef systems and endemic coral communities. The paper also notes that the introduction of foreign topologies, such as steep wall formations in the red sea, to a marine environment can assist invasive coral species to take hold.

6.7. Project location: Farasan islands

The Red Sea is one of the most bio-diverse coral reef regions in the world both in terms of sea flora and fauna; of which both are under threat through over fishing, pollution and reef degradation (Khalaf and Kochzius, 2002, Zakai and Chadwick-Furman, 2002, Riegl, 2001). The Farasan Islands are located in the South West of Saudi Arabia, close to the boarder with Yemen; approximately 500km North of the Bab El-Mandeb Strait between the Red Sea and the Gulf of Aden (refer image Figure 167). These islands are an ideal location for an ecosystem test reef, the area is classified as a marine protected area with existing partially degraded coral reefs and is subject to existing coral reef scientific research (Gladstone et al., 2003).

The location for the two proposed reef sites are adjacent to the Saudi Arabian coastline and surrounding islands and is in close proximity to natural reefs, which fringe the Farasan Islands in this location. The site is afforded favourable protection from rough seas, with islands located to the West and South. The site is also expected to have favourable upwelling and currents from the North in summer, as the site straddle a ridge that falls steeply in depth to the North.

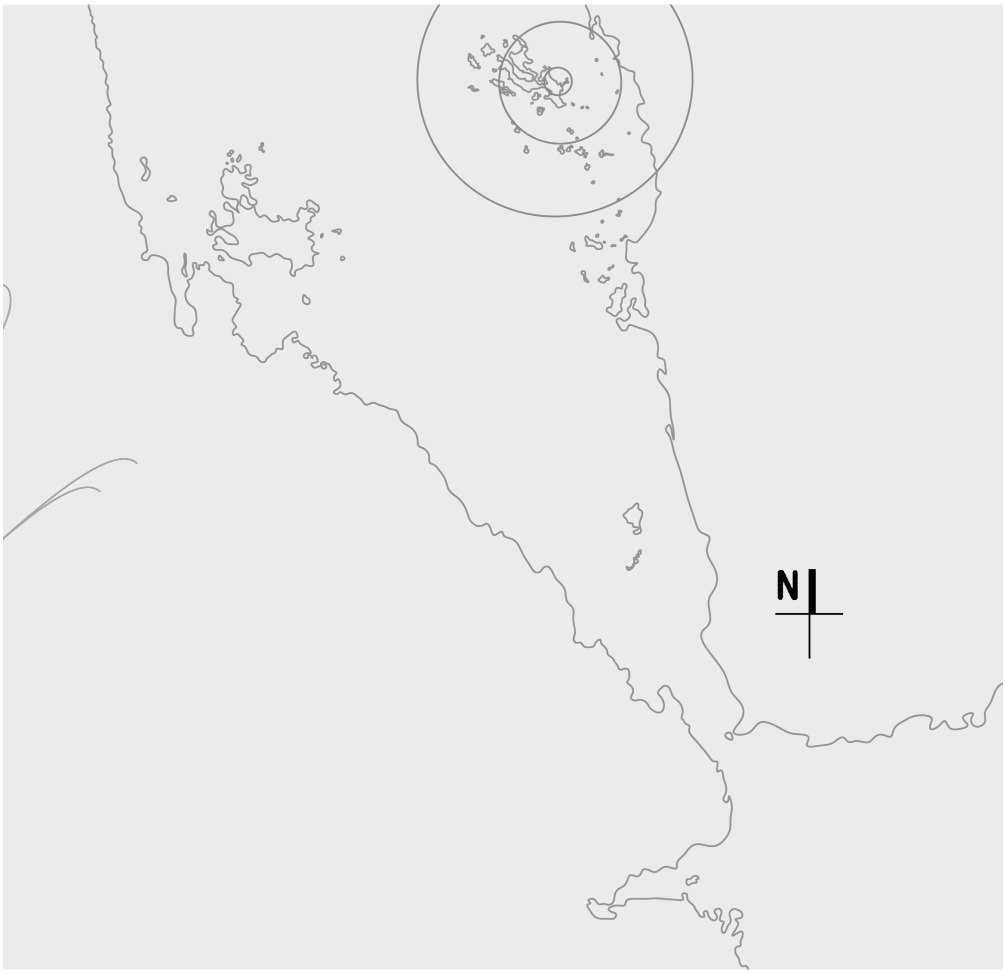

Figure 167 - Location plan showing the Farasan Islands in the Red Sea. Approximately . Drawing by James Gardiner

Figure 168 - Site locations for the two constructed reefs. Drawing by James Gardiner

The two reefs are located approximately 700m apart (refer Figure 168), which is within the ideal distance range described by Nakamura (Nakamura, 1985). The reef is located in proximity to existing small natural reefs at less than 50m intervals, enabling sea life to move easily between them. In such a location with natural reefs in close proximity, the artificial reef scaffold would be quickly and easily colonised by spawning coral polyps naturally, due to the close proximity of natural reefs, rather than rely on seeding or coral transplantation (Bohnsack and Sutherland, 1985). The location of the reef within the Marine Protection Area, which has an ongoing reef monitoring program, should provide an ideal situation for the monitoring of the colonisation of the reef by marine flora and fauna and contribute valuable scientific data in a new field of research; the creation of topographically and structurally complex reef ecosystems.

6.8. The Design of the (in)human habitat Project

The (in)human habitat constructed reef is intended to create a diverse ecosystem, rather than be targeted to a specific species as are many ‘fishing reefs’, With species ranging from microscopic (Holoplankton and Meroplankton) through the scales, including a myriad of soft and hard corals, crabs, squid, fish, turtles up to white-fin reef shark and whale shark. Some of these species are transient, such as the migratory hawksbill turtle that lays its eggs on the Farasan islands and soft corals that transform into jellyfish. Others species are permanent residents such as the giant moray eel that dwells in caves and crevices.

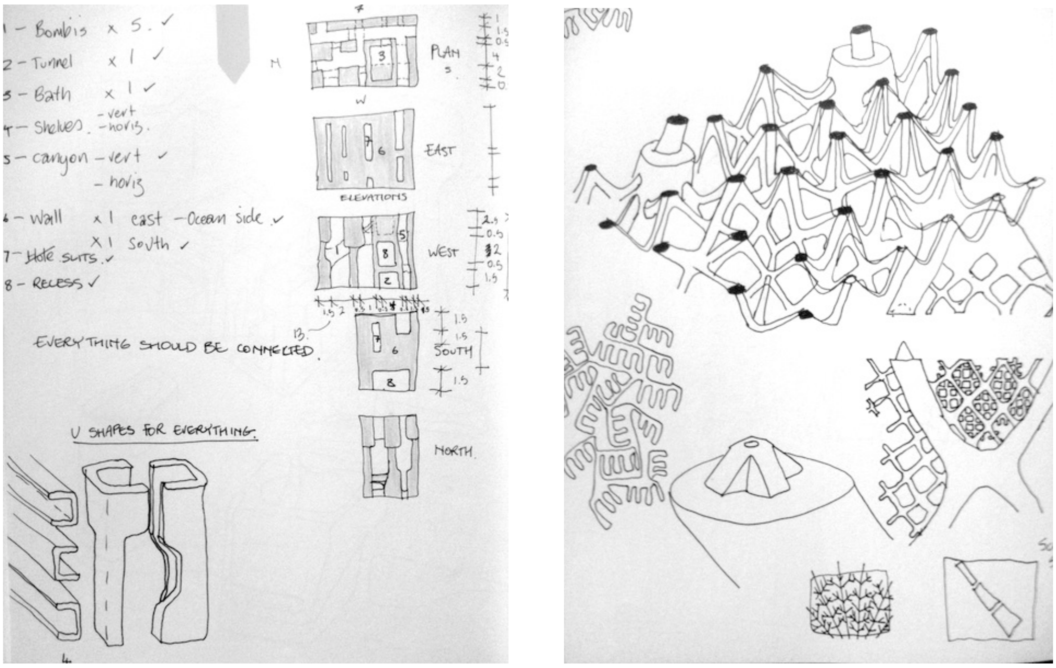

Figure 169 - Development sketches from the sketch design phase of the (in)human habitat project. (a) Developing a strategy for the location of the different topologies (b) Developing ideas about the way to join fabricated parts of the reef and arrangement of multi-scalar characteristics of the reef. Drawings by James Gardiner

A series of sketches and physical models were used, in tandem, to tease out a series of ideas based on background research discussed above (chapter 6.6). As with the case study projects described in earlier chapters, the sketching and/or physical modelling was where much of the thinking, which underpins the project was first developed. A number of the concepts developed during this stage of design development were then further developed using a suite of 3D digital design tools to create the (in)human habitat project.

Figure 170 - Design thinking development model. Note the different medium level detail topologies developed: Scalar branching, perforated infill plates.

Figure 171 - Design thinking development models. Medium level detail topology developed: Holes within holes. Models by James Gardiner Photos by Nigel O’Neal

The sketches became the dominant mode in the development of thinking that was applied to the final project: such as the identification of the topologies to be included within the (in)human habitat reef and the development of the concept of the deep scaffold. These concepts will be described in detail below. The fabrication of the sculptures was useful for freeing up my thinking, which I felt at times was beginning to stagnate. The sculptures were also useful for developing concepts for medium and fine level detail topologies and structures (refer images Figure 170, Figure 171 & Figure 172).

Figure 172 - Sculpted reef structure. Note the different medium level detail topologies developed: cross cut shelves (left back) and tight vertical plating.

The interesting outcome from the development of physical sculptures was that because these were subtractively fabricated (cut out and sculpted with power tools from a block of material) the forms were not very efficient in terms of material. Meaning that there was a lot of material and weight relative to the amount of surface area created. In addition to this if one were to try to model these geometries subtractively, using ‘boolean’ operations within software such as Rhino™ the digital models would soon become very complex and memory intensive to work with, rendering this mode of working virtually impossible after several of these boolean operations. This observation is based on using software tools such as Rhino™, Maya™ and Netfabb™, the same trend may not be present with other programs such as solid modelling tools such as Solidworks™.

As noted above in (chapter 6.6) a broad range of topologies and micro-environments are required to best accommodate the plethora of sea life found naturally in coral reefs; including the coral reefs of the Farasan islands.

The central premise of the project is that the creation of a diverse range of habitats, through the creation of topologies and micro-environments that more closely emulate natural coral reef habits, would provide habitat that could support greater diversity than contemporary constructed reef assemblies.

6.8.1. Defining Reef Topologies

At the macro level, as discussed in (chapter 6.1) there are three main types of coral reefs, first identified by Charles Darwin; which include fringing reefs, atolls and barrier reefs. These natural reefs also have a series of zones including; Deep fore reef, fore reef, reef crest, back crest, reef flat or lagoon zone.

Figure 173 - Aerial photo of a natural coral reef, note the different topologies. Image source - http://www.reefmagiccruises.com/downloads/agents/ Date accessed 20th August 2011

Within these reef zones named above are a series of topologies or features (refer image Figure 173), that are a result of the organic formation of the coral reef over thousands of years and destructive wave forces that regularly damage them[165]. I have, after significant literature review and discussion with experts in the field[166], found no clear and accepted naming standard for these features[167]. For the purposes of this project I have therefore adopted some non-standardised names and applied others names which seem appropriate and easily understandable. These following names will be used to describe topological features for this project:

Wall – A near vertical surface, this may be the steep side of a coral reef or a feature within it.

Tunnel - An enclosed passage through or under a coral reef

Pool – A depression in a coral reef shelf

Bomby – A tall freestanding coral reef feature

Valley – A shallow gap or depression in or between coral reefs

Canyon - A steep gap between coral reefs

Shelf – A near horizontal surface, this may be the top of a coral reef or a feature within it, such as within a reef wall

Slit – A thin vertical or horizontal recess

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[165] There are other forces that form coral reefs that will not be discussed here.

[166] Discussions with Dr Michael Lowry Senior Research Scientist, Wild Fisheries, NSW Industry and Investment on the 28th September 2010, Australia and David Lennon, Director Sustainable Oceans international 5th of November 2010.

[167] This was to a lesser extent also an issue with the naming of rock formation artefacts for the Villa Roccia case study project.

Slope – A wall or shelf feature that is neither near horizontal or vertical that inclines, this incline may be between gentle and severe.

Drop-off – A face on the side of a coral reef that drops a significant distance (i.e. more than 2m) usually descending to natural ground.

The listing of terms above is not meant to be an exhaustive or a definitive listing of all coral reef features. The listing is intended for use within this project to enable the description and design of coral reef topologies. The sketch below (Figure 174) shows some of the features listed above and communicates some of the complexity found in natural coral reefs, albeit in a rectilinear format.

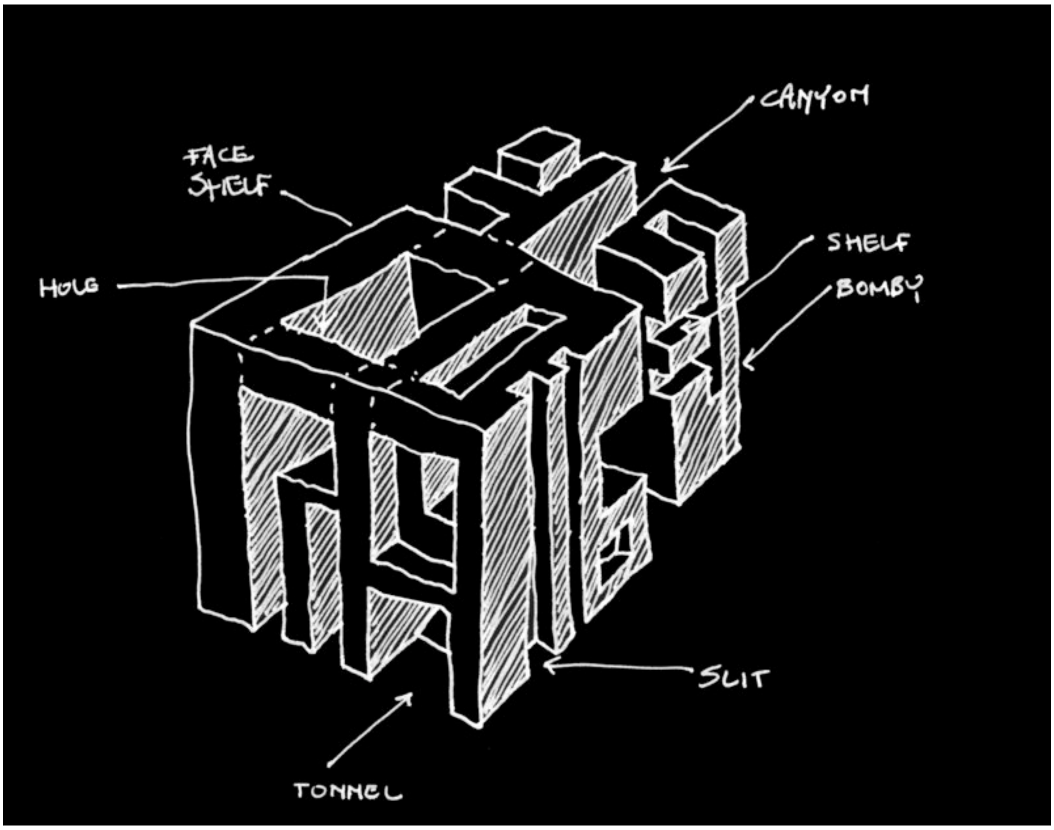

Figure 174 - Sketch describing the different types of topologies present in reefs surveyed. Note this sketch does nopt describe sloping, concave or convex geometries that are almost always present within natural coral reefs. Image by James Gardiner

The intent of this project is to design a reef that can immediately emulate the diverse spaces that are required for the diversity of species found in natural coral reefs and particularly in the Farasan islands. It is understood that it will take years for coral polyps to both attach themselves after spawning and to grow to a level where they can offer protection for marine fauna, therefore it is anticipated that the constructed reef complex should include these feature when fabricated, which the corals will attach to and eventually completely cover. The features described above, such as shelves, tunnels and bomby's will go some way toward creating the multiplicity of spaces required for the different flora and fauna that are intended to occupy the constructed reef structure; for example rays and sharks are often found resting in tunnels and under ledges, while sharks when active will often swim around near drop-offs when active.

