FREEFORM 3D PRINTING

A SUSTAINABLE, EFFICIENT CONSTRUCTION ALTERNATIVE

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A SUSTAINABLE, EFFICIENT CONSTRUCTION ALTERNATIVE

BY

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A 120-point thesis submitted
to the Victoria University
of Wellington in partial
fulfilment of the requirements
for the degree of Master of
Architecture (Professional)

Victoria University of Wellington
School of Architecture

2018

P R E F A C E

I have always been intrigued with the current state of the construction industry, with one of the most alarming statistics being that 50% of New Zealand's waste is comprised of construction waste. In 2017 I was awarded a scholarship to undergo research that involved investigated a new construction methodology called 3D freeform printing. This process included; an array of computation tools and methods, an ABB robotic arm, and an ambition to prove the effectiveness of a potential construction system that could mitigate this construction waste. The research has demonstrated great promise, hence my interest in continuing this study through a doctorate. Furthering to develop this concept of mass manufacturing and customisation through robotics could prove as an entirely viable solution to reduce future construction waste.

A B S T R A C T

Since the beginning of the 20th century, modernism introduced to the world an architectural composite that consists of concrete, steel and glass. Heading into the 21st century, the use of these three materials has only expanded as it continues to be the most economically efficient means of construction. While digital technology in design and construction continues to evolve, the materials at which we construct architecture has remained the same. Given the rapid growth of the human population, new and more sustainable approaches to construction methodologies and materials need to be explored and utilised.

This research will demonstrate the potential of freeform 3D printing as a sustainable and efficient alternative building method. It outlines contemporary digital design techniques including computation and simulation tools as a means to define and test this proposed building method including structural optimisation tools to create the most structurally efficient form from additive manufacturing. The computational methods described are then applied to a manufacturing process that includes a 6-axis robotic arm. The final result is a building methodology that supports a computational workflow from design conception to manufacture.

Keywords: Freeform 3D Printing, Mass Customisation, Structural Optimisation, Material Efficiency, Robotic

Contents

1	INTRODUCTION	1
1.1	ADDITIVE MANUFACTURING & FREEFORM PRINTING	2
1.2	NEW TOOLS OF CONSTRUCTION	3
1.3	METHODOLOGY	4
2	PRECEDENTS	6
2.1	BRANCH TECHNOLOGY	8
2.2	WORLD'S FIRST FREEFORM 3D-PRINTED HOUSE	9
2.3	AI BUILD	10
3	CHALLENGING CONVENTIONALISM	12
3.1	INTRODUCTION	14
3.2	TIMBER FRAMING	15
3.3	STEEL FRAMING	16
3.4	CONCRETE PANELS	17
3.5	REFLECTION	18
4	INDUSTRY PROBLEM & SOLUTION	20
4.1	CONSTRUCTION WASTE	22
4.2	WASTE MANAGEMENT	24
4.3	SYSTEM SOLUTION	26
4.3.1	CONSTRUCTION PROCESSES	27
4.3.2	PRE FABRICATION	28
4.3.3	ON-SITE FABRICATION	30
4.4	REFLECTION	32
4.5	MATERIAL SOLUTION	33
4.5.1	COMMON FILAMENTS	36
4.5.2	CHOSEN FILAMENT	37
4.6	REFLECTION	38

5	STRUCTURAL OPTIMISATION	40
5.1	APPLICABILITY	42
5.2	FORM FINDING & FINITE ELEMENT ANALYSIS	43
5.3	REFLECTION	52
6	COMPUTATIONAL APPROACH	54
6.1	GLOSSARY OF TOOLS	56
6.2	ROBOTIC CONTROL & PROGRAMMING	57
6.3	SIMPLE EXEMPLARS	58
6.4	COMPLEX EXEMPLARS	62
6.5	REFLECTION	66
6.5.1	REFLECTION CONT.	67
7	REAL-LIFE PRODUCTION	68
7.1	SMALL SCALE EXPERIMENTS	70
7.2	REFLECTION	78
7.3	MEDIUM SCALE EXPERIMENTS	84
7.4	LARGE SCALE EXPERIMENTS	98
8	FINAL SYSTEM METHODOLOGY	108
8.1	COMPUTATIONAL RESOLUTION	110
9	LOOKING FORWARD	126
9.1	ENVISIONED DEVELOPMENTS	128
9.2	CONCLUSION	129
10	REFERENCES & FIGURE LIST	130
10.1	REFERENCES	132
10.2	FIGURE LIST	134

How can **freeform 3D printing**,
combined with **structural optimisation** tools
provide a **sustainable and efficient** construction alternative?

INTRODUCTION

1

1.1

ADDITIVE MANUFACTURING & FREEFORM PRINTING

Additive manufacturing (AM) methods were first introduced in the 80's as a promising approach toward construction automation and fabrication (Oxman, 2013). Until now there has always been a certain degree of scepticism toward applying this technology to large-scale projects (Chalcraft, 2013). However, architects and engineers who have been researching this field for a number of years have gone from predicting that this may not be applicable for another 50 years, to now being convinced that this technology will very soon make the shift into the architectural realm (Krassenstein, 2015). AM differs from conventional processes such as subtractive processes (i.e., milling or drilling), formative processes (i.e., casting or forging), and joining processes (i.e., welding or fastening) (Conner, 2014).

Freeform 3D printing - a form of additive manufacturing - can offer a new form of construction that utilises contemporary digital technology to its fullest. AM traditionally involves manufacturing a part by depositing material layer-by-layer with support material, however, in this case, it would be used target by target. This method involves moving to targeted points in 3D space as opposed to layering, thus using significantly less material. Because the robot has six degrees of freedom, it is not limited to the typical layering system used in conventional 3D printing processes. This freedom, combined with a fast curing material, allows 3D prints to be made without support material as the material extruded from the robot becomes self-supporting.

The emphasis here is on the capability of the processes to fabricate complex geometric shapes. Sometimes the advantage of these technologies is described in terms of providing “complexity for free” (Gibson, 2010), implying that it doesn't matter what the shape of the input object is. A simple cube or cylinder would take as much time and effort to fabricate as a complex anatomical structure with the same enclosing volume. The reference to “Freeform” relates to the independence of form from the manufacturing process. This is very different from most conventional manufacturing processes that become much more involved as the geometric complexity increases (Gibson, 2010).