Figure 175 - An example of the lattice type structures created by branching corals. Image source - http://www.britannica.com/bps/media-view/128852/1/0/0 Date accessed 20th August 2011

6.8.2. The Reef as a Deep Scaffold

A further level of detail, the fine level, is required to further articulate the reef to create the range of surfaces and niches required for small marine creatures and plant life (refer image Figure 175). The strategy adopted on this project to create this fine level of detail is to create what I have named a 'deep scaffold'. This deep scaffold is intended to form the basis for coral growth, while providing habitat for a diverse range of marine life as the corals and other sessile (stationary) flora and fauna to grow.

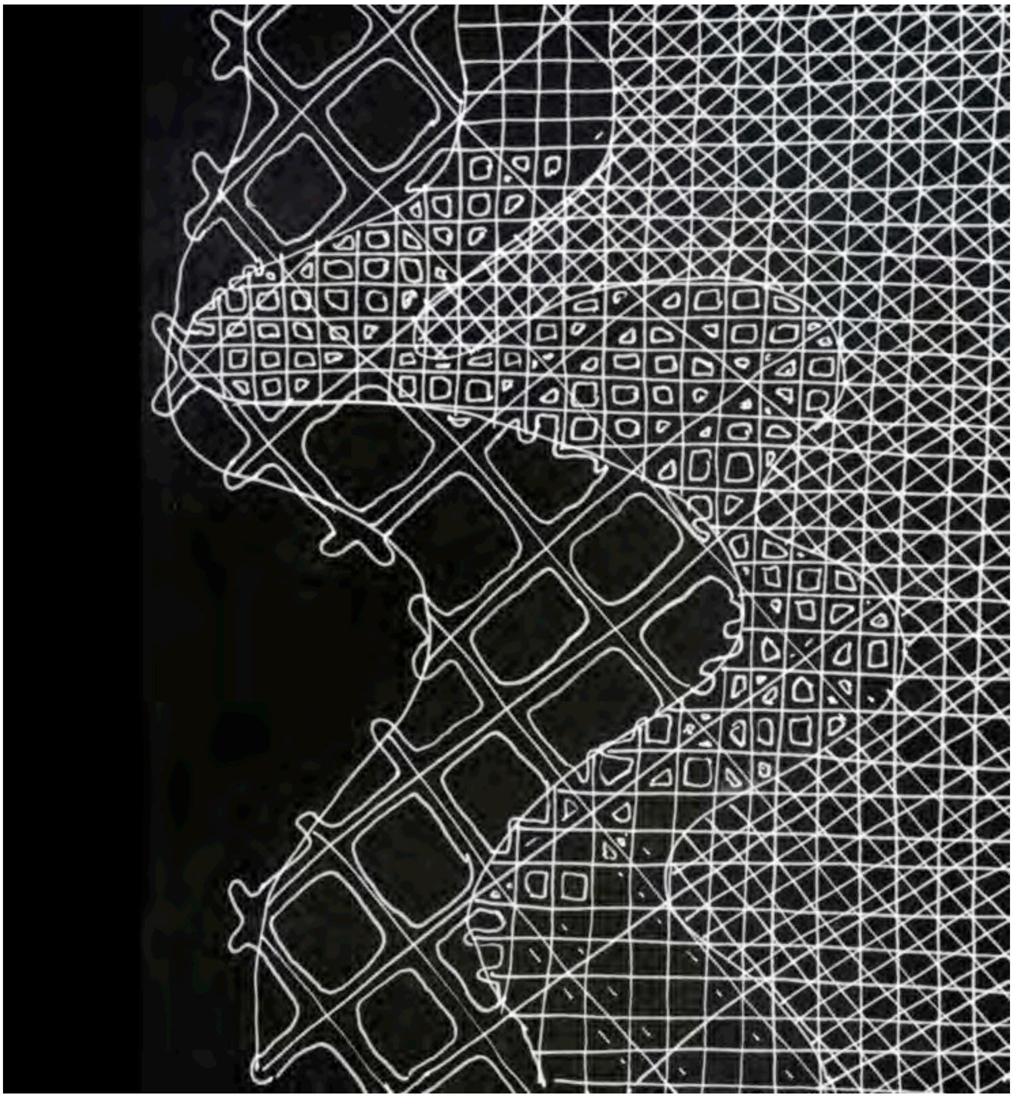

Figure 176 - A sketch of the deep scaffold concept. Image by James Gardiner

The ‘deep scaffold’ concept as described above in this sketch (Figure 176), shows a hierarchy of three separate scaffold structures, the concept here is that instead of having the densest scaffold structure in the middle and the finest structure (detail) on the outside (like a tree) is to reverse this order. The reason for this reversal of the structures is that by gradually increasing the density from outside to the inside you can create more diversity of habitable spaces. If the reverse were the case with the course structure on the inside and the finest structure on the inside, refer image (Figure 177), you can see that the two larger fish cannot enter the structure, because they cannot move through the finest outer structure. When you reverse this order (refer image Figure 176) the large fish can only move within the course structure, the medium sized fish can move through both the medium and course structure and the smallest fish can move within all three. This creates three habitable zones within the reef. When these three habitable zones are combined with the topographic types listed above you get a highly complex structure with a diversity of habitable spaces.

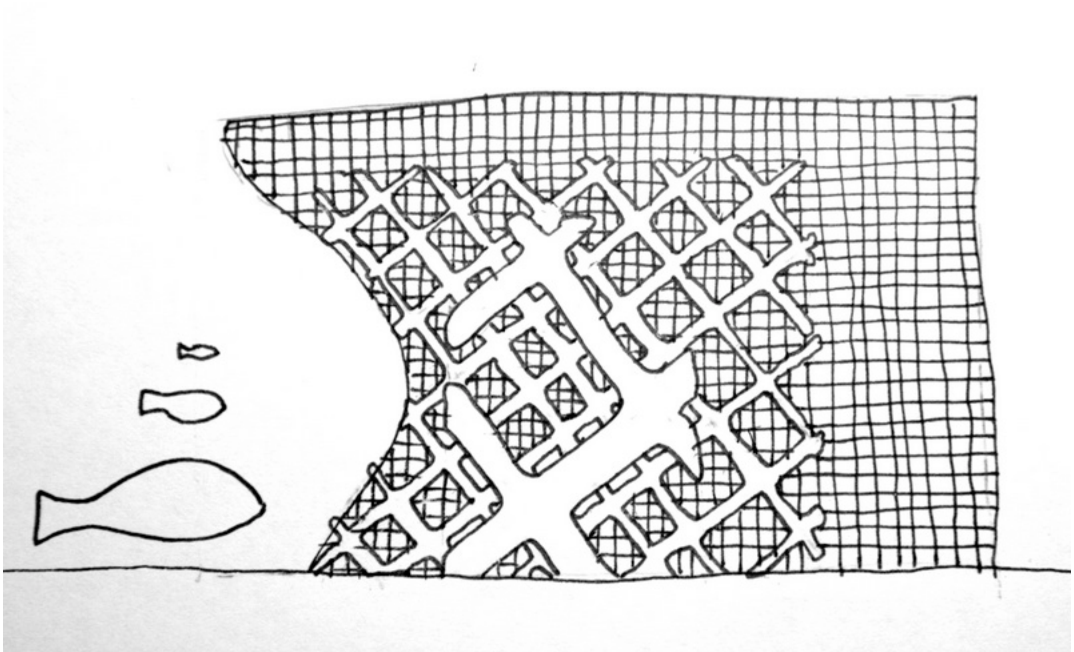

Figure 177 – ‘Normal’ scafold structure with heaviest structure occupying the centre and structure loosing density toward the outside. Sketch by James Gardiner.

Beyond the benefit of the creation of a massive diversity of spaces the deep scaffold provides a very robust protection against predation, this allows small fish or marine animals to take shelter within these scaffolds safe from larger predators. Coral fish such as those pictured in the image above (refer Figure 177) will dart in and out of the protection of the coral as predators pass, a similar level of protection is afforded by the deep scaffold. With the gradual agglomeration of corals within the structure it is imagined that the inner structure would eventually become solid as the space is occupied by corals, this would essentially reinforce the structure as the coral cover and weight of the coral increases.

Reefs of such complexity can take thousands of years to grow to this state naturally. The design concept provides a scaffold, which will be attractive to sea creatures immediately, while corals and other sea flora will take longer to grow and eventually envelope the structure.

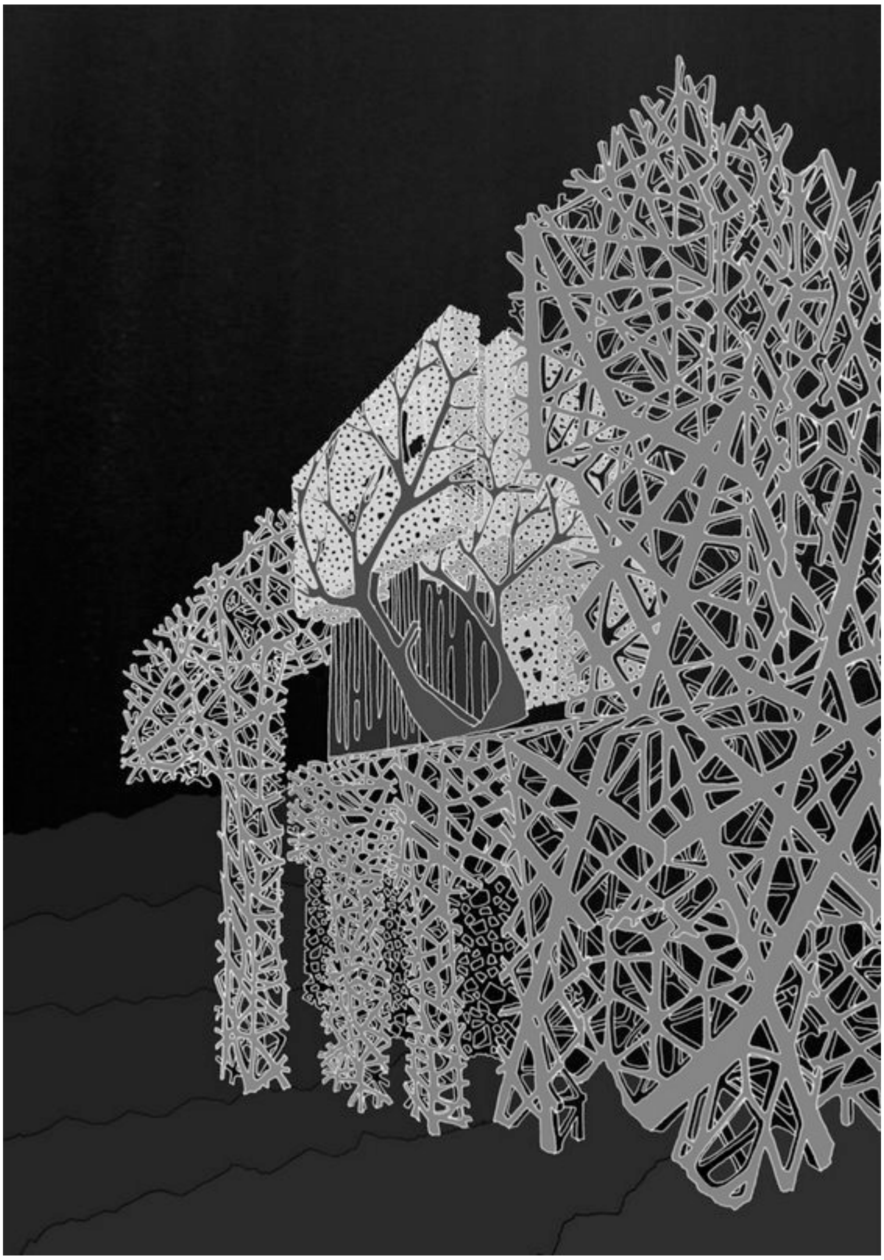

Figure 178 - Sketch perspective of various scaffold types. Image by James Gardiner

The perspective (refer image Figure 178) shows how a variety of different scaffold structures and surfaces could be used to create a constructed reef complex; each of the different scaffold and surface types could be targeted to different marine flora and fauna relative to the topology within which it sits. This fine tuning could allow for the targeted creation of specific marine ecosystems and communities within certain locations within a constructed reef complex. The physical characteristics, created through the three scales of detail (course, medium and fine), could as much create opportunities for some species, as exclude others.

By using topologies to create different environments, articulation of those spaces in the form of scaffolds and surfaces and the use of textures at the finest level of detail we can begin to create structures that could assist with the creation of truly diverse ecosystems that will come significantly closer to those of natural coral reefs

6.9. Creating the Digital Definition of the (in)human habitat reef complex

The purpose of this stage was to design and build in digital form the first ecosystem constructed reef complex. The digital design phase went through a number of stages: the first was to define the reef complex topologies within a pre-determined envelope, the second was to use a structural optimisation software to optimise this structure from which three iterations of optimisation of the envelope were exported for use in defining the three scaffold and surfaces used to build up the digital definition. The two outer envelopes were then used within a space filling software to create structural scaffolds and once these scaffolds were created they were then combined with a refined version of the inner envelope to create the reef complex. The base of the reef complex was then cut to fit the contours of the Farasan islands site and then the reef complex was broken down into large blocks for fabrication using a Z-Corp additive fabrication machine and printed.

Unlike the other two case studies presented in this exegesis I had a reasonably clear idea about which digital design software tools that I wanted to use prior to commencing the design of the ‘digital definition’. This was largely due to having developed methods in Villa Roccia case study (chapter 5) that were transferrable to this project, although the outcome was completely different. The methods used were: the use of Netfabb™™structural optimisation software to optimise a predefined articulated envelope, the use of Maya™polygons modelling to recreate a ‘course’ detail outer envelope and the use of Netfabb™ space filling software to create scaffolds within the two outer scaffolds.

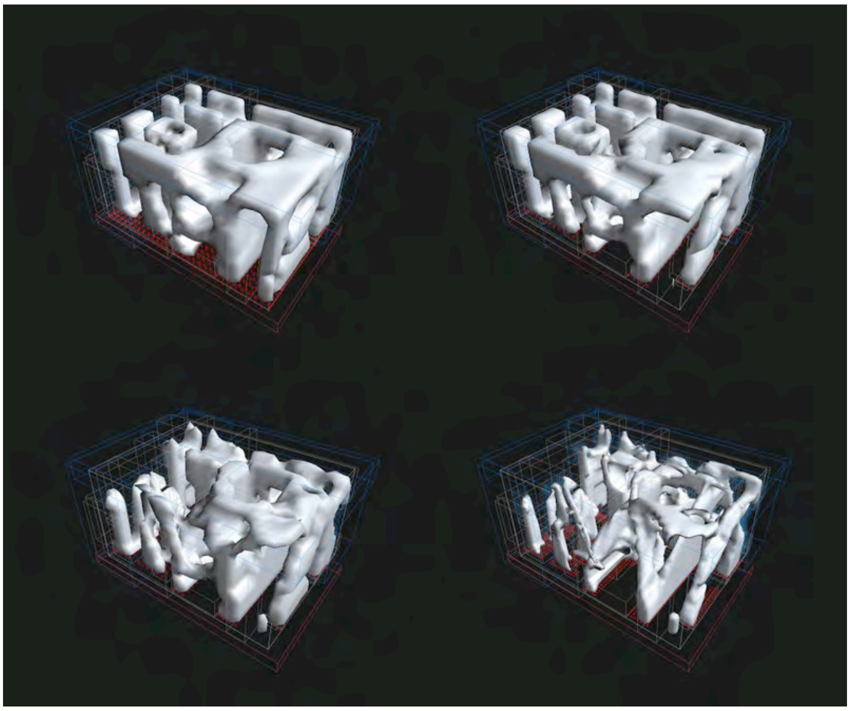

Figure 179 - The four stages of Topostruct™ optimisation. Images run left to right then bottom left to right (a) Topology envelope defined (b) Course envelope defined (c) medium envelope defined (d) fine envelope defined. Image by James Gardiner

The image above shows the four stages of structural topology optimisation with Topostruct™. The first stage was to define the topologies within the envelope within Topostruct™. This was done by creating ‘density regions’ with a density of zero to create voids, cutting away from the rectangular envelope until the desired starting topology was achieved. This defined envelope included a range of topologies as described above including; wall, tunnel, pool, bomby, valley, canyon, shelf, slit and drop-off. The envelope did not include the topology slope, which came about later through the use of the optimisation software.

Forces were then defined within Topostruct™ to emulate ocean currents, material weight and gravity. The software then split the geometry down into a large number of voxels and calculated the forces acting each on of these voxels. The software then iteratively removes (or adds) material from the defined envelope. Each of the three stages of envelope optimisation were exported from Topostruct™ in .dxf format to be imported into other digital design tools. These optimised structures, like the optimised structure used for the Villa Roccia project were to be used as a guide for the distribution of loads and materials, rather than a final envelope.

Figure 180 – (a) "piping' the vertices of the envelope mesh with Rhino™. (b) Articulating the inner envelope surface using Mudbox™. Images by James Gardiner

Some experimentation was done at this stage to check that the suite of programs selected was the best fit for the purpose. I experimented with a number of programs including as Rhino™, 3DStudio Max to check the result of 'piping'[168] the vertices of a refined version of the exported mesh from Topostruct™, the result (refer image Figure 180 a) was in my opinion quite ugly and too regular for my liking so this method was abandoned. While using Netfabb to define the scaffolds it was found that the computing power required to create and work with the fine detail scaffold was too high for the capability of the computers being

[168] Extruding pipes or tubes along vertices.

used[169]. One of the fine scaffolds created had approx 600,000 faces. The reason for using a solid inner structure in the case of this project was therefore largely related to the capability of the software and computers used. A micro-structure (a very fine scaffold) would have been used if it were possible to compute.

Another test was undertaken was to apply a texture to the solid inner structure using the Mudbox™ software, an animation tool used to compliment the capabilities of programs such as Maya™. A number of iterations were produced using a variety of textures to see if this method would produce a result that would be applicable to the constructed reef (Figure 180 b). After completing these iterations it was decided not to continue with this procedure, as the results were hard to control and the desired texture could not be achieved. This tool however could be quite effective if the desired level of control could be easily achieved, this relative lack of control probably had as much to do with a lack of user experience as with the software itself.

The Mudbox™ program was used to refine the inner envelope, as the exported envelope from Topostruct™™ was quite lumpy (refer to image Figure 179 d). A smoothing tool within Mudbox™ was used and this both smoothed out the lumps and slimed down the structure. This fine-tuning of the inner structure added a level of refinement that one would expect within architecture. While at the same time bringing the structural sizes down to be more in line with dimensions I would expect for a structure of its size that is complimented by the outer scaffolds for support.

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[169] Quad core Macintosh desktop computer running windows XP with 32GB of ram and a very fast graphics card.

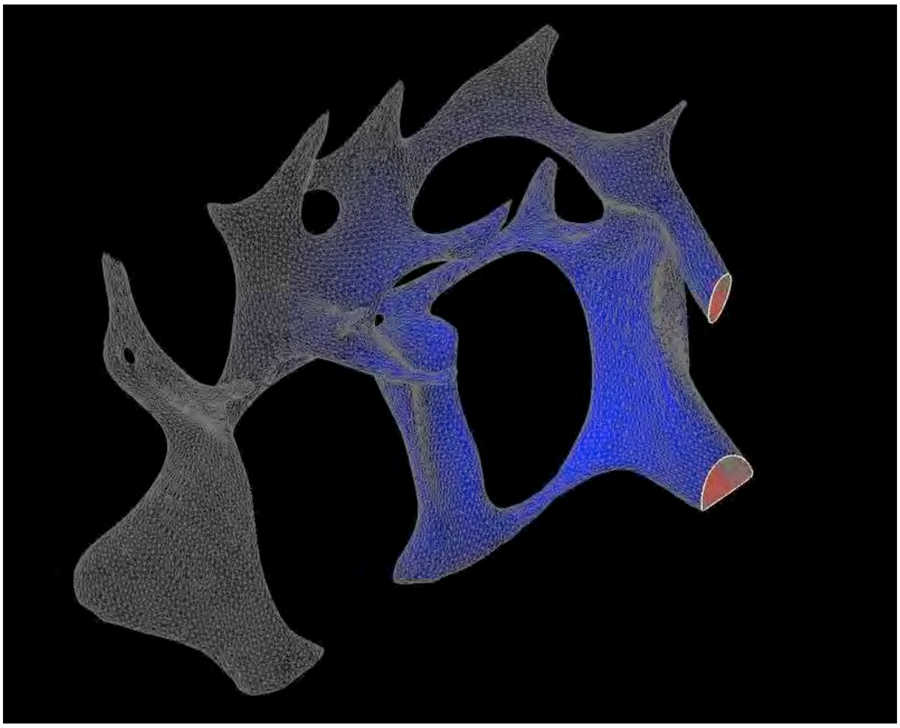

Figure 181 - The smoothed inner structural envelope. Image by James Gardiner

The outer envelope was used, without refinement, within Netfabb™ space filling software to create the course scaffold structure. A scaffold cell was defined within Netfabb™ that was similar to an offset diamond shape. This shape was based on an experiment within Topostruct™ to find the right geometry to counter the predominant North-South currents acting on reef complex. Unfortunately the Netfabb™ software was producing a number of anomalies and crashing continuously. After much trial and error the right settings were established and a workable scaffold cell was defined that didn't throw up too many errors.

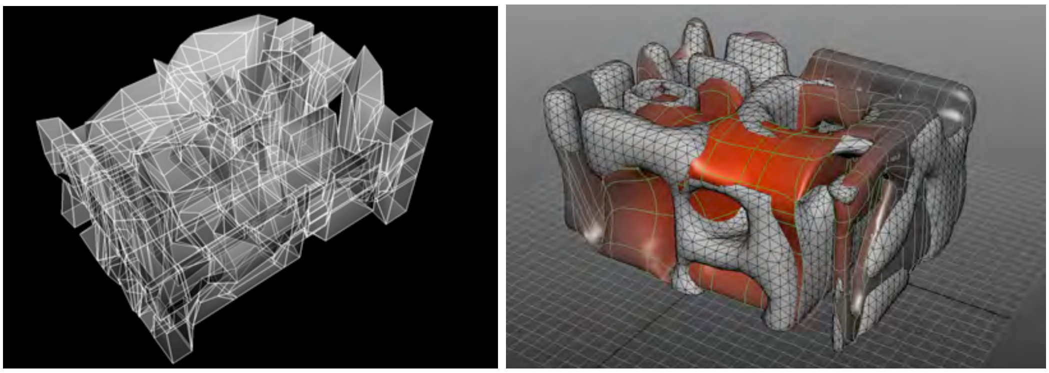

Figure 182 – (a) Polygon model in Maya(tm) used to refine the outer envelope developed in Topostruct(tm). (b) Smoothed polygon model overlayed with the optimised Topostruct™ envelope. Image by James Gardiner

Once I had successfully filled the envelope, with the right size scaffold cell geometry, it was decided that the outer envelope needed refinement, as the clunky envelope from Topostruct™ was still clearly visible in the profile of the scaffold produced. This remodelling was done within Maya™ using polygon modelling (refer image Figure 182 a). The Topostruct envelope was imported into Maya™ and the Polygon model was created to closely match the imported envelope. Once this match was achieved the envelope was then refined through adding slope and curvature. The geometry was also pushed and pulled to create a more dynamic form.

Once the two scaffold structures for the two outer envelopes had been created the three envelopes were then booleaned together using Netfabb™ to form a single structure. Once structures had been untied the base of the reef complex digital definition model was then cut to the profile of the 3D modelled Farasan island site. If this had been a 'real' project the site could have been scanned to a high level of detail, a 3D model of the site would then be used to cut the profile of the digital definition file, to ensure an excellent fit on-site for the constructed reef.

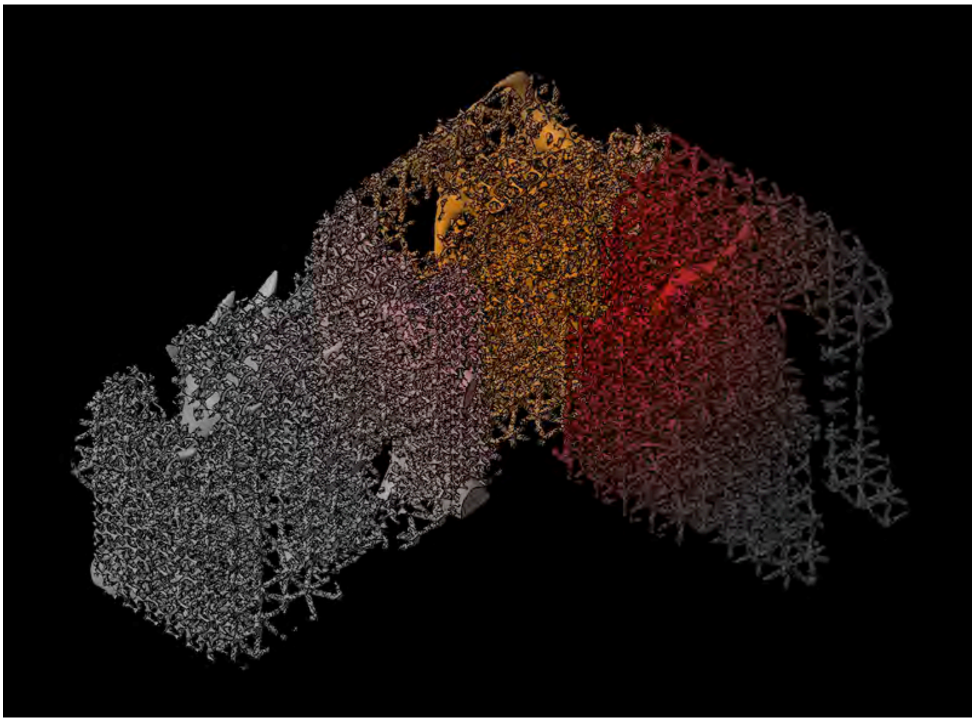

Figure 183 – The three envelopes have been booleaned togther using Netfabb™™ the digital definition is now being split (notice the separate colours) to create blocks for additive fabrication with the Z-Corp printer. Image by James Gardiner

Once the digital definition of the reef complex had been cut to the profile of the site it was then ready to be broken down into blocks for fabrication. In this case fabrication was planned to occur at the scale of additive fabrication rather than Construction Scale 3D printing.

Initially I had planned to use the Stratasys Fused Deposition polymer printer at UTS. Though when we tried to do a test print of a block with the Stratasys it was found that there were too many minor errors for the machine to be able to print. These errors were caused by the complex boolean operations and could not be completely resolved with either Magix™ repair software or Netfabb™ (which also has repair functionality). Knowing that Z-Corp printers are a little more forgiving in terms of being able to print a project, despite there being minor errors, I contacted the workshop at SIAL RMIT and found that the files could be printed. The rest of the project was then broken down into blocks to fit the Z-Corp printer. The fabrication process of the Z-Corp machine is remarkably similar to that of D-Shape™, with both processes printing material to create selectively state change of a powdered material. Both machines D-Shape™ and Z-Corp™ are also quite forgiving, in terms of being able to print digital definition files that are either not completely closed or have minor errors.

Figure 184 - Two blocks being removed from the Z-Corp 3D printer at RMIT. Photo by James Gardiner

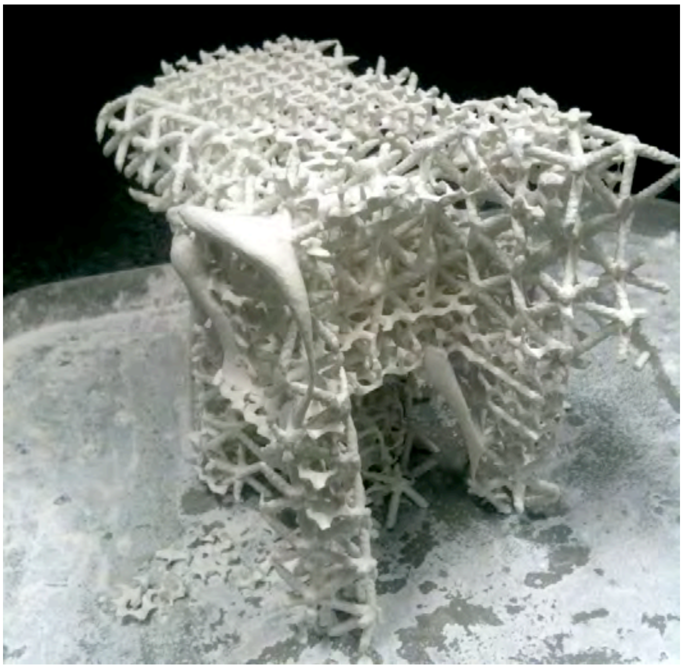

Figure 185 - One of the printed blocks after having the unbonded powder removed. Photo by James Gardiner

Once the pieces were all fabricated using the Z-Corp machine they were assembled together to create the model of the eco-system constructed reef complex.

The image below (refer image Figure 186) shows the North and East faces of the reef complex, these two faces are the most exposed to currents (predominantly form the North in summer) and weather facing out to open water. The inner structure of the optimised model (which is the solid section in the model) is wide and heavy at the base and dissipates into a heavy branching structure as it ascends through the complex. This is very likely a response to the forces that were defined by me in Topostruct™. As stated above once the model is created and loads/forces applied in Topostruct™, the program then analyses the model by breaking it down into small box shaped voxels (3D pixels), voxels that are exposed to low levels of stress are removed first and this process is repeated through a series of iterations. The solid structure at the front of the reef would have been exposed to a higher level of load in comparison to the rear section of the reef and hence the structure is much heavier at the front, to counter the loads.