1.2

NEW TOOLS OF CONSTRUCTION

Robotic arms have been in industrial use since the 1970's. Designed to perform the same task over and over with precision, they have become the tool of choice for most systems of automation. While initially complicated and time-consuming to program for a single task, recent advancements in software development have made this a fairly simple task. Because of this, the industrial robotic arm is now capable of running bespoke programmes with very little effort.

The robot arm operates around 6 axes, which is what gives it its advantage over more typical 3D printers and CNC machines. This is what provides the most potential for freeform printing as it can reach any nearly any point in space with immense precision. With a customised extruder attachment, the potential of freeform 3D printing sees its full potential. The spatial precision of the robot arm combined with the flexibility of the extruder creates endless possibilities to what can be output in the 3D space surrounding the robot.

Robot arms have the opportunity to become an industrialised construction tool, which would give companies and governments more incentive to adopt such a technology if made more affordable and readily available.

1.3

METHODOLOGY

This research proposal follows a design-led research method, using an incremental process of modelling and testing of freeform 3D printable building elements that will be scripted, allowing structurally optimised outputs to be simulated before printing. The reason for using this approach is the project requires a degree of risk-taking in order to develop and experiment with new building methodologies. For example, in the simulation of the printing toolpath, the line segments need to be perfectly straight, and all the nodes need to connect. The goal of the physical model is to achieve these criteria with precision and with as minimal errors as possible. However, through failure, the system must account for constraints evident in the real world i.e. gravity and the physical properties of the filament. Through an ongoing process of evaluation, redevelopment of the workflow will be required. This will follow an iterative process, where schemes will be tested and re-configured based on developments from previous iterations.

The research utilises the advanced digital fabrication technologies available at the Te Aro Campus of Victoria University of Wellington. An ABB 6-axis robot arm is the primary tool that is used with an extruder head attachment, which generates the freeform plastic geometries. This was created in collaboration with an industrial design master student, Liam Gilbertson, whom I intend to continue to work with to further advance the manufacturing capabilities of this freeform 3D printing process. What controls these technologies is the computational logic that is generated through programs such as Rhino (3D modelling software), Grasshopper (parametric modelling software) and Millipede (structural optimisation software). However, to develop this technology even further, more advanced coding programs need to be investigated, such as Python or other native coding that will allow more complex algorithms to be developed. During this entire testing process, a lot of waste filament is produced, which can be reused by shredding the plastic into reusable filament with a piece of machinery available at Te Aro.

The following page illustrates the research process.

BRANCH TECHNOLOGY

Branch Technology is a company that is aiming to redefine the way we construct buildings by combining freeform 3D printing with conventional construction materials. Branch is an important precedent for this thesis work, as it is a successful and well-established company in this research. The structures they are creating are achieved by using a process called cellular fabrication which utilises a form of biomimicry. This creates a 'matrix' structure with this freeform 3D printing method, and the void space is then filled with secondary support in the form of concrete, foam etc (fig 2.02). While the biomimic studies they undergo does contribute to a large majority of the structure's strength, there is also plastic filament itself, which is a carbon fibre coated ABS filament. The combination of these two factors creates a structure that is able to support well beyond its own weight. To complete the aesthetic of a wall, commonly utilised lining materials such as internal lining and weatherboards can then be applied to the interior and exterior of the wall (Boyd, 2016).

Michael Molitch-Hou. 2015.
Branch Technology Matrix. 2.01.

Branch uses biomimicry because nature is one of the best informants on structurally sound forms. Hence the term 'cellular fabrication', as they primarily look at cell structures to inform the structural composition of their designs. Their concluded freeform construct was cuboid or pyramid spaceframe geometries (fig 2.01). In acknowledging Branch's success with this approach, it was logical to use this scheme as a starting point for how this research will initiate its own experimentation. Alterations and improvements could then be added as necessary to cater to the specific requirements of this research i.e. the structural optimisation.

This method provides an initial concept of what a structurally sound freeform matrix should be based upon their biomimic studies. But what Branch hasn't done is create a logic which can analyse the structural integrity of that matrix when introducing variable external conditions. The research will aim to create a structural optimisation system that can customise the initial matrix based upon structural feedback. Future material studies will be necessary to conclude the most viable filament to use for this system.

Michael Molitch-Hou. 2015.
Branch Technology Matrix. 2.02.

WORLD'S FIRST FREEFORM
3D-PRINTED HOUSE

This is the world's first 3D freeform printed structure (fig 2.03). The design was created by London architecture firm WATG, and Branch Technology has been challenged to create the structure entirely from freeform 3D printed plastic. 3D printed buildings have been constructed before, however, this will be the first done through a freeform method.

To assemble the structure, 28 panels will be 3D-printed off-site, they'll then be joined together on-site to create two exterior walls, the roof and the interior core. To ensure these components can support the required loads, test beams and partial wall sections will be printed. For example, a 1m long beam could carry a load of approximately 1,360kg while only weighing 2.3kg. The freeform printed matrix is a small space frame, making it highly efficient. To clad this space frame matrix, WATG and Branch Technology are researching a variety of gypsum material components that could be applied on the printed structure as fire protection, structural reinforcement and to create a substrate for the application of finished wall materials (Collins, 2018).

Tim Collins. 2018.
World's First Freeform 3D Printed House Exterior. 2.03.

This project acts as a milestone that this thesis has the potential to reach; to be able to create a full-scale building or building component with the use of freeform 3D printing to fabricate the structural framework. WATG and Branch are investigating ways to install a passive mechanical system to make the home net-zero-energy. The aim is that the house will produce as much energy as it consumes, reducing its carbon footprint. This integration of high-performance mechanics, electronics and plumbing is an inevitable next step for this research, as they will be integral if this system is to be applied to full-scale buildings (Collins, 2018).