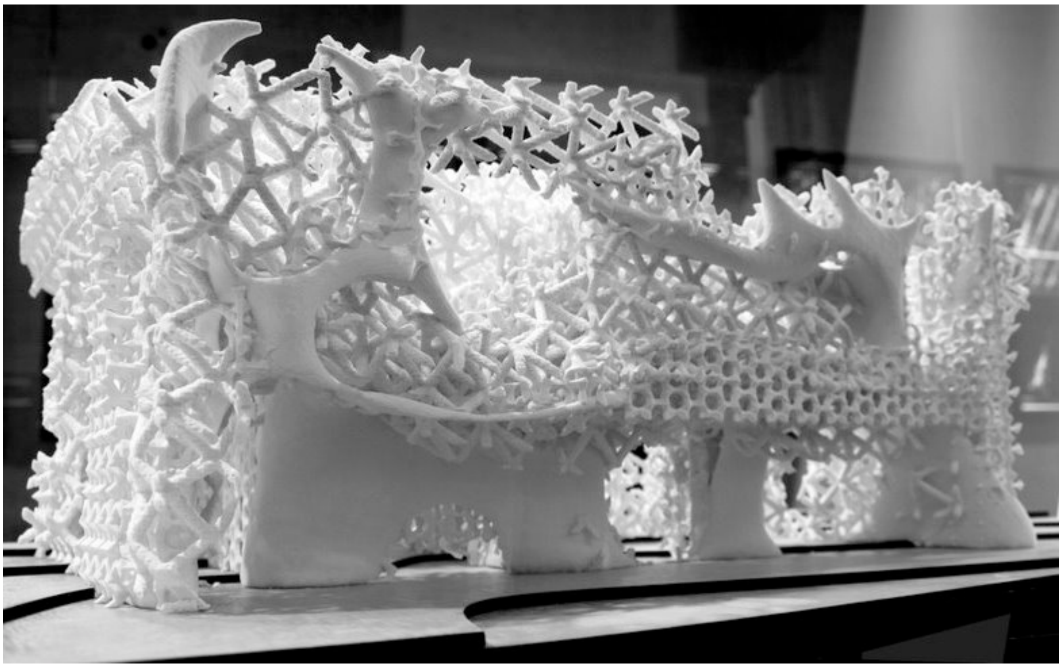

Figure 186 – North and East (far left) faces of the Z-Corp™ printed model of the (in)human habitat reef complex.

A series of tunnels and openings were created in this North face of the reef complex, which allow water columns to form through and around the reef, this disturbance of the water flow creates favourable locations for fish to congregate: in the lee wave, water columns and in areas of water stagnation behind or within the reef (Bohnsack and Sutherland, 1985, Nakamura, 1985). The locations with higher water velocity are favoured by a range of fish in and around the reef as the concentration of water also concentrates food in the form of larvae, plankton and other marine organisms.

The three detail levels; course, medium and fine can be observed in the perspective image (Figure 188) and in the plan (Figure 187) of the reef complex. The fine level of detail in the case of this project is represented by the solid inner structure. The three levels of structure can be seen to overlap and present themselves on the outside of the reef complex envelope in some instances (refer image Figure 186), this does not reflect the resulting envelopes exported from Topostruct™, as the structures were generally reduced at each stage, which resulted in the course structure almost always sitting over the top of the medium and fine structures. It was considered when the three envelope scaffolds were first overlaid, that the overall appearance of the reef complex looked too homogeneous and not as diverse in appearance and texture as had been initially imagined. Therefore the three envelopes were shifted in relation to each other so that the structures would each be individually expressed on the outside envelope of the finished digital definition model. You can observe, by studying the plan (refer image Figure 187) that the middle envelope (the medium density scaffold) has been shifted to the east (to the right) and the inner envelope has been shifted to the North (up the page). The structures remain in close contact despite these shifts and appear to still provide the structural support function that they would if the envelopes had not been shifted. This close contact and overlapping can be clearly observed in the image (Figure 186), where it is evident the structures are still in close contact.

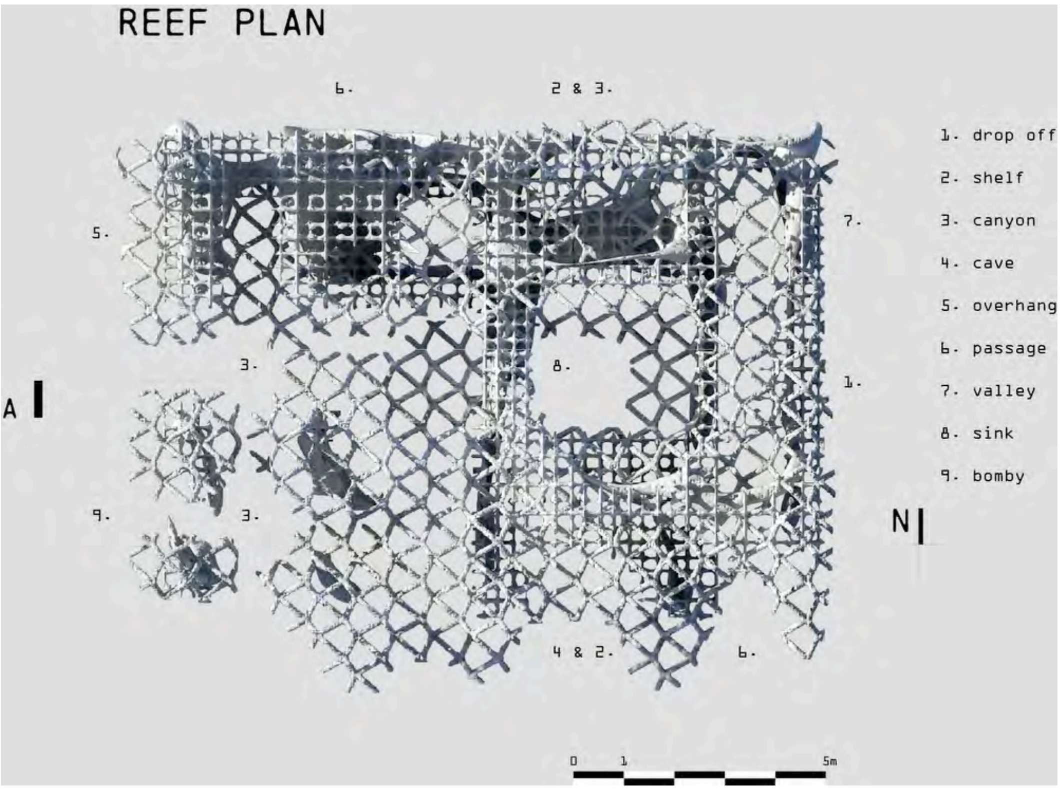

Figure 187 - Plan of the (in)human habitat reef complex. Image by James Gardiner

The rendered section perspective (refer image Figure 188) shows a cutaway view of the centre of the (in)human habitat reef complex. This section perspective speculates on the type of species that may occupy this reef after the first two weeks after assembly at the Farasan islands site location, based on the habitat preference of those species (refer appendix G) although the image is quite small here, one should be able to observe different species of marine fauna located in and around the reef.

Blackfin Barracuda are, illustrated in this image, located near the top of the reef complex taking advantage of the water column created by the reef. The White Tip Shark is illustrated here as moving the bombies on the left, which is a sheltered daytime location, the shark would also likely be found to occupy the shady cave near the centre of this perspective. A moray eel is shown on the left hand side of this cave sheltering in the deep scaffold, the eel would move (toward the viewer) to the drop-off on the North side of the reef at night to feed. A well camouflaged blue spotted ray is located on the sandy flat (on the bottom right of this image) in close proximity to the reef, this ray would move around the reef and sand flats throughout the day to feed on worms, shrimp and crabs. A hawksbill turtle is illustrated on the top of the reef (near the centre top of the image), the turtle move around the surface of the reef to feed on plant matter growing on the reef. The turtle when resting locate themselves on shelves or in recesses within the reef. Smaller reef fish: such as Black Backed Butterfly fish and Lemon Damsel fish: are illustrated occupying the reef scaffold, particularly near the top of the reef.

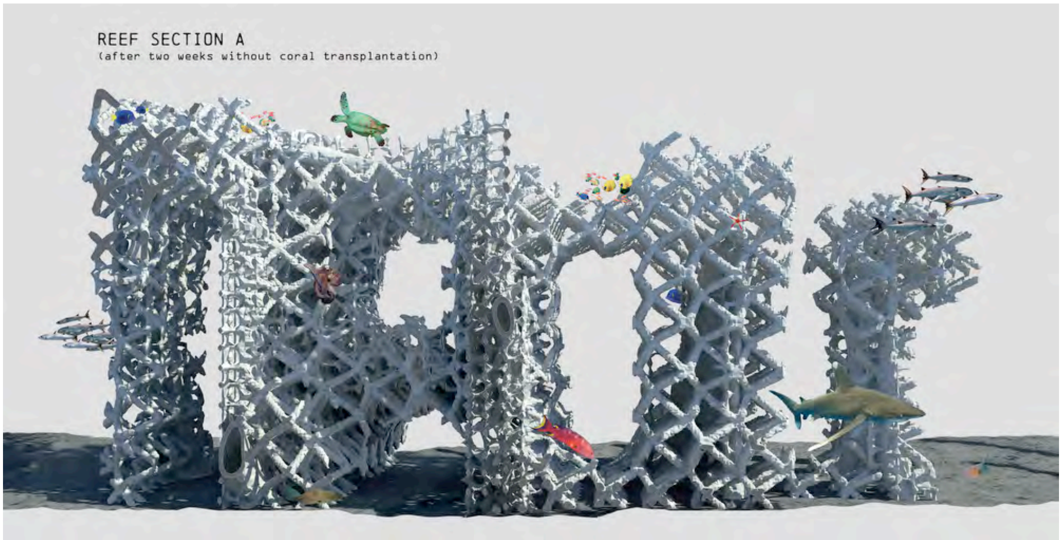

Figure 188 - Section of the (in)human habitat reef complex. Image by James Gardiner

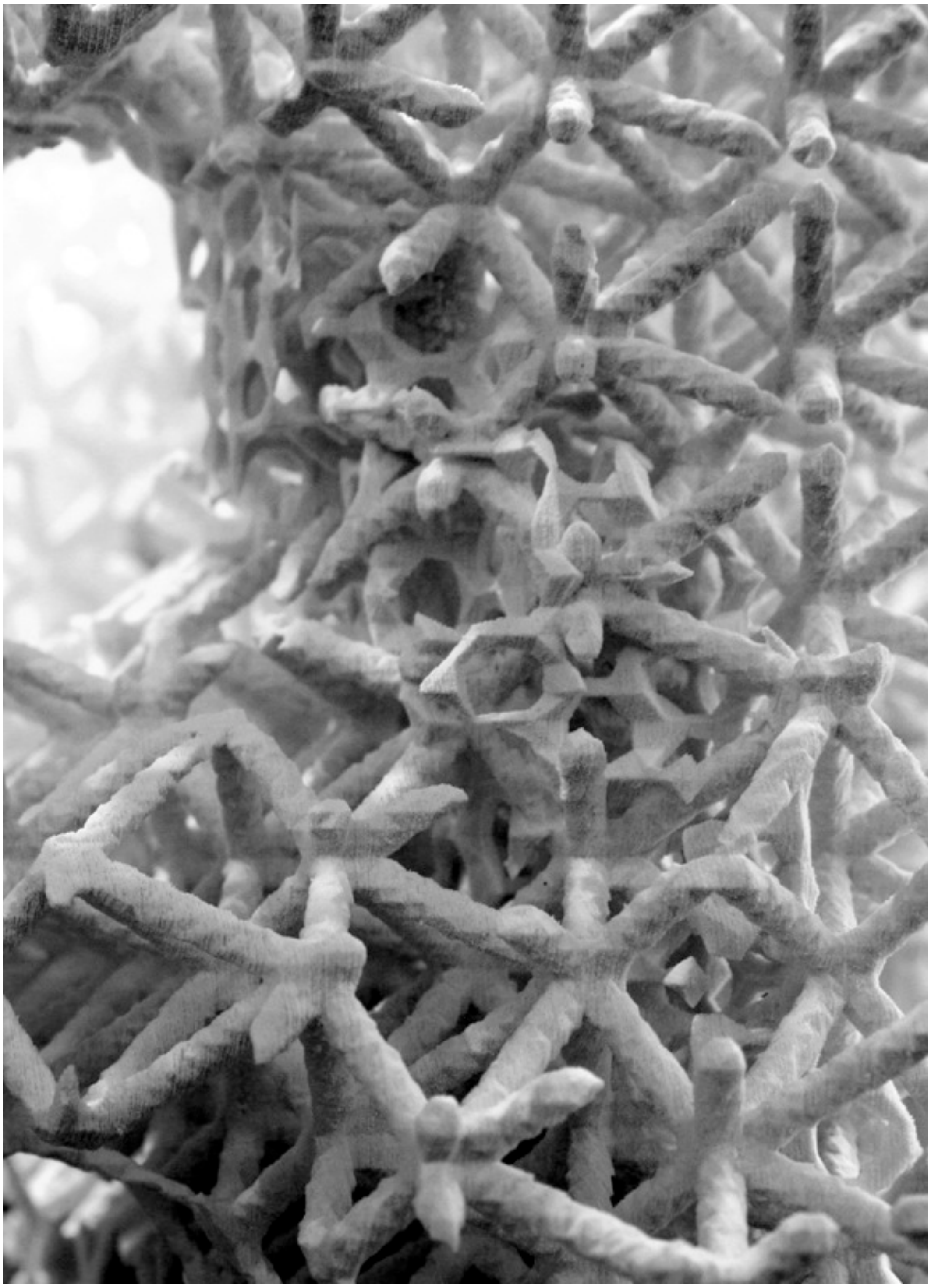

Figure 189 - Detail of the (in)human habitat Z-Corp model showing surface roughness which is a factor in constructed reef success. This scaffold in the image above is similar to the scaffold used in the Roccia Assembly, although this version has been manipulated to counter the wave forces acting on the structure.

The image above (refer image Figure 189) shows a detail of the course and medium detail scaffold as fabricated on the Z-Corp additive fabrication machine, this image shows the, fine detail, surface roughness of the scafold. This surface roughness was created intentionally by experimenting with .stl file export functions (tesselation) within the Netfabb™software. This was a bonus feature discovered in Netfabb™, I would expect that the setting was probably not intended for the creation of surface texture, but rather to manage exported .stl file size. This feature, intended or not, was a bonus for this project as it negated the need to add this level of detail once the model was complete. Surface texture, as discussed in chapter (6.2.1), in the form of uneven and rough surfaces are the easiest for coral polyps and other sessile (stationary) marine life to attach themselves to. Providing these surface types aids the colonisation of the reef by these marine creatures.

6.10. (In)Human Habitat Project Summary

This case study project has demonstrated novel concepts for the conceptualisation, design and fabrication of constructed reef complexes. The seed that led to the creation of this project idea was planted in Italy in 2009 at D-Shape™ and has been developed almost continually since with literature review, photographic surveys, SCUBA dives on the Great Barrier Reef and discussions with experts on the subject of constructed reefs. The project described in this chapter was initiated from seed funding awarded as the result of the Open Agenda competition. The project was exhibited at Customs House in Sydney from October 2010 until April 2011.

In the presentation of this case study the foundations upon which it was built were first presented which included the nature of corals and coral reefs, how they are formed and the terminology used to describe these formations. The development of artificial reefs was then briefly described, including the materials used and reasons for their deployment. A definition was made for two types of man-made reefs; artificial reefs that are made from waste products and constructed reefs that are created from new materials specifically for their use as reefs. A critical appraisal of current constructed reef types and deployment methodologies was then discussed. An emergent theory for the consideration of reefs within the framework of urban design principles was then discussed and my emergent concept of considering a reef complex as equivalent to an urban landmark building was briefly introduced.

The current trend in the West of locating constructed reefs on flat or gently sloping sites, was discussed in the context of the contrasting Japanese approach of locating their constructed reefs in the most productive zones, in areas where there is significant topography change. The opportunity was then discussed of a means of taking advantage of the Japanese approach, through the use of 3D scanning technologies. Such information could provide highly detailed information on which new digitally designed reefs could be tailored.