Also with the design freedom of freeform printing combined with mass customisation, ergonomic design is more easily achieved. The curved and streamlined shape of this scheme will allow for a more natural interaction with environmental conditions. For example, if exposed to high wind zones, the wind can more naturally be manipulated around and through the design (fig 2.04). Whereas with conventional timber and steel homes, the only viable solution is to increase structural member sizes to endure such winds.

Tim Collins. 2018.
World's First Freeform 3D Printed House Interior. 2.04.

AI BUILD

Ai Build is a London based company developing Artificial Intelligence and Robotic technologies for large-scale additive manufacturing. Their Autonomous Large Scale 3D Printing Technology is available for a broad range of applications, such as construction, high-performance products, custom moulds, interior finishes and furniture (fig 2.06). They have a business philosophy that additive manufacturing is the core technology for achieving a sustainable environment and a highly efficient on-demand economy. Their goal is to empower factories of the future to make manufacturing easy, smart, sustainable and affordable (Ai Build, 2016). Ai Build aims to develop the goal of toolpath refinement, as their full attention is committed to refining their own software for optimising their toolpath. These developments have allowed them to create the extremely complex and abstract forms illustrated in projects such as the Daedalus Pavilion (fig. 2.05). Ai Build's innovative and novel program software applications eliminates all limitations; thus their production capability is drastically broadened.

Ai Build. 2016.
Daedalus Pavilion. 2.05.

Throughout this body of work, Grasshopper was the main computational tool used. The main limitation of Grasshopper is that it's more difficult to produce highly complex code as it has a default layout that has pre-defined inputs that must be worked around to create the desired result. However, to surpass the likes of Ai Build, pure coding programs such as Python will need to be investigated, hopefully while furthering the work established in this master thesis. In Comparison with Branch, Ai Build is the most relatable to this thesis' research approach. Branch is investigating how freeform printing can become accentuated by other materials, thus creating a hybrid system. The downfall to this strategy is their reliance on old construction properties. For example, they will create a lattice structure made from plastic, and combine this with spray foam or concrete to enhance is the compressive strength. Whereas my research in this thesis is in relying primarily on the toolpath optimisation as the main source of structural cohesion, as is with Ai Build's research. Despite this, researching hybrid systems is still important, and is an aspect I wish to investigate in the future.

Ai Build. 2016.
Wall Prototype. 2.06.

Jordan Loa. 2016.
Lightbulb. 2.07.

Jordan Loa. 2016.
Lightbulb. 2.07.

Jordan Loa. 2016.
Lightbulb. 2.07.

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“Combining freeform 3D printing with conventional construction materials.”

- R.Platt Boyd IV -
Founder / CEO

“Our technology embeds sensors and cameras in the printing head so the robot can learn from its mistakes and correct itself on the fly.”

- Daghan Cam -
Founder / CEO

Combining freeform 3D printing with a structural optimisation system.

CHALLENGING CONVENTIONALISM

3

3.1

INTRODUCTION

The purpose of this section is to identify the flaws with current construction methods, and why new construction technologies need to be explored to mitigate the ongoing issues attributed to these more traditional construction methods: high expenses, construction waste, safety and health hazards, structural form variety limitations, inability for mass customisation.

3.2

TIMBER FRAMING

In 2000, 'leaky house syndrome' was exposed in the New Zealand press as over 15,000 homes were believed to be affected by aggregate repair bills estimated at over \$1 billion. By December 2006, this had increased to between \$5 and \$10 billion. Many of the homes built in New Zealand during the late 1990s were showing signs of decay in the timber framing due to water ingress raising moisture contents. These houses will typically have claddings and building wraps that are subject to high moisture retention. The walls are highly insulated which restricts air flow. (Clifton, 2015). This put the structural integrity of the buildings at risk and also provided a breeding ground for *Stachybotrys* whose spores could affect the health of the inhabitants (SCION, 2007).

Timber framing was New Zealand's predominant structural material, although due to the stated issues, timber framing has lost more than 10% of its market share during this decade. In 2002 it accounted for 98.1% of the framing market while in 2012 it decreased to 87.8%. Despite this decrease, timber framing evidently still holds the majority of the market, as timber framing still holds some advantageous benefits: more environmentally friendly, superior thermal insulation, natural electrical insulator, ease of use building with timber (Burgess, 2013).

Although, these benefits mean significantly less if the building is deemed 'leaky'. The main reason these buildings failed was due to poor design and construction, thus allowing water to seep into the wall cavities. Since the exposure of leaky homes, the industry has since enhanced the way it treats and grades timber for strength leading to a far better product.

Despite these efforts to improve the quality of timber framing, in many ways the damage has already been done. Many New Zealand homeowners have become wary of the risk of having a leaky building that is attributed to timber framing, thus they are beginning to look elsewhere (Burgess, 2013).

3.3

STEEL FRAMING

Steel framing has been the dominant option for commercial construction, however, it is beginning to demonstrate its viability in the residential realm also. It has seen a considerable rise in usage over the past decade. It has risen from just 1% of framing market shares in 2008, to 8% in 2013. Master Builders Federation of New Zealand chief executive Warwick Quinn estimated about 5% of the 20,000 new houses built in 2013 would utilise steel framing. The primary benefits of steel are: it does not warp/twist/absorb moisture, its fire resistant (timber is not), seismically safe, not treated (won't release any chemicals), approximately 1/3 the weight of timber, a lot faster to erect (Burgess, 2013).

Many claim steel framing to be the best current solution to leaky buildings and chemical issues, and in many ways this is true. However, it still has disadvantages: it can rust if left wet even if coated, it conducts heat opposed to insulating which can cause condensation (requires thermal breaks), will buckle and twist in a fire, and has poor sound insulation (McDonald, 2010).

Steel framing is one construction method that is attempting to counter the 'leaky home syndrome' crisis. Despite it only attaining to a very small majority of the framing market shares, it is on the rise and is continuing to prove its efficiency in the residential realm.

3.4

CONCRETE PANELS

The introduction of precast concrete panels is a fairly new residential construction method. Its most prominent feature is that it can be attributed to industrialisation, and mass manufacturing. Being an industrialised process, the standardisation of the elements is an important characteristic. This standardisation guarantees the reuse of metallic forms, a greater control in the consumption of materials and in the facility to anticipate openings or installations.