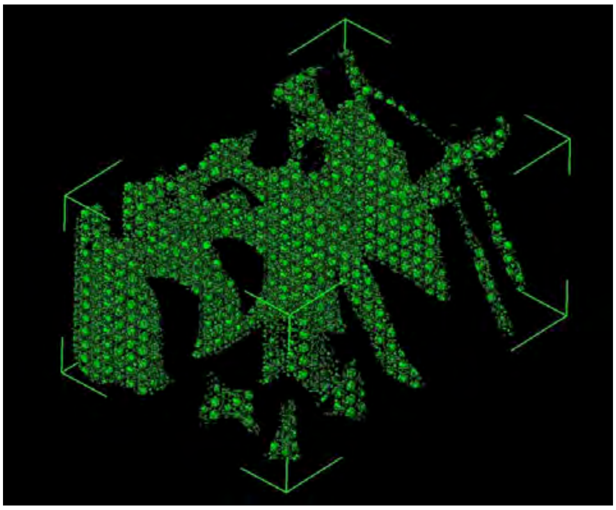

Figure 190 - One of the internal structures tested on the inner envelope. Image by James Gardiner

This research identified, based on critical literature review, photographic surveys and field research, three levels of detail required for the successful design of constructed reefs. The importance of these levels of detail was been described in reference to specific authors, and have been described under the following names; topology, articulation and texture. These three levels of detail are considered by a number of authors to be directly responsible for attracting specific species and being directly linked to the creation of diverse reef eco-systems.

The potential and suitability of using the D-Shape construction 3D printing technique was discussed in reference to fabricated objects that have been fabricated using the technique, the ability of the technique to fabricate objects with the three levels of detail described throughout this exegesis including: course, medium and fine levels of detail. The suitability of the material is discussed in reference to its chemical neutrality as well as demonstration of biological on the material established through prolonged marine exposure.

The key premise of this project was that constructed reefs could greatly increase in their provision of high diversities of habitat, following the precedent of natural coral reefs. Two novel concepts have been developed and deployed in the design of this project. The first was the consideration of the physical design of the constructed reefs through three scales: topography, articulation and texture. The second is the concept of the ‘deep scaffold’ for the formation of articulation within constructed reefs. A gap in literature was identified in the identification and naming of specific reef topologies, for the purposes of this project a number of reef topologies have been named, based on literature review and terms in common usage. The terms defined include: Wall, Tunnel, Pool, Bomby, Valley, Canyon, Shelf, Slit, Slope and Drop-off.

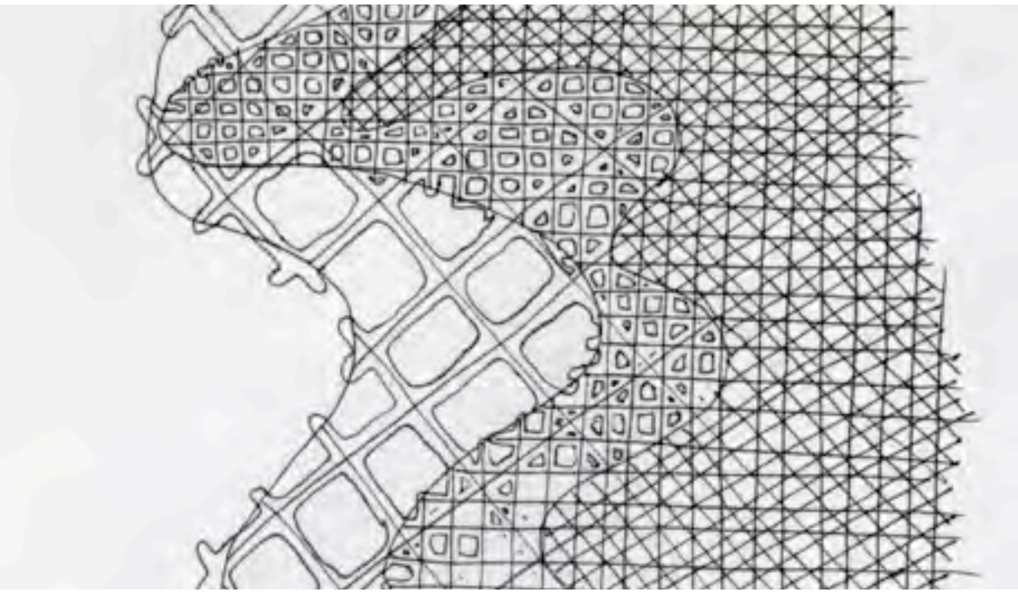

Figure 191 - The deep scaffold concept sketch. Sketch by James Gardiner

The original concept of the ‘deep scaffold’ was also defined (Figure 191), this scaffold, a three dimensional structure of varying dimensions here is described as having three layers, course, medium and fine. With the course layer occupying the largest envelope, the medium and fine layers each occupying progressively small envelopes. This scaffold arrangement has been described as having the benefit of creating multiple zones, with the size of the zones and hence the size of the marine creatures that can inhabit them becoming progressively smaller. This multi-layered scaffold has the benefit of providing shelter and protection from larger predators.

The reasoning for the location of the hypothetical project within the Farasan islands was described, in reference to the protection afforded by surrounding islands, native coral reefs that will seed the constructed reef, the presence of suitable topography at the site chosen for providing upwelling, presence of suitable currents as well as marine protection and monitoring that is in place making the location an ideal testing site.

The initial sketch design phase of the project used two methods: hand sketching and sculpting. The sketching method was found to be the most useful for the development of the central theories underpin the project. The hand sculpting was found to be less productive in the generation of ideas, although it was useful in shifting thinking when stagnation had occurred and developing novel ways to articulate the reef.

The key concepts developed through literature review, photographic survey, field research and the sketch design phase were then applied to the digital design of the (in)human habitat constructed reef complex. Three digital design tools were used which included; Topostruct™, Maya™ and Netfabb™ although some experimentation and refinement was performed using rhino™ and Mudbox™. A series of topologies were first mapped into the program Topostruct™ based on the defined topologies. The Topostruct™ program was then used to structurally optimise this defined envelope through a series of analysis and material removal operations, three iterations from this process of material removal were chosen to be used to create the three envelopes of articulation based on the deep scaffold concept.

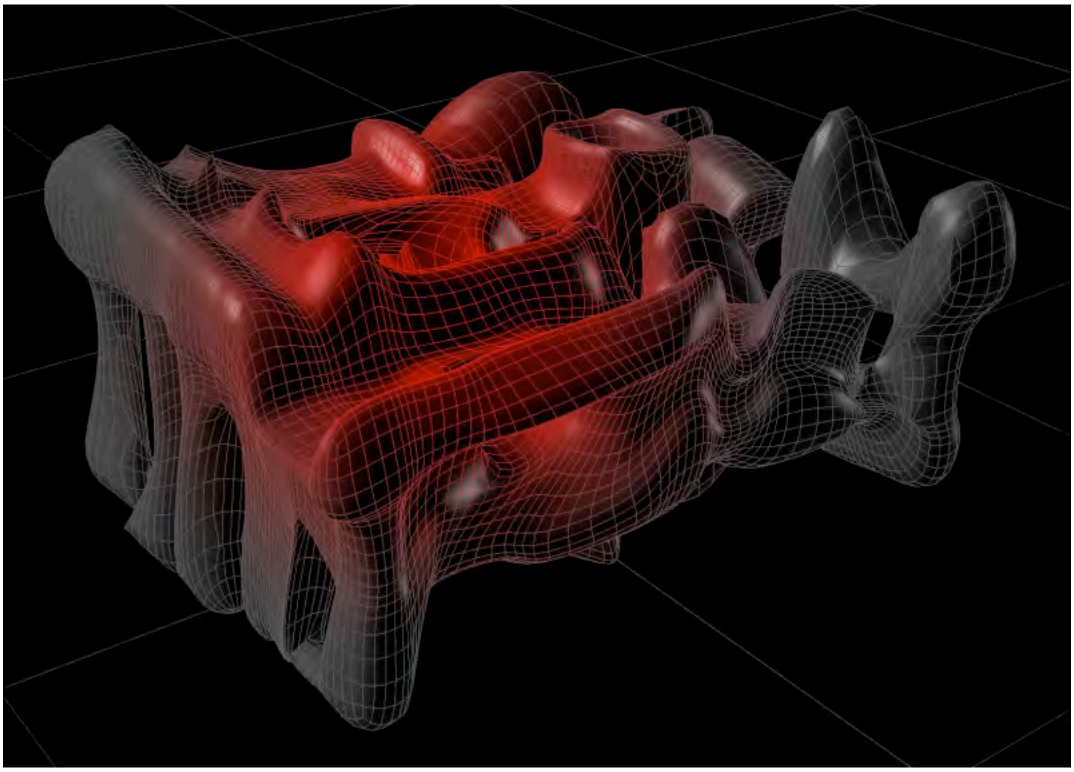

Figure 192 - The remodelled outer envelope of the reef complex, based on the initial topostruct optimisation. Image by James Gardiner

These envelopes were then each refined and in one case completely remodelled (Figure 192) to achieve a visually interesting design and to enhance the articulation of the design. The space-filling program Netfabb™ Selective Space Structures™ was used to create the scaffolds from the two outer envelopes, creating a scaffold for the inner envelope was abandoned due to the difficulty in computing the complex structure and other factors.

After some manipulation of the locations of the envelopes in relation to each other had been completed to improve the diversity of the external envelope, the three envelopes were booleaned together to form a single object. The envelopes were then cut to the profile of the digitally defined site and broken down for fabrication using a Z-Corp 3D printer. It was found that the Z-Corp 3D printer was more forgiving, in terms of being able to fabricate digital definition objects with minor errors than an alternative fused deposition printer. It was concluded that this was largely due to the method of 3d printing fabrication.

6.11. (in)human Habitat Project conclusion

The project is the first to attempt the design of a constructed reef complex for construction 3D printing. The level of complexity achieved in this project is far beyond the complexity and diversity of constructed reefs precedents identified. It is likely that most of the digital tools used for this project have not been used for reef design in the past, and had certainly not been designed for such a novel application. The digital design of the reef complex was extremely challenging and frustrating at times, largely due to the complexity of this model and minor issues in the way the digital design tools complete specific tasks such as boolean operations. Similar issues were experienced with the Villa Roccia project and the issues can be attributed to the complexity of what was being attempted.

Literature review searching for a clear set of terminology for types of topologies has been unsuccessful and from the broad range of literature reviewed, the terminology appears to be ad-hoc. The identification and definition of topologies for the purposes of this project, proved to be useful in identifying the range of topologies required within this project and the attempt to define topologies should at least serve to highlight more attention needs to be made in this area.

The identification of the three scales to be designed to in constructed reefs, topology, articulation and texture is a novel categorisation of existing theories that have not been so simply expresses. The development of the deep scaffold concept is entirely novel and from assessment of the project could be a significant contribution to the future design of constructed reefs. The theory in this case used to create uniform scaffolds, could be easily be applied with more dynamic and responsive tools such as DLA3D tool mentioned in chapter (3.2.1).

A number of significant potentials were identified within the reef project which could have significant implications for the fishing and leisure industries as well as for global sustainability and coastline protection. These potentials have been teased out through in-depth natural and constructed reef literature review, consultation with experts in the field, field experimentation, in depth knowledge of construction 3D printing techniques and creative thinking. These potentials can be summarised as follows:

- Construction 3D printing has been demonstrated to be appropriate for constructed reefs in a number of areas; the material (mainly synthetic stone) is already widely used for constructed reefs. The D-Shape™ material has an inherent surface roughness which is ideal for coral polyp adhesion, the construction 3D printing technique is ideally suited to creating complex non-uniform structures which can mimic natural reefs

- Due to the flexibility of construction 3D printing each element created can be different from the last. This reduces the need for mass production of similar elements as is common for constructed reefs. This allows the development of truly topologically diverse constructed reefs where no element is similar to another. This increases the opportunity for bio-diversity as the range of different habitats reduces the chances of domination of one or a small number of species.

- The concept for the deep scaffold which was developed for this project has enormous opportunity value for the creation of complex constructed reef structures which can contain more habitat opportunity than natural reefs, within a structurally robust modular building system.

- It is possible to create parametrically responsive reef modules that can compliment or replace existing modular constructed reef systems. This allows for the generation of variation within the module which can respond to local conditions (such as tides, currents, nutrient levels, accommodate or exclude certain species through provision or reduction of habitat. This allows for each module to be different without having to individually model each one.

- Natural reefs are well know to be a key source of costline protection. There is an opportunity to use construction 3D printing for the creation of reefs that can aid in coastline protection, especially for areas that are prone to Tsunamis.

- The leisure industry which is responsible for some of the destruction of natural reefs could also benefit for the creation of constructed reefs that are similar to their natural counterparts or are created to be scenographic to emulate other natural or fantasy environments. Development of constructed reefs could also be used as a teaching resource.

The contribution to the field that this project has made has been acknowledged with the 'Inaugural Sustainable Ocean Innovation Award 2010', this project was recognised for its:

"pioneering combination of digital design and D_Shape freeform additive manufacturing technique to create topographically complex reef modules that closely mimic the diversity and complexity of natural reefs."

David Lennon director of Sustainable Oceans International stated about the (in)human habitat project and the D-Shape™ technique:

"*This process has the potential to revolutionise the effectiveness of constructed reefs…Reefs are diverse and topographically complex structures. Current artificial reef modules used to replace damaged reef structure are effective but tend to provide only moderate complexity and often look artificial. It is usually too costly to cast a range of different modules to create the complexity required to mimic a natural coral reef. This technology enables us to create reef modules that have a complex network of branches and voids similar to a coral reef.*" (Lennon, 2010b) p1

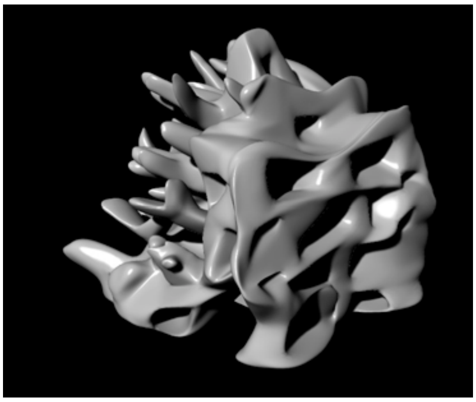

Figure 193 (a) sketch for a multi environment reef module. (b) Final design of the reef prototype. Sketch and image by James Gardiner

This speculative project has resulted in a commission to prototype a reef module using similar methods for fabrication using the D-Shape™ technique, albeit at a much smaller scale, for now (Figure 193 a & b and Figure 194). This outcome demonstrates that a speculative action research approach can result in new opportunities and potentially change practices, even when the speculation is into an unrelated field (i.e. architecture to marine biology – reef design)

Figure 194 - Eight printed reef modules at the D-Shape factory in Tuscany. Commissioned by Sustainable Oceans International. Designed by James Gardiner

Further research is required for the development the concept and application of the ‘deep scaffold’ concept; especially with generative, responsive and simulation CAD tools. Additional definition of the topologies of natural reefs is considered important to the future design of constructed reefs. Definition should also be possible of the fine level texture topologies.

7. Conclusion and discussion

I Believe mankind is at the beginning of a digital design and fabrication revolution. This transformation is shifting the way we design and fabricate and is likely to be as transformative to our industries and society as the industrial revolution of the 18th and 19th centuries. This transformation based in digital design and fabrication is beginning to change the products that are available, the way that these are made and the types of products that people have access to. Additive fabrication and construction 3D printing will be at centre of the shift in design and fabrication due to their unique capabilities for fabricating geometrically and materially complex and customised products. This dramatic change in the way objects are designed and fabricated presents significant opportunities for the construction industry. This research has begun to explore the design territory that construction 3D printing makes available through its unique capabilities.

Additive Fabrication techniques have already being used to build living organs cell by cell and enabled levels of customisation in toys, jewellery and consumable products barely considered accessible just a few years ago. The significant difference between this digital design and fabrication revolution and the industrial revolution is that craft will flourish rather than falter. We will have access to highly customised products, some of which we may design or customise ourselves then 3D print at home.

The primary concern of this research has been to fill the gap in knowledge around the practical application of construction 3D printing within the construction industry, which necessitates new methods of digital design and construction methodologies. A central hypothesis formed the primary theoretical question for the research:

"*A hybridisation of new and existing design practices, digital design tools, off-site fabrication methods combined with construction 3D printing techniques could lead to significant advances for architecture and construction. To better* *understand the potentials and limitations of construction 3D printing combined with off-site fabrication methods and digital design tools, further detailed architectural exploration is required.*"

Three of my architectural and research projects completed between 2004 through to 2010 have been used to form a central core of research around which this exegesis is based. Each of these three projects; Freefab, Villa Roccia and (in)human habitat; is quite different from the others and explore different themes around the central topic of design for fabrication using construction 3D printing techniques.

Freefab was a speculative project that focused on the development of a high-rise prefabricated construction system based on the Contour Crafting™ technique. The Villa Roccia project was a commissioned project for the design and construction of a house in Sardinia and focused on the development of a new construction system that adapted to the capabilities and limitations of the D-Shape™ technique. This project went through a number of detailed design stages and included the prototyping of a column that physically tested the construction methodology developed and the capabilities of the D-Shape™ technique.

The third project (in)human habitat focused on an entirely new application for construction 3D printing with the fabrication of artificial reef structures. This project focused more heavily on the development of a completely new type of artificial reef typology and the complex digital design process required to create it. Despite the substantial differences between the projects there is continuity, as stated above, from one project to the next in the development of thinking, understanding of the strengths and limitations of construction 3d printing, development of digital design methodologies, strategies for detailing and physical construction.

Through these projects, limitations of particular construction 3D printing techniques have been identified and potentials have been identified, developed and demonstrated, resulting in new knowledge and potential within this emerging industry. This research has filled this gap in knowledge through the development and exhibition of a number of unique architectural projects and the distilled findings that have resulted from their analysis in this exegesis. A number of novel and hybridised design and construction methods have been developed, that have immediate and future potential within the building industry and the constructed reef sector.

7.1. Additive fabrication

Additive fabrication has developed since its initial invention the late 1980's and has transformed from prototyping applications to fabrication of parts to be used directly by consumers and industry. The term additive fabrication has been defined and selected for use in this exegesis over a number of alternative terms coined by academia and industry, such as rapid prototyping, due to its slightly greater accuracy and descriptive quality.

A wide variety of applications for additive fabrication techniques have been identified within this paper within industries and sectors such as aerospace, industrial design, medical and jewellery. The use of these techniques has been shown to focus on the fabrication of products that have added value over alternative products made by alternative means or are unique in their geometric complexity. Construction 3d printing is beginning to emerge from Additive Fabrication and has the potential to offer similar benefits to those of additive fabrication at a larger scale.

7.2. Construction 3D printing

This paper has identified a number of construction 3D printing techniques that are in a process of development, three techniques that have demonstrated capabilities have been described and analysed within this paper; including Contour Crafting™, Concrete Printing™ and D-Shape™. The D-Shape™ technique has been shown to be the most advanced of these three techniques, through the regular fabrication of a variety of large 3D freeform objects in the form of sculptures, furniture and construction elements.

Direct technology transfer from smaller additive fabrication machines has not been a process of merely scaling up, significant further developments have been required in development of all three techniques discussed. The development of Construction 3D printing techniques has been by no means a simple task, meeting the challenges that arise with the scaling up additive fabrication techniques, inventing new processes and adapting suitable materials can be considered an important advance: perhaps equivalent to the developments in reinforced concrete techniques in the 19th century (Kind-Barkauskas et al., 2002). Construction 3D printing techniques are at present, considered by me, to be most suitable for niche areas of application, which would be difficult or costly to fabricate using other techniques: following a similar tread to that of additive fabrication.

The short-term prospects for the three construction 3D printing techniques analysed vary considerably. The Contour Crafting™ and Concrete printing™ techniques appear to be struggling to bring their techniques to commercialisation. To date these two techniques have demonstrated to date prototype walls and other artefacts, that at present, offer only small advantages over conventional means of construction. These fabrication techniques have been shown to struggle to fabricate 3D freeform geometries that are one of the key benefits associated with additive fabrication techniques. In contrast the D-Shape™ technique is in the process of commercialisation of its technique with the commissioning of projects such as the Radiolaria in Tuscany, the Villa Roccia project in Sardinia. After having demonstrated the production of large 3D freeform objects. D-Shape™ still has hurdles to overcome with their technique, including issues with material strength, productivity and reliability of the machine. These factors will have significant impact on the commercial viability of this technique in the near future. I would expect that each of the three machines discussed in detail in this exegesis and others that are emerging will in time overcome the obstacles they are facing, perhaps one or two will fall away in time. I believe that construction 3D printing will follow the trajectory of additive fabrication techniques: progressively improving quality, adding new materials and increasing the productivity of its machines.

The emerging Construction 3D printing sector can leverage its strengths in three key areas to develop niche markets in the future. The first is the ability to create freeform structures and elements, the second to take advantage of the flexibility of additive fabrication techniques for customisation (Tuck and Hague, 2006) and the third to add value through meeting the needs of construction sustainability. Rather than emulating existing materials or assemblies, there is an opportunity to develop an entirely new palette to be used in the future. Internationally the construction industry has been indentified as needing to modernise and achieve greater efficiency (NAHB, 2001, Egan, 1998), while also facing the formidable challenges of carbon reduction and sustainability.

7.3. Design for construction 3D printing

This analysis of D-Shape projects, prototypes and testing makes clear the challenges of developing and applying Construction 3D printing techniques to meet the requirements and responsibilities inherent in the of construction of buildings. On face value design for Construction 3D printing appears to be simple, in comparison to contemporary building processes, although, as has been demonstrated through the case study project examples, substantial hybridisation of methods and practices has been required, from fields of construction, engineering, design and the parallel industries.

The implications of this technique on all aspects of the design to construction process cannot be underestimated, as has been demonstrated in the three case studies presented in this exegesis. This exegesis has documented and reflected on the first steps in prototyping with Construction 3D printing techniques at construction scale. This research has demonstrated that design, fabrication and assembly methods used in conjunction with construction 3D printing techniques differ, in most cases, substantially from those of contemporary architecture and construction practice. Novel strategies have therefore been developed for the case study projects, presented in this exegesis, to take advantage of these construction 3D printing techniques.

These new and original strategies have been developed after significant broad ranging investigation which has taken the form of; literature review and analysis, photographic surveys, international and local field research, sculpture and individual physical investigations, interviews, discussions, project based action research and embedded practice within a construction 3D printing company. The quote by Hensel and Menges reflects the approach applied within the projects discussed within this exegesis:

‘*The far reaching potential of computer-aided manufacturing (CAM) technologies is evident once they turn into one of the defining factors of a design approach seeking the emergence of form generation and materialisation processes.*’
(Menges and Hensel, 2008) p57

Novel strategies that have been developed for design to fabrication, using construction 3D printing, have been presented; for a house, a high-rise apartment building and a man-made reef structure. The strategies employed in some cases have been a hybridisation of existing design and construction techniques and in others entirely new. One example of hybridisation of an existing technique is the adaptation, in the Roccia assembly project, of precast concrete detailing practices that have been altered for freeform panel geometries and modified to incorporate internal geometries.

An example of an entirely new novel strategy developed for the design and fabrication, using construction 3D printing techniques, is the development of the constructed reef complex presented in the (in)human habitat case study. This project formalised the definition of reef topologies and then developed a strategy for constructed reef design based on consideration of three scales: topology, articulation and texture. An entirely new design concept was then introduced named the ‘deep scaffold’ for the creation of the mid scale articulated geometry within the constructed reef concept.

The Roccia Column, part of the Villa Roccia project presented in case study 3, demonstrated the application of the theory, and practice with additive fabrication, of creating internal geometries within a fabricated column. The fabrication by D-Shape™ of the coffee tables for Freedom of Creation discussed in (chapter 6.5) and the D-Shape™ materials testing in marine environments discussed (chapter 6.4), demonstrate the applicability of D-Shape™ technique for constructed reefs.

The discussion of design within this exegesis has often referred to the levels of detail within a project including: course - generally referring to the form, envelope or topology of the structure or building, medium – refers to the articulation of that building or structure that can take the form of windows, doors, lattice geometries, panels and features, the fine level of detail then relates to the detail or texture which can be manifested in the joints details, reinforcement or surface textures. These three levels of detail have been manifested in all three of the case study projects presented within this paper and have been largely absent from the designed and fabricated construction 3D printing precents such as the R&sie project by Francois Roche et al. and the Radiolaria by Andrea Morgante. The focus on these three levels of detail has significantly added to the effort to understand the potentials and limitations of construction 3D printing.

7.4. Digital definition and design

Digital design software capabilities have improved immensely in the fifteen or so years in which I have been using them, and even in the seven years over which the projects presented in this exegesis were developed. 3D digital design tools have improved the most over this period with the recognition of the capabilities and efficiencies that this type of software make available by software architects and the users within architecture, engineering and construction. This shift in focus away from 2D digital design tools reflects changes that have already occurred within the parallel industries, the construction industry is very much a follower rather than a leader in this regard.

Analysis of the Delivering Digital Architecture in Australia construction and parallel industry interviews and questionnaires identified that the parallel industries especially aerospace rely much more heavily on 3D digital design tools than does the construction industry. The parallel industries also make far greater use of their 3D data than does the construction industry, through the creation of a central model to which all stakeholders add information and through the sharing of this information throughout their businesses.

The term ‘digital definition’ has been defined and used within this exegesis, to refer to the 3D digital design file that is increasing in importance both in the construction and parallel industries with the increased use of CAD/CAM and additive fabrication techniques. As the sophistication of 3D digital design tools increase, and hence the files that they create, more information is being stored and becoming available through interrogation of the digital definition file. A very simple illustration of this, which is not particularly sophisticated, is when I was asked how much the prototype reef that I have designed weighed, I was able to interrogate the file to find its volume and then multiply the result by the weight per cubic meter of the D-Shape™ material. If the design documentation for that reef prototype had been 2D documentation it would have been virtually impossible ascertain a precise volume due to the complexity of the design.

Parametric design tools are now more accessible to architects today than they were just ten years ago with the creation programs for architects such as: Digital Project™ (based on CATIA), Generative Components™ and Grasshopper™ (a plugin for Rhino™). Two of these software packages have been used within the course of the projects presented as case studies in this exegesis. The first of these programs, Grasshopper™ was used for the generation of the Roccia Column Prototype and Generative Components™ was used within early testing on Roccia Assembly project.

Although the merits of the use of parametric software have been well established through their use on highly prestigious projects such as the Sagrada Familia (Burry and Burry, 2006, Burry, 2007) and the Disney Concert Hall (Kolarevic, 2003). The use of parametric digital design tools has been shown to have marginal benefit in the projects presented in this exegesis, this lack of effective contribution has been attributed to the scale of the projects to which the digital design tools have been applied and thus parametric digital design tools could be much more applicable for larger scale projects.

No attempt, beyond the use of parametric software tools, has been made to automate or semi automate the panelisation or modularisation of buildings for off-site fabrication, automation within software tools in the form of scripts, plugins, parametric method etc could substantially reduce the time required to detail the digital definition file to a level ready for fabrication using construction 3D printing techniques.

A type of multi-criteria optimisation is already practiced by architects today[170], sometimes using analysis tools but often at a personal level informed by training and experience by weighing up priorities and developing design options that are then evaluated and selected on their ability to create the best fit for a client. Software optimisation tools make the analysis and optimisation process more explicit and (in most cases) are based on mathematically accurate formulas. Optimisation software was used within a number of the projects presented here as case studies. The use of optimisation software is considered to have potential to create a level of responsiveness within design for construction 3D printing that is largely unattainable within contemporary construction techniques. Single criteria optimisation was used within the projects presented although this option was considered less than ideal and multi-criteria optimisation would have been used if available.

"*Multi-parameter effectiveness rather than single parameter optimisation and efficiency, must from the start of the design process include both the logics of how*

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[170] This is based on my professional experience of using analysis tools, calculating efficiencies and negotiating engineering efficiencies against other performance criteria.

material constructions are made and the way they will interact with environmental conditions and stimuli" (Menges and Hensel, 2008)

Significant opportunities will potentially become available for design, fabrication, engineering and sustainability with the combination of multi-criteria optimisation digital tools and Construction 3D printing, due to the reduction of geometric constraints offered by construction 3D printing techniques.

A number of other 3D digital design tools were used to model the projects presented in case studies one, two and three. Autocad™was used in 2004 for the modelling of the Freefab tower due to difficulties experienced at the time with reliably exporting the digital definitions to .stl file format required for fabrication using additive fabrication. Autocad™, at that time, was found to be far from the ideal software to use: due to limitations in the generation of smooth 3D curvature and freeform geometry as well as issues with creating 2D documentation from the 3D geometry (as required as part of the assignment). Issues were also experienced with the joining of 'solid' geometry (named boolean operations by Rhino™ and Netfabb™), necessary for output of a unified model to .stl format for 3D printing.

Maya™ was used for the Roccia assembly and the (in)human habitat reef project and proved to be an excellent program for creating fluid 3D curvature and freeform geometry. This program was used for remodelling the output from Topostruct™ structural optimisation software. The only hurdle in the use of this software identified was the difficulty of dimensionally accurate modelling for which Rhino™ was later adopted. Rhino™ was used for the detailed modelling and panelisation of the Roccia assembly and performed these functions with a high level of dexterity. Issues with both Rhino™ and Netfabb™ were experienced with boolean operations, with Netfabb™ performing better than Rhino™ although still producing errors and occasionally crashing. The main benefit of using the Netfabb™ software was for the creation of internal geometries within the panels of the Roccia assembly and for the generation of the deep scaffold for the (in)human habitat project. Control limitations were identified with Netfabb™ software functionality with the creation of 'selective space structures'. These limitations in the control of the placement and orientation of its 'space structures' resulted in compromise solutions being adopted. Alternative means of generating such structures will be sought for future projects with these requirements, possibly with generative or parametric digital design tools.

The projects presented in the case studies have shown that the choice of software tools for a project has a significant effect on the quality of the digital definition generated. Scale, purpose, functionality and output required have all been identified as being critical to the choice of digital design tools and the outcome produced. One of the major issues for digital design for construction 3D printing is identified as the ability to efficiently and effectively perform boolean operations. Some of the digital design tools used within these projects have been found to be inadequate or flawed, significant testing prior to the commencement of a project has been useful in identifying some but not all of the problems experienced.

7.5. Off-site fabrication

One of the initial questions that I was concerned with at the commencement of this research was 'why is off-site fabrication not more prevalent today'. This question was substantially answered through the international and local field research studies conducted in 2006 and 2009. These two field studies of the construction and parallel industries focused primarily on off-site fabrication and digital design tools and the findings from this research are included as an appendix to this exegesis (Appendix C). The answer to the above stated question is complex and multifaceted and will not be detailed here. Some of the methods for improving the effectiveness and performance of off-site fabrication have been identified as being present in the practices of the leaders within the parallel industries (Egan, 1998). These industries including aerospace, automotive and shipbuilding have dramatically improved the quality of their products in the last decades, some of the practices that are relevant to the construction industry are: significant or complete 3D digital design of their products, which in many cases includes analysis, optimisation, clash detection, prefabrication and assembly and the use of CAD/CAM fabrication techniques.