Because this method is a form of industrialising construction components, it has many benefits. The project duration is reduced because the fabrication of the components can be planned as the work progresses.

The services of frames, carpentry and facilities are minimised, and the primary means of erecting the panels can be done with a crane. Combining these factors reduces the need for hands-on manual labour (LoreCentral, 2018).

The main drawback of this method is its limitations in relation to possible architectural form. Different companies will manufacture different wall types that a client can choose from. However, this is not to be mistaken by having different wall forms to choose from i.e. curved precast concrete walls or other one-off forms. The selection range typically remains as planar constructs. The differences between different manufacture options are typically only by the material's aesthetic, strength and insulation qualities. Changing a layout of a pre-moulded home is also more complicated. Renovations or extensions should be planned and well-studied, as it's difficult to make modifications once a section is complete. For example, to break a wall to create a wall or window in an attempt to enhance the environment (LoreCentral, 2018).

3.5

REFLECTION

These construction methods have proved effective enough for the duration of the 20th and 21st centuries, however, in most cases, their negative attributes outweigh their positives. The primary issue is that they produce excessive construction waste. Some are more sustainable than others, for example, concrete panels can economically be crushed and turned into more panels. However, with timber and steel, the economic hardship that is undergone to recycle timbers is not worth it to most companies, thus the landfill/clean fill is generally the most viable option. However, this nation simply cannot afford to create any more construction waste. New Zealand cannot continue to sustain this, and if these current construction methods continue to be used, the environment will continue to suffer the consequences. It is imperative that zero waste construction methods are investigated not only nationally, but globally, if construction waste is to be reduced.

These traditional methods are more difficult to tie to parametric processes for design and manufacturing. They are very limited in the shapes and forms that they can achieve. It is, of course, possible to create abstract curvatures etc. with specifically engineered steelwork. Zaha Hadid and Frank Gehry are famous for achieving this with their work. However, this sort of design is very rare in the residential sector, as homeowners want quick, cheap, well insulated, weather-tight homes. All of these factors are difficult to achieve if attempting to add a parametric design quality to a timber, steel or concrete home.

With the inclusion of time and construction expertise, freeform 3D printing, combined with structural optimisation software and mass customisation, has the potential to eliminate these constraints.

INDUSTRY PROBLEM & SOLUTION

4

4.1

CONSTRUCTION WASTE

Building methodologies need to be updated to take advantage of contemporary processes we have for creating the built environment. Advancement in computational and manufacturing techniques, as well as material science have provided the methods necessary to reconceive how we build.

Waste is generated on building sites during each phase of the building lifecycle. Evidence suggests that construction and demolition (C&D) waste may represent up to 50% of all waste taken to landfills in New Zealand and the majority of waste taken to clean fills or C&D dumps. That means that up to 1.7 million tonnes of C&D waste is sent to landfills and 3.4 million to clean fills every year. Products end up as waste during construction through offcuts, mistakes, temporary works, poor workmanship, inefficient installation or use or because of damage. During demolition, products become waste when they cannot be salvaged efficiently or cannot be recycled or reused. This is filling up the valuable landfill and clean fill space and contributing to serious environmental problems such as air and water pollution (REBRI, 2014).

In the United States, in 2014 alone, there were 534 million tonnes of construction and demolition waste generated – more than twice the municipal solid waste. This amount of global waste is unnecessary, unsustainable and can be prevented. Given the extensive amount of waste generated by the building industry, an efficient alternative to typical construction methods is required. A potential solution defined in this research is a newly defined building methodology that incorporates several approaches to reduce waste. Together these individual approaches could have a profound impact on the amount of construction waste produced globally and significantly change how buildings are produced (EPA, 2016).

A current example of this impending crisis is the fact that from January 1st, 2018, China has administered an environmental act that has forbade the importation of 24 different kinds of solid waste. In more pressing terms, this means “\$21 million worth of New Zealand waste a year” (Hunt, 2018) must find somewhere else to go (Hunt, 2018).

4.2

WASTE
MANAGEMENT

The most common means of managing waste is landfills and this is because it is the easiest and cheapest solution. The two most important issues with landfills in relation to construction waste are toxins and leachate. If New Zealand's construction waste contributes to 50% of this issue, we have an opportunity to eliminate this 50%, and thus its toxins and leachate within it (Bausback, 2016).

Toxins:
An immense amount of materials that are disposed within landfills contain toxins that eventually release and seep into the groundwater and soil. Items such as paints, treated timbers, PVC plastics, asbestos, fibreglass etc. all contain extremely toxic chemicals (Bausback, 2016).

Leachates:
Leachate is a type of liquid that is created when water filters through toxic materials. Hence whenever it rains, the rate at which leachate is produced is increased. If left untreated it can and will continue to pollute both the earth and oceans (Bausback, 2016).

The primary issue with this is that it is extremely difficult to control, manage, and treat. The current process of treatment is as follows; leachate drains to the management system, where it is transferred to a central collection pump and piped to an on-site holding pond. If necessary, the leachate is transported to an approved offsite wastewater treatment plant for disposal. This system does prove effective, but only to a certain extent. Its downfall is that it is impossible to ensure 100% of the leachate is collected. Considerable amounts still seep into the surrounding earth, thus causing unwanted environmental harm (Sherlock, 2010).

THE MODERN LANDFILL

In addition, landfills require large amounts of land space – hundreds of thousands of acres in New Zealand and millions worldwide. There are 50 landfills across New Zealand alone. When landfills reach their capacity, there are but two options: one, make them bigger, or two, simply build more. Unfortunately, all landfills will eventually reach their capacity, and when they do, they don't disappear; they remain full of our waste. Hence it is imperative alternative waste reduction methods are investigated. In order to avoid resorting to these two options, there is another option that should be the point of interest; how can we reduce this 50% construction waste contribution to 0%? (Sherlock, 2010).

A.P. 2018.
Landfill. 4.02.

- 1 Plastic Liner
- 2 Cap System
- 3 Refuse
- 4 Bentonite Clay Beneath Plastic Liner
- 5 Leachate Management System

4.3

SYSTEM SOLUTION

This research proposal is defined by two key factors; automation and industrialisation that produces a mass-customisable building system that is sustainable and innovative.