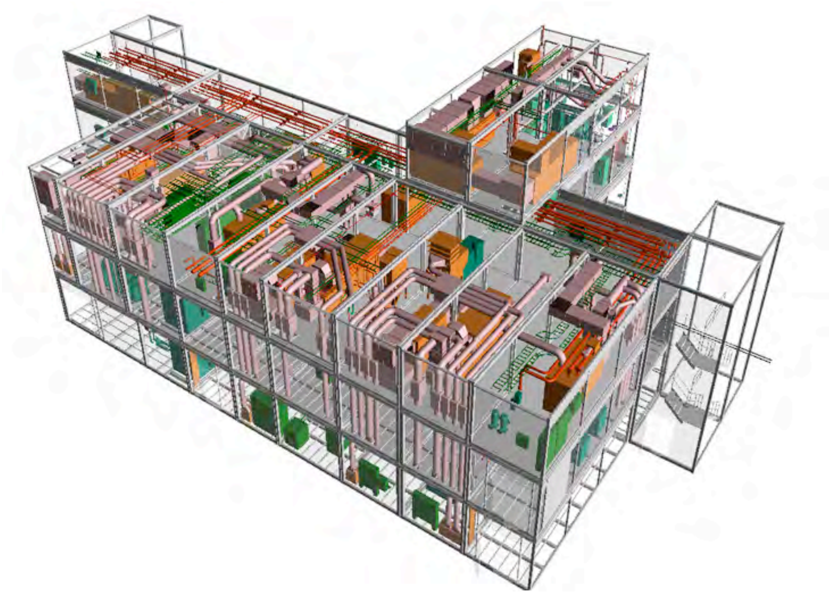

Figure 195 – Pharmadule™ modular pharmaceutical plant modelled and tested digitally prior to fabrication. Image courtesy of Pharmadule™.

Construction 3D printing techniques have been identified as being particularly well suited to off-site fabrication for the following reasons; the complete reliance on ‘digital definition’ for the creation of the data required for fabrication, the need (at least for now) to locate construction 3D printing fabrication machines in a atmospherically controlled environment (a shed or factory) and the requirement to break down large objects for fabrication due to machine fabrication constraints. Therefore many of the requirements of construction 3D printing essentially pre-suppose the use of off-site fabrication practices.

Off-site fabrication can also significantly benefit through the use of construction 3D printing techniques, as construction 3D printing reduces the need to join many materials and elements together to form its assemblages. An example used to demonstrate this concept was presented in (chapter 4.1), with the drastic reduction in materials required to create a wall, this can potentially reduce labour, decrease the potential for error, increase recyclability and add value. The adoption of construction 3D printing and in particular D-Shape™ can also add significant potential for the off-site fabrication industry to break its mould of serial production to instead focusing on customised products.

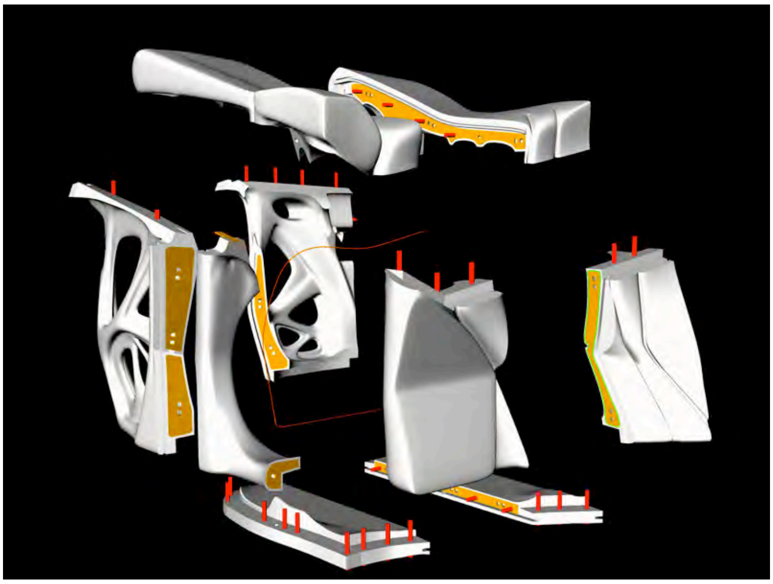

Figure 196 - Roccia asembly - Exploded view of the panels and reinforcement. Image by James Gardiner

Off-site methods have been adopted, adapted and hybridised for use within the case study projects. Modular 'double wide' construction was hybridised in the Freefab project to create the 'sliced' monocoque 'shell' modular concept. Practices from the precast concrete industry (panelised off-site fabrication) were adapted and hybridised for the Villa Roccia project with the adoption of panelisation, post-tension reinforcement and sophisticated weatherproof joints to develop the Freeform split panel with internal lattice geometries.

Off-site fabrication practices have already been applied to a project fabricated by D-Shape™ with the Roccia column, with the splitting of the column for assembly, the use of the mortise and tenon joint and post-tension reinforcement strategy. I believe that the D-Shape™ fabrication technique will soon demonstrate off-site fabrication practices on increasingly challenging projects. Both construction 3D printing and off-site fabrication benefit through the union of the method and the technique, this union could be highly significant for both sectors.

7.6. Construction sustainability

Construction sustainability, as defined and discussed in this paper, presents significant challenges for the construction industry worldwide. Due to difficulties in locating an adequate definition of sustainability, a definition has been described for the purposes of discussion within this paper based on literature review. This was defined as *'state in which components of the ecosystem and their functions are maintained for present and future generations'* (ISO, 2008) and the following components of the eco-system to be considered were defined as: material and energy use, air, water, bio-diversity and human factors.

The construction sustainability of construction 3D printing have been identified as a characteristic of the additive nature of construction 3D printing, by potentially using less materials and producing less waste than subtractive and formative fabrication techniques. However it has also been argued that the construction sustainability of a construction 3D printing technique has to take into account further attributes the specific technique that relate to the components listed above. Therefore the construction sustainability of construction 3D printing needs to be considered based on the assessment of individual techniques rather than for construction 3D printing as a whole.

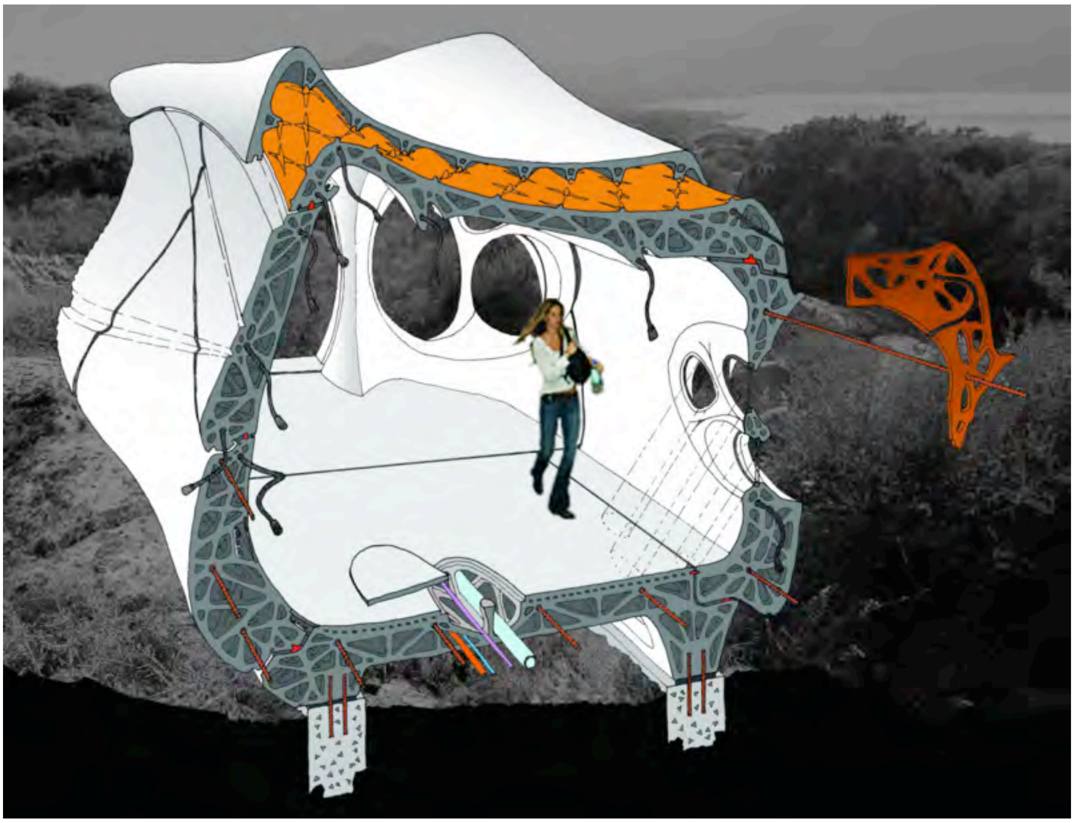

Figure 197 - Roccia Assembly sketch perspective. Developing the construction system for the Villa Roccia. image by James Gardiner

The design and operation of new buildings as integrated systems has been identified as one method by which energy use could be reduced by 75% (Mets et al., 2007) and an important method by which such reductions in energy use could be achieved was identified as the adoption and implementation of ‘passive design’ principles that assist in the control of building environments.

Construction 3D printing techniques have been identified as having a potential advantage over conventional construction techniques due to their ability to fabricate elements with a level of control that allows for detailed arrangement of materials that can be designed in such a way to passively respond to specific environmental conditions of a building. This capability is obviously dependant on the responsiveness of the design and digital definition from the construction 3D printing bases its fabrication.

The case study 1 Freefab project demonstrated through reference to design perspectives how responsive design could be manifested into elements fabricated using construction 3D printing which included the integration of thermal insulation, sunlight control, integration of seals, acoustic treatments and the targeted use of materials as required to achieve these goals. The Roccia assembly further demonstrated how material use could potentially be dramatically reduced in panels while responding to structural and thermal requirements.

Off-site fabrication has a quantified sustainability benefits that include: reduction in waste through improved recycling and reductions in rework, reductions in energy use and the ability to integrate innovative material and design solutions (Blismas and Wakefield, 2009). Construction 3D printing has been demonstrated to be well suited to the adoption of off-site fabrication techniques, therefore the benefits of both off-site fabrication methods and construction 3D printing fabrication techniques can potentially lead to greater levels of construction sustainability than can be achieved by both conventional construction and off-site fabrication methods.

7.7. Contribution to knowledge

The significance of this research is in its intellectual and practical contributions to the following fields; architecture, engineering, construction 3D printing, off-site fabrication and constructed reef design. The predominant contribution of this research has been in the development of design strategies for the construction 3D printing.

Richard Rogers stated in 1985 "*The architect must understand and control the machinery – the instruments that build buildings – where necessary developing and inventing new ones…only by studying and controlling the means of production and by creating a precise technological language will the architect keep control of the design and construction of the building. The correct use of building process disciplines the building form, giving it scale and grain*" (Jencks and Kropf, 2006) p253

These contributions were first manifested with the first case study project, the design of the Freefab tower; this project saw the development of a comprehensive construction system for high-rise residential towers, which was comprised of a number of smaller innovations. Namely the development of the: open construction system of checkerboard arrangement of apartments providing sky-yards, the development of the sliced apartment concept to break down apartments into transportable chunks while ensuring the spatial quality of the apartments was not compromised, the development of the construction 3D printing fabricated monocoque apartment shell and the early development of the single material construction system to remove many of the materials from wall assemblies while providing a greater level of responsiveness.

The second case study the Villa Roccia project contributed to knowledge with developments in the following areas: the development of a design language based on the study of eroded rock formations and the structure of bones, this design language was demonstrated on the design of the Villa Roccia, the column prototype and the Roccia assembly projects discussed in case study two. A detailed design method was developed for the design of columns and for the panelisation and reinforcement of freeform geometries, to be fabricated with construction 3D printing.

Further innovations also included the development of a split panel system that responded to specific design for fabrication issue of the D-Shape™ technique, namely the removal of unbonded material. The panel system and column design methods included the integration of internal lattice geometries that could significantly reduce structural weight of fabricated items: through the provision of lightweight structural reinforcement that was inspired by the trabeculae reinforcement in bones. A novel digital design working method was developed with the assistance of Alina Mcconnochie, that focused first on the developed of the freeform external geometry using Maya™™, then used Rhino™ for the splitting and detailing of the panels and Netfabb™ for the creation of the internal panel geometries.

The third Case study made contributions within a broad number of subject areas: through literature review, photographic survey, discussion with experts and field study a series of reef topologies were defined. The classification of three levels or scales of design for constructed reefs was identified that included topology, articulation and texture. Although this, similar to the definition of topologies above, is not necessarily the creation of completely new ideas or names it does from my research appraisal categorise these features for the first time.

The novel concept of the deep scaffold was introduced for the first time. The deep scaffold is a new methodology for the creation of diverse multi-scale spaces using lattice structures appropriate for constructed reef design. The method of designing reef complexes with a range of topologies is also a novel concept with no precedent identified. Another contribution is the design of a reef complex with the combination of the concept of design for the three scales: topology, articulation and texture, multiple topologies and the deep scaffold.

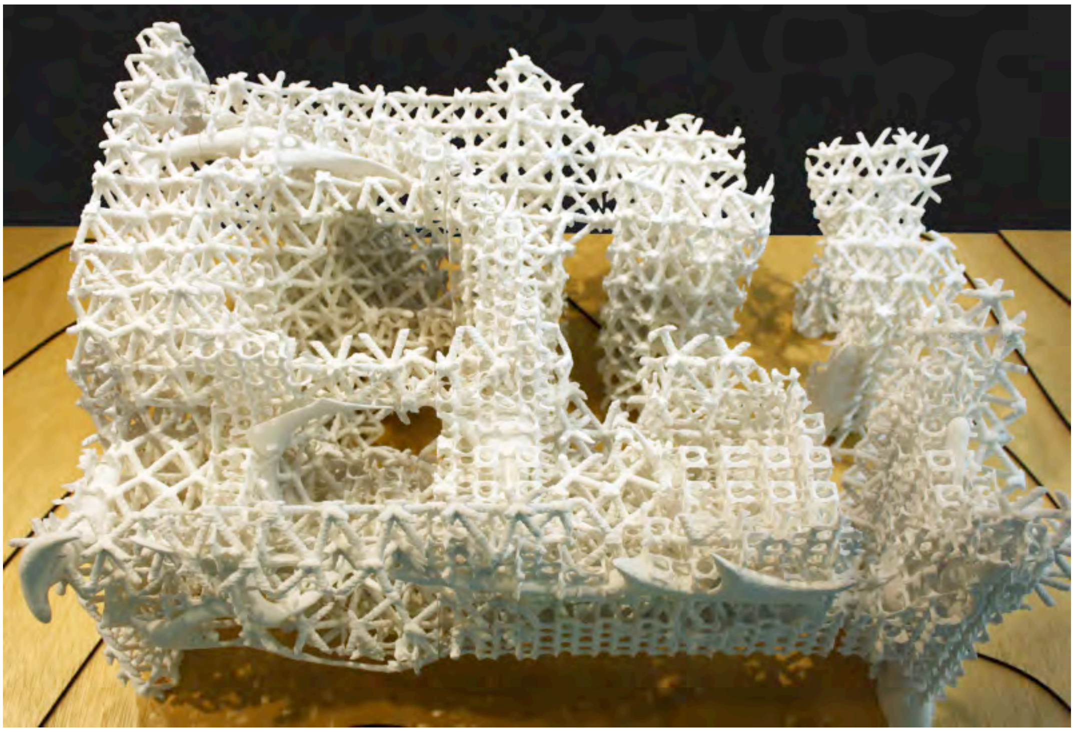

Figure 198 - The 3D printed model of the (in)human habitat reef complex. Note the three levels of articulation that make up the deep scaffold. Photo by Nigel O'Neill Model by James Gardiner

Further contribution to knowledge of the (in)human habitat and Villa Roccia projects was made in the development of working methods that combined digital design tools such as: Topostruct™ optimisation software for the development of multiple envelopes, the use of Maya™ and Mudbox™ for the refinement of these envelopes, the use of Rhino™ for construction detailing and the use of Netfabb™ to create the scaffolds and for the joining these envelopes and then splitting into element of the size appropriate for fabrication. The specific combinations of software tools may not be adopted although the method of combining digital tools to perform similar tasks is likely to be influential to design for construction 3D printing.