The research focus is on an automated, customised means of production that will create an output that is directly linked to structurally optimised data. The process itself creates a form of industrialisation where robots will be used to build the structural foundation of any building. The primary considerations of this system are the potential to improve cost-efficiency, enhance the lifecycle value of the project, and enable interoperability among a project's lifecycle entities. Accordingly, technology integration, analytical modelling and simulation and distributed intelligence, offers immense opportunity to create an integrated and automated design environment. It will reduce errors through automated structural optimisation and verification (Neelamkavil, 2009).

These factors together create an innovative building technology – one that is being researched in only a few places globally. With this, New Zealand has the potential to be a global leader in producing construction alternatives as well as an alternative to reduce New Zealand's construction waste from 50% to 0%.

4.3.1

CONSTRUCTION PROCESSES

The primary benefit of this system is the exactitude of material placement only where needed and the ability of the process to run continuously, safely and precisely. Through the benefit of the structural optimisation component of this research, the material will only be placed where it is needed to support the required structural loads. The goal of this is to minimise the need for excessive and unnecessary material where it is not needed - either through the building process or excess material such as off-cuts. The wasted support material is a primary issue with traditional 3D printing technologies that use a layering technology. Not only does this immensely increase print time, but it produces unnecessary structural support that gets discarded. With a structurally optimised printing toolpath, a freeform structure can easily be created that possesses similar, if not improved structural qualities to a traditional structural system.

The construction process becomes automated with the introduction of a robot, and the requirement for manual labour is minimised. The high cost associated with labour would be reduced by approximately 30%. Health and safety issues that are commonly attributed to manual labour accidents are also eliminated. Scaffolding and manually operated heavy machinery would all be minimised, if not made redundant. A new skilled workforce would be created adding value to the construction system (Bock, 2014).

4.3.2

PRE FABRICATION

Prefabrication is a promising option for the proposed building methodology, and there are three primary benefits attributed to its incorporation.

Firstly, the system combines highly customisable design through parametric modelling, allowing high levels of mass manufacturing and customisation that is available for the user and client.

Secondly, with the use of modelling tools and simulation, the constructability aspects can be verified prior to being built, and an optimum construction plan can be derived.

Thirdly, is the ability to produce all of the components within a controlled environment. The structurally optimised material can be applied, tight tolerances achieved, all while the built products are not affected by outside climatic conditions, as is the case for site-built housing. Also it is envisioned that these components would possess the ability to be designed to respond to the climate conditions of that particular site more efficiently compared to traditional construction methods. For example if a site experiences high winds, the design would be parametrically customised to endure high wind zones.

An example of a potential building system would be to have robot arms producing multiple building components such as walls, columns, beams or floors off site, that are then delivered to the construction site to be assembled (fig 4.03). Production efficiency would be much higher in relation to onsite production, as being in a controlled environment means that there will be no requirement for constantly adapting to its surrounding conditions. Hence the robots will only require a single logic for identifying where and how to produce a structural form (Neelamkavil, 2009).

A.P. 2018.
Pre-fabrication. 4.03.

4.3.3

ON-SITE FABRICATION

Another example of an innovative building technology using this system would be to produce the components on site (fig 4.04). An automated, on site construction methodology can face many risks: technological, economic or a safety. An example of a safety hazard is that the robot must cope with the complexity of the construction process involving a dynamic and evolving site. The unpredictability of climate conditions is one such barrier, as the production will not be within a controlled environment i.e. the ground conditions may be uneven, thus deeming it unsafe. For example, it may begin to unexpectedly rain, which could cause the robots to malfunction if water damaged. Numerous precautions would need to be put in place to mitigate issues such as this. An example of a technological barrier is that the robotic logic will require the need for performing multiple tasks with differing characteristics (Neelamkavil, 2009). For example, the toolpath at which the robot prints will have to consider different terrain conditions. Or if other robots are in use, they must be aware of what robots or people are where in relation to themselves, and what aspects of the building each robot in producing. And in order to carry out all of these tasks the robots would require the use of tracks and wheels of some description to provide it with full mobility. The issue with this method is that it would require a high degree of artificial intelligence to be deemed fully operational and safe. Technology this advanced is extremely difficult to achieve and we are far from achieving it. However the system proposed in this research can happen now.

Given that these issues could be controlled and treated, this option becomes viable, and in some ways more beneficial than prefabrication. This would allow the continuous printing of a building, thus eliminating the need for prefabricated modules. Increasing the number of robots being employed could also ensure the efficacy of a project. The fabrication time would also be drastically reduced, two or more robots could be utilised in such a way that would allow the fabrication of more complex geometries that would prove less achievable with a single robot.

A.P. 2018.
Onsite-fabrication. 4.04.

4.4

REFLECTION

In summation, both methods have their evident advantages and disadvantages to counter each other. Following are some key comparative aspects drawn from the previous pre-fab and on-site analysis:

Quality Control:

Pre-fabrication has the advantage due to a number of factors. Firstly, because the work is produced in a factory, ideal conditions and exacting precision can be maintained throughout the process.

With on-site production, the process is subject to all environmental conditions that become apparent on that day. Hence unnecessary supervision would be required to avoid errors. The result would be an inferior construct even if it were completed in the ideal weather conditions (Jones, 2014).

Labour Efficiency:

Prefabrication is the much more labour efficient option. Because the work is done within a factory environment, the work has the potential to be maximised through the robotic machinery at hand that will likely become much less effective on-site. Hence work that could have been done through machinery, may have to be conducted through manual labour. The main disadvantage to this is that labour and production cost will rise (Jones, 2014).

Full Strength:

Depending on the filament being used, it will require a certain amount of time for it to fully harden and be at its maximum strength. Either way, prefabrication is again the most efficient option. Before they can be erected, the supervisors would have to ensure they're at full strength. This puts the process at risk of again, increasing cost and delaying construction. It is a much more time and cost-efficient option to ensure the structural components are fully hardened before they're transported to site (Jones, 2014).