7.8. Identified potential of construction 3D printing

Critical analysis of the case study projects has enabled the identification of the following potentials for construction 3D printing. These potentials have been described in more detail in the conclusion of each of the case study projects and are briefly summarised in point form below;

Freefab

- The development of highly integrated modular and panelised off-site construction systems.

- The development of new building typologies based on leveraging the strengths of construction 3D printing.

- The creation of monocoque building elements that can integrate a wide variety of functions within a single or very limited number of materials.

- The utilization of articulated arm robots for construction 3D printing can allow greater flexibility with deposition of materials while taking advantage of the inherent robustness and reliability of these platforms. The robots can also be swapped out easily and can be employed with other tasks such as post processing

Villa Roccia

- Construction 3D printing techniques bring a new flexibility to the creation and deployment of new design languages that can be either whimsical or functional.

- Optimisation software is ideally suited to be used for the development of designs to be fabricated with construction 3D printing techniques due to the flexibility of construction 3D printing technique to create complex and non-uniform geometries.

- Construction 3D printing techniques are presently more suited to factory rather than on-site environments. Construction 3D printing techniques are well suited to factory environments as there is a need for post processing of fabricated parts to ensure dimensional accuracy and level of required finish are achieved.

- The production line automation of the many of tasks required to complete construction 3D printing fabricated elements is well suited to reducing the limitations of construction 3D printing techniques as well as leveraging its strengths. By locating construction 3D printing machines within production line environments it should be possible to maximise return on investment and speed up production.

- The use of scripting and parametric modelling are well suited to the creation of flexible and efficiently generated models for construction 3D printing.

- The adaptation of the ‘digital definition’ methodology is virtually required for fabrication with construction 3D printing. Leveraging all aspects of this digital definition will likely result in the large productivity gains obtained within the parallel industries.

- Construction 3D printing techniques (especially D-Shape) are well suited to the creation of complex and fine filigree structures that can be used for the creation of internal geometries and other structures such as reefs.

(in)human habitat

- Construction 3D printing is appropriate for the creation of constructed reefs which can equal or surpass the complexity of natural reefs.

- Construction 3D printed reefs can produce truly diverse topologies and environments (especially when employing the deep scaffold concept), increasing the opportunity for highly levels of bio-diversity within man made reef environments.

- Parametric and scripting tools can be used for the creation and customisation of reef modules. Allowing every module to be different while still achieving economies of scale production.

- Constructed reefs can be used as a low impact form of coastline protection. Construction 3D printed reefs can be designed to adapt to changes in ocean bottom topography, allowing for installation on irregular bottomed sites.

- Construction 3D printed reefs can be employed for use at leisure facilities such as tropical hotels and can be used as teaching aids.

7.9. Dispersing myths and assumptions

Meeting the challenges that arise with the creation of a new fabrication technique and material science on which construction 3D printing techniques rely can be considered a significant step from development of reinforced concrete in the 19^{th} or 20^{th} century. On face value Construction 3D printing appears to be simple, in comparison to contemporary building processes, this exegesis disperses the myth or assumption that this technique will dramatically simplify the design and construction process, while identifying and assessing the important benefits that the D-Shape technique and construction 3D printing techniques can deliver over contemporary construction practices.

The increased reliance on digital design tools in the creation of the digital definition is one of the factors that can increase the complexity of the design process for construction 3D printing. This complexity arises partly out of the to necessity to completely define the elements to be fabricated prior to commencing fabrication. In conventional construction it is rare that documentation is complete at the time of construction commencement, due to tight schedules. Paper documentation also relies on the generalisation of details that are applied, in many cases, in many instances across a building, with a tolerance for slight variation in each instance. This is not the case with the generation of the digital definition for construction 3D printing, where the detail must be defined throughout the building and work in each instance (i.e. if a detail does not work it will often create errors within the digital definition which can make the element un-fabricatable).

Another factor that makes construction 3D printing as complex as conventional construction, instead of simpler, is the increased capability of digital design tools and the construction 3D printing techniques. This increased capability, almost by default, obliges the designer to take advantage of these capabilities. This capability was explored and demonstrated, with the use of internal structures in the roccia project and the deep scaffold in the (in)human habitat project, and can be said to have significantly increased the complexity of designing and creating the digital definitions for these projects.

In order to leverage the opportunities of Construction 3D printing, for application in niche areas of application, which are difficult or costly to fabricate using other techniques, tangible challenges have been met in areas such as reinforcement, structural performance and material integrity. Construction methods using this technique differ substantially from those of contemporary construction practice. Therefore novel strategies for addressing these and other issues have been created, with the development of new techniques and reinterpretation or adoption of techniques used in fields of construction, engineering and design.

Design for construction is another factor that must be taken into account when designing for construction 3D printing. In the case of the Roccia Assembly (case study 2) design for fabrication was a big issue that took a large amount of effort to design for and document to create the digital definition. When you create large buildings or assemblies that need to perform like conventional buildings (i.e. don't leak) and can be fabricated effectively (i.e. the parts don't break when you lift them) then these factors must be taken into account in the design and creation of the digital definition. Therefore an assumption that construction 3D printing will remove the complexities of design and construction can be considered incorrect.

As such construction 3D printing may not simplify construction or the documentation of projects for the three reasons listed above: the design must be completely defined prior to fabrication, the design should take account of construction and fabrication issues and (in my opinion) take advantage of the potential of construction 3D printing and the particular technique to be used.

7.10. Future direction of my research

As noted in the conclusion of the Case Study 3 (in)human habitat project I am now actively developing applications for reefs with Sustainable Oceans International as a result of the Open Agenda competition and subsequent exhibition. The first prototypes should be complete by the time that this exegesis is first read, with plans to install a number of prototype modules both in Bahrain and in Sydney waters.

I am due to start a new role in October 2011 at the completion of this PhD as Lead of Design Innovation with the Engineering Excellence Group in Sydney, an innovation lab for the international construction company Laing O'Rourke

I have to date taught three separate masters of architecture studios focused on design for construction 3D printing. The first two focused on tower design, which were taught at UTS Sydney 2008 and RMIT University in Melbourne 2009. The third studio taught at UTS in 2010 focused on the conversion of a decommissioned oil platform for the creation of an artificial island with multiple habitats both on the surface and underwater. I would expect to continue to develop studios related to the topics of construction 3D printing, digital design and digital fabrication techniques, design of habitats such as constructed reefs and teach as the opportunities arise.

I am also continuing to talk and work in close collaboration with the leaders in the field of Construction 3D printing and will be actively promoting and seeking opportunities to energise this emerging field.

7.11. Future research opportunities

This research is intended to form a foundation for a larger field that will likely grow up around construction 3D printing, design for construction 3D printing and engineering for construction 3D printing. It is expected that this new field and field of enquiry will grow significantly in the coming years as the capabilities of the existing machine increase and as new techniques are invented.

7.11.1. Construction 3D printing

The need for independent testing of materials is of vital importance to the acceptance of construction 3D printing as a viable option for the construction of buildings and other artefacts that are required to perform structurally and stand the test of time. As was demonstrated with the Villa Roccia assembly engineers had too little information on which to base there calculations and therefore could not have done engineering on the project had they been engaged to do so.

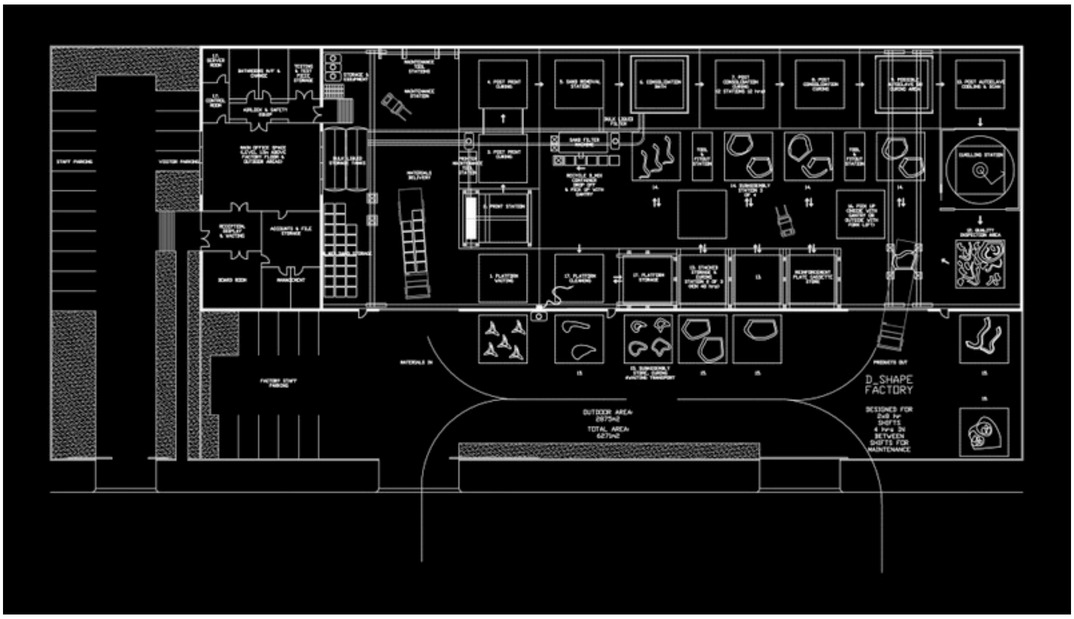

Figure 199 - Industrialisation of the D-Shape technique into a multi-station production line. Drawing by James Gardiner

One of the areas of particular interest to me is the industrialization of construction 3D printing. The reason for my initial interest in this field was as a technique that could unlock the potential of off-site construction. I have personally looked at the industrialisation of both the contour crafting and D-Shape™ techniques and developed strategies for their implementation within multi-station production lines. For the Contour Crafting™ technique this was quite speculative and done as part of the Freefab project (Case study 1). For D-Shape™ this was done as part of business plan development, I wanted to demonstrate how the D-Shape™ process could be industrialised

Analysis will need to be made, to substantiate claims about construction 3D printing techniques in terms of cost, time and quality. This will most likely only be possible once construction project(s) have been built or are commissioned, to quantify the competitiveness of construction 3D printing with alternative construction practices. This quantification will need to start by addressing issues of cost effectiveness/competitiveness, time required for fabrication and assembly and commissioning the building and quality.

Each of the construction 3D printing techniques use different materials and fabrication processes and thus each have different potentials, in terms of base technique performance and material output, related to sustainability, waste production and recycling. As the field of construction sustainability increases in importance and legislation in these areas increases, independent quantification will be required to establish the environmental credentials of these techniques.

Assessment of the barriers to the entry of Construction 3D printing to the construction sector is another area that will require consideration. Currently a large number of regulations and standards and other controls that govern construction practices throughout the developed world. These regulations include the specification of standards for the structural stability, quality, safety and longevity of materials amongst many other criteria. Individual construction 3D printing techniques will need to achieve certification or exemption from such regulations, as has been achieved for the Villa Roccia project in Sardinia under the auspices of testing and research and development. If the construction 3D printing techniques are to achieve broad application in the construction industry regulations and standards will either need to be met, exemptions granted or changed. Negotiating these legal requirements will be a significant future challenge for construction 3D printing techniques if they seek to compete with conventional construction techniques.

7.11.2. Architectural design & engineering

Peter Rice engineer for the Centre Pompidou, the Sydney Opera House, Lloyd's of London in discussing the distinction between architects and engineers stated in 1994 "*I would distinguish the difference between the engineer and the architect by saying the architect's response is primarily creative, whereas the engineer's is essentially inventive…*" (Jencks and Kropf, 2006) p260

Throughout this exegesis architecture and engineering have been considered together because, in many ways, design for construction 3D printing brings forth much greater opportunities for collaboration than are traditionally required in conventional construction design practice. This potential for collaboration is evidenced through the design of the projects Villa Roccia and (in)human habitat case study projects, which integrated structural engineering practices or both mechanical reinforcement and analysis/optimisation, both of which are normally the realm of engineers rather than architects. Far greater implementation and engagement with analysis, optimisation and responsive CAD tools would have been preferred on these projects and will be sought in future projects.

For engineers to be able to collaborate in the design of structures for construction 3D printing techniques their basic requirements including the quantification of material structural strength, durability and longevity will need to be met. Such quantification of construction 3D printing materials are, from my knowledge, just beginning to be done, for example with the informal testing by D-Shape™ and myself and formal testing for D-Shape™ through independent agencies. A similar series of tests, are likely, being conducted by the other groups engaged with the development of Contour Crafting™ and Concrete Printing™. Material properties such as acoustic absorbance and thermal conductivity will also need to be quantified if effective engineering is to be performed for future projects using construction 3D printing. This lack of quantitative data signals that there are significant challenges and opportunities ahead for engineers engaged with design and engineering for construction 3D printing. Close collaboration with architects has been demonstrated to result in increased richness of project outcomes (Holzer, 2009, Nicholas, 2008). My experience with collaborating with engineers in a variety of professional projects has been a very positive experience. Findings from the DDAA research interviews with professionals from the parallel industries show how much closer the collaboration can be between designers, engineers and fabricators. I believe, based on my experience with the case study projects presented, that with design for construction 3D printing the most successful outcomes will be the result of close collaboration between architects and engineers.

As was evidenced by the sub-chapters, on design for additive fabrication (3.2.1), design for construction 3D printing (3.2.3) and the case study chapters, there are significant opportunities for architects with design for additive fabrication. This emerging field, design for construction 3D printing, is completely open for the rethinking and re-conceptualisation of design. This research has considered only two narrow applications: single dwelling housing, multi-storey residential building design and constructed reefs. Further exploration could be made of design for construction 3D printing in the fields mentioned above, while other entire sectors such as commercial, retail, hospitality, medical, leisure, civil and defence sectors remain completely unexplored.

7.11.3. Software design

It has become apparent through the use of digital tools for the case study projects that there are opportunities for development of software tools that can do the following (or do them better than they do presently):

- Improve interoperability between digital design tools – the open source program developed by Arup Sydney Designlink™ tool.

Areas that I identify to be of particular importance in the near future are the development of multi-criteria optimisation techniques which can bring together the broad areas as mentioned above such as structural and material optimisation, thermal, natural and artificial lighting, ventilation, acoustics, structural performance through the macro and micro levels. This synthesis of monitoring and responding to variables and prerequisites within the design and construction process would help assist architects and consultants assess optimal or near optimal solutions and move the design process closer to truly informed decision making in the future.

7.11.4. Other fields

It has become apparent from the development of the (in)human habitat reef project that other fields outside of the construction industry could derive significant benefit through the adoption of construction 3D printing fabrication techniques and the potential to rethink design and fabrication of objects. I can't wait to start exploring such topics further and be an agent for change!

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