4.5

MATERIAL
SOLUTION

The market for the filament, the majority of which is made from virgin plastic, is growing rapidly. A report by a leading markets analyst predicted that the 3D printing materials market would grow by approximately 266% over the next five years, to be worth 2 billion dollars by 2021.

However, in its current state, it is viewed as too expensive due to production and export costs. Hence filament produced from recycled plastics will be cheaper than buying commercial filament because waste plastic is a free resource. This is a solution that is aimed to make this system more accessible to the industry (Paddison, 2016).

Plastic shredders provide a mechanism for using recycled plastics; these machines are specifically designed for the reuse of waste plastics. Te Aro campus of the Victoria University of Wellington possesses a plastic recycling system, thus all of the experimental waste that has been produced over the year of this thesis research will be sent through this machine to create usable filament for future use. These machines will accept any recyclable plastics, grind it into digestible pieces, melt it, extrude it, and winds it into a previously used spool.

The only drawbacks to recycling plastics are that it gets progressively weaker every time this system is utilised (Harding, 2016).

RECYCLING PROCESS

LIKELINESS TO BE RECYCLED

#1 PET (Polyethylene Terephthalate)

#2 HPDE (High-Density Polyethylene)

#3 PVC (Polyvinyl Chloride)

#4 LDPE (Low-Density Polyethylene)

#5 PP (Polypropylene)

AVAILABILITY OF RESOURCE

4.5.1

COMMON FILAMENTS

There are three filament types that are most commonly used with 3D printing. These include:

- Polylactic Acid (PLA). This is the most common of the three filaments. PLA is made from renewable, organic resources like corn starch or sugarcane. Its most common use is for the production of food packaging and biodegradable medical devices and implants.

- Acrylonitrile butadiene styrene (ABS). This filament is cost-effective and flexible. However, because it's petroleum-based and not biodegradable, ABS is losing popularity in comparison with the stronger, more eco-friendly PLA plastic.

- Polyvinyl Alcohol Plastic (PVA). This filament isn't typically used for creating the finished product, but instead to create a support structure for portions of a product that may warp or collapse during the printing process. One extruder can be used to create a support structure of PVA while other extruders work to create the finished form out of other materials (Polymer Solutions, 2016).

4.5.2

CHOSEN FILAMENT

In testing these filaments, they proved ineffective in meeting the structural requirements that would be required for architecturally applicable forms. Some of the main issues are:

- These filaments don't come in large enough diameters, thus they cannot possess the required compressive strength for architectural application; subject to bending, snapping etc.
- They don't adhere to themselves or the substrate. This is a key factor for the creation of freeform structures, as the nodes at which the plastic sticks to itself is the only form distributing force.

Further investigation of filaments occurred, and a product called Pro HT from BigRep (a much stronger type of PLA) was deemed as the most efficient option to use for the remainder of the research. A few of its most desirable qualities are:

- It's a non-toxic alternative to conventional filaments solutions.
- It possesses excellent adhesion to itself and the print bed, as well as minimal shrinking and warpage factor.
- And most importantly, its high heat-resistance, UV and weather resistance, and extremely high strength properties (BigRep, 2013).

4.6

REFLECTION

Pro HT was the filament of choice for this research due to its high strength, ease of extrusion and ability to be shredded and recycled for future use. However, there is still great opportunity to investigate other options that possess greater strength, flexibility and sustainability traits. For example it may prove viable to investigate options that aligns more with the structural qualities of Branch Technology's carbon fibre coated filament. At the beginning of the research I was in discussions with Scion about experiments with bio-polymers. This advantage of this would be that the scientists creating them would be able to manufacture the filament for the specific purpose of construction components. One example given was to implement fibres within the filament to provide strength in tension as well as compression. This is research I wish to investigate in future work.

5.1

APPLICABILITY

Structural optimisation is a key component of a new efficient building methodology. Without it, there will be a tendency to use the AM process to reproduce methods that are currently used for building. The optimisation processes offer another level of efficiency and waste control by dictating exactly where the material is required for performative reasons over aesthetic or conventional choices. Combined with AM, the material will be deposited where it is performativity required. In the case of using filament as a building material, lightweight structures will be considered.

A lightweight structure is defined by the optimal use of material to carry external loads or pre-stress. The material is used optimally within a structural member if the member is subjected to membrane forces rather than bending. The objective of an optimisation procedure is to determine the layout and shape of a lightweight structure, therefore, minimising bending, or minimising the strain energy rather than structural weight as the term 'lightweight' may imply. This notion is extremely applicable in this case, as plastic structures are arguably the most lightweight structures available to the construction market today. (Bletzinger, 2001).

5.2

FORM FINDING & FINITE ELEMENT ANALYSIS

For this section, I will be investigating two structural optimisation strategies, of which are all achieved through Millipede (structural optimisation software):

Form Finding:

The benefit of form finding is to computationally determine the most structurally efficient natural form to use for the entirety of a building/building component. All that is required is a form to be analysed, a series of force and supporting geometries which can vary in size and quantity, and a structurally optimised form will be generated based on those parameters (Bletzinger, 2001). For this research, a geometry is placed into the 3D modelling program, a series of load forces and supports are applied to said geometry, and an optimised form is produced based upon the shape of the initial geometry and the relative positioning of the loads and supports.

Finite Element Analysis:

The toolpath is then inserted within the optimised form to produce an initial freeform matrix. Finite element analysis is applied to the optimised form which determines the geometric and material behaviour information that indicates the resistance of the element to deformation when subjected to loading. A uniform force is applied across the top of the form, and structural feedback is produced that visualises deformation effects, such as, axial, bending, shear, and torsional. FEA is important because it enables the structural analysis of complicated geometries, loadings and material properties that are to be investigated throughout this research (Modlen, 2010).

01

Form Finding Analysis

FF Test 1 (fig 5.04) uses fixed supports, a geometry to be optimised and a gravity force. With the adjustment of a slider, the visualisation of the form's structural optimisation becomes evident in the images 01, 02, 03. With the force in the centre of the two supports, the two members on either side are the same size. However if the force shifts to either side, the corresponding member thickens to support the force.

STRUCTURAL
OPTIMISATION
01

STRUCTURAL
OPTIMISATION
02

STRUCTURAL
OPTIMISATION
03

FORCE SHIFT
LEFT
04

FORCE SHIFT
RIGHT
05

A.P. 2017.
FF Test 1. 5.01.

01a Cube

STRUCTURAL
OPTIMISATION
01

STRUCTURAL
OPTIMISATION
02

STRUCTURAL
OPTIMISATION
03

A.P. 2017.
FF Test 2. 5.02.

01b Cube

STRUCTURAL
OPTIMISATION
01

STRUCTURAL
OPTIMISATION
02

STRUCTURAL
OPTIMISATION
03

A.P. 2017.
FF Test 2. 5.03.

The following shows an example of how force and support application can be applied to a cuboid form. 01c (fig 5.03) is an extension of 01b (fig 5.02) as one face of the form has been extruded to create the cuboid. The result is a much different optimised structure. A more arched form is created which extends the length of the cuboid. 01d (fig 5.04) is an entirely different experiment to conclude a result with a uniform support and two force points at two different corners of the cuboid. The result is a sheltered form with two curved column structures.

02

FA Test 1 (fig 5.05) enables the simulation of maximum deflection for any specified lattice structure. In this case it is the desired form of the space frame. The experiment analyses a space frame system with two fixed supports at either end of the geometry. The following illustrations convey what would become of the form with an applied force to its centre. As shown, the most stress occurs at the supports at each end, and in the centre where the force is being applied.

- SUPPORTS
- LOW STRESS
- HIGH STRESS

FA Test 2 (fig 5.06) sees the addition of a mirrored extra layer. These changes moves the majority of the load to this top layer and gradually into the anchor points. The issue that remains here is that there is unwanted bending in the centre of the matrix. Solutions will be explored in following tests.

02a

w/o Horizontal Members

02b

w/ Horizontal Members

In attempt to mitigate the bending that occurred in the centre of the previous matrix form, horizontal members have been added (fig 5.07). These members have added much greater rigidity to the matrix. While there is still evident sagging, the amount that occurs will be dependent on the strength and thickness of the filament being used.

A.P. 2017.
FA Test 3. 5.07.

5.3

REFLECTION

The purpose of the previous tests are to simulate a foundation of how to use the form finding and finite element analysis components available in Millipede. Form finding has acted as a design tool, in that it aids in producing an optimised overall form for a given condition. For the form finding testing, simple experimentation occurred that determined how the program reacted to different variations of load and support placement. For example, various force and support geometries were added to the same initial diagram (a cube), however, eventually the output become relatively predictable; support members would appear between the force and support geometry. The next studies introduced a single uniform force/support that covers the entirety of either the top or bottom of the cube. This generated a much more unique output as it wasn't was not something that could be predicted as easily.

Initially, it was envisioned that this method of form finding would repeated throughout the physical experimentation phase of the research, particularly with the medium – large scale models. However, as the research arrived at the larger scaled designs, this method gradually moved into redundancy. It became apparent that the inclusion of this method disabled the user's creative ability. Ultimately, it proved more efficient to enable the user full control over the initial design phase, as this is how it would be in practice when approached by a client.

Finite element analysis would then be implemented upon concluding the initially designed form by the user. Finite element analyses the axial, shear, bending and torsional effects acting upon the spaceframe members that are inserted within the resulted form. Simple spaceframe geometries were analysed through the Millipede system to determine how the program would respond to different segment arrangements. For example, with or without the inclusion of horizontal members, where the most load occurs through the various line segments, and where it is necessary to densify the segments to provide greater strength, or lessen to avoid consuming inordinate amounts of filament.

In conclusion, this sytem was deemed as the most effective, as it enables design freedom in the initial design phases, and provides structural feedback to enable informed revisions upon the initial design.

COMBINED SOLUTION

COMPUTATIONAL APPROACH

6

6.1

GLOSSARY OF TOOLS

Rhinoceros – 3D Modelling Software

The initially designed form is created in this program, and can be manipulated at will.

Grasshopper – Algorithmic Modelling Software (Rhino Plug-in)

This is where the coding logic is created that allows for the parametric control over the printing toolpath, the structural optimisation parameters, and how robot arm is to operate.

Millipede – Structural Optimisation Software (Grasshopper Plug-in)

This is what produces the structural optimisation feedback in the form of form finding and finite element analysis.

HAL Robotics – Enables Full Robotic Control (Grasshopper Plug-in)

This is what enables full control over the robot arm i.e. its speed, plane reorientation, identifying where the extruder is to print in relation to the substrate etc.

6.2

ROBOTIC CONTROL & PROGRAMMING

The industrial robotic arm is an extremely valuable tool when combined with mass customisation and structural optimisation software and one that is ideal for the freeform printing process. It is easily programmable, quickly re-programmable and extremely flexible with its six degrees of freedom. Parametric software such as Grasshopper and its plugins have provided a previously unseen accessibility to a complex tool. Combined with the customisation of the end effector – the tool at the end of the robot – and the environment in which it interacts, complex fabrication methodologies can be developed. In general, there are two areas of knowledge that need to be considered in the use of the robotic arm, two of which will be discussed in detail related to freeform printing.

1. Robot control and programming.
2. End-effector: tool design and integration with the robot.

The ability to control a complex CNC machine, such as an industrial robotic arm has been facilitated and simplified by advances made in software interfaces with commonly used 3D modelling programs. A machine once programmed to repeat the same task over and over can now be programmed to produce one-off tasks utilising parametric applications – a change in a design parameter will instantly generate a unique programme for the robot. The research in this paper took advantage of these advancements and utilised HAL Robotics, a plugin for the parametric plugin Grasshopper for Rhino.

The process of learning Grasshopper and HAL Robotics first began with learning the required data inputs for Grasshopper that would allow the creation of a toolpath for the robot to follow. The mastering of this process utilised HAL to produce a series of light drawings.

6.3

SIMPLE EXEMPLARS

This section marks the beginning of my computational experiments. It consists of using Grasshopper to experiment with a range of simple geometric forms. The script used to create each form is then transferred through the data collection process that is available through the HAL robotics software. The Grasshopper code is then translated into the robot arm, which produces a series of light drawings in 3D space with an LED head. A camera is set up with the shutter open to allow the camera to capture the light in one single long exposure image from start to finish.

Conducting these experiments was crucial to learning this technology, as it allowed me to progressively develop my knowledge of how to manipulate the data that is input into HAL, as well as create more complicated forms. In doing so I became proficient enough to operate the material extruder, in that I acquired the knowledge to efficiently and safely conduct the required experiments and tests to produce structurally optimised forms.

The 'Simple Cube' test (fig 6.01) marks the first attempt at creating a parametrically responsive geometry. My initial response to this challenge was the 'Construct Point' parameter.

This is not an efficient means of design, as creating individual parameters for each point results in difficulty when attempting to alter width, depth and height. Ideally each face should possess the ability to move parametrically, however instead only each point can be moved at once.

01 Simple Cube

A.P. 2017.
LED Test 1. 6.01.

02 Complex Cube

A.P. 2017.
LED Test 2. 6.02.

The 'Complex Cube' test (fig 6.02) implemented a more parametric solution that in that prior test with the use of the 'Range' parameter. Instead of having to individually change every single point, this allows for the compiling of each relevant point to create a face that can be parametrically changed. This is portrayed through the width, length and height of the cube, as well as the amount of steps that can be duplicated within. For example, the above image has 6 steps. To achieve the remainder of the cube form a series of 'move', 'line' and 'divide curve' parameters were used.

03

Randomised Cube

A.P. 2017.
LED Test 3. 6.03.

04

Hexagonal Form

A.P. 2017.
LED Test 4. 6.04.

The 'Randomised Cube' test (fig 6.03) investigated the potential use of the 'voronoi' parameter for future designs. This tool allows the creation of randomised lines and points within a square form. This does prove as a quick means of producing structural members within a form. However, the main issue is that because they are randomised, individual lines cannot be manipulated to suit a certain structural requirement. This may not be an issue for these LED drawings, but if this concept were to be carried onto real-life prints, this would be a parameter that be need to be controllable.

The 'Hexagonal Form' test (fig 6.04) investigated the creation of hexagonal forms in a parametric setting. In order to do so, points were rotated from the previous points at 60° until a full hexagon was created. The scale, height and amount of steps were all parametrically controllable. This experiment will serve as an important milestone as a hexagonal wall form will prove a viable structurally optimisable solution for this thesis. The next step will be to learn how to apply this knowledge in a grid system so that this creation can be parametrically arrayed and controlled.

05

Single Coloured Sphere

A.P. 2017.
LED Test 5. 6.05.

06

Multi Coloured Sphere

A.P. 2017.
LED Test 6. 6.06.

The 'Single Coloured Sphere' test (fig 6.05) experimented with the creation of a sphere form. Its application toward structurally optimised building construct isn't entirely relevant, however this script could prove valuable for testing the various aspects of the material extruder. The mid-section should prove the easiest to print as they are mostly vertical. However as the lines move toward to top and bottom sections, where the lines begin to cantilever, aspects such as speed will need to be considered. For example, as they extruder prints on an angle the robot will need to adjust accordingly to ensure that the lines print straight and rigid.

The 'Multi Coloured Sphere' test (fig 6.06) utilised the same script as the previous, however with the use of the HAL Robotics plug-in, the parameters shown above allowed in insertion of a second layer of lines with a different colour. This is possible by changing the LED commands from only red (LED_R) to also including green (LED_G). An issue that was discovered was that separately drawing each line a different colour, the robot identified the logic as draw the entire circle one colour, and repeat in another. Understanding this logic of changing the robot's output will prove important when it comes to altering its speed etc.

6.4

COMPLEX EXEMPLARS

The 'Simple Exemplars' section provided a superficial understanding of how Grasshopper and HAL Robotics interact. For example, to establish a basic understanding of parametric control over all customisable parameters of the forms i.e. the number of segments in any which direction, the overall scale of the form etc. These experiments demonstrated the freeform capabilities of the system through these simple LED images.

The 'Complex Exemplars' section also includes more complex geometries that begin to present more realistic applications for the built environment. Despite having the appearance of a fully developed structure, there were many factors that had to be resolved before this system could move from LED drawings, to real-life scale structures.

07 Array

The 'Array' test (fig 6.07) utilised the array parameter. In attempt to parametrically duplicate the space frame form in the X, Y, Z directions, 'Array' was the most logical first solution. However, it was discovered that this parameter would utilise a mirroring method in the Z direction, opposed to in the X and Y directions which was the requirement. This resulted in an immense amount of unnecessary lines being created in order to mirror each element in the Z direction.

08

Split List

The 'Split List' test (fig 6.08) utilised the split list parameter. This parameter did have the ability to select and rearrange the required items sets, however it couldn't be achieved parametrically. As more geometry got added in the X, Y, Z directions, the script would become invalid as once the geometry exceeds what the parameters could achieve, it would revert back to the incorrect order. More 'Split Lists' would need to be implemented manually in order to maintain the correct order.

09

Split Tree

The 'Split Tree' test (fig 6.09) utilised the split tree parameter. Unlike the previous solutions, this one enabled the parametric rearrangement of the required items as the overall geometry increases in all 3 directions of X, Y, Z. A data entry was required for the parameter to identify which items are to be rearranged. In this case the requirement was for every second set to be reversed, thus allowing the extruder's printing order to not draw unnecessary lines in order to reach its next destination.

6.5

REFLECTION

The previous experiments highlighted the primary challenge with 3D printing toolpaths; that the extruder cannot overlap any existing toolpath. It must be a single continuous line without interruption throughout the entirety of the print. This led to redefining the programming of the toolpath, leading to rigorous experimentation with Grasshopper and its data handling. Various data inputs were tested to parametrically create a lattice structure with one single toolpath line, however, the majority of these attempts were failures because the toolpath was generated from the default logic of Grasshopper which had its own predefined interpretation of the toolpath. The point order could be manipulated to an extent, however, there was always a line overlapping in one or more instances.

It was determined that using Grasshopper's predefined data generators was not sufficient and toolpaths would have to be created from scratch. The new definitions would allow any toolpath to be parametrically created, forming any lattice structure with one single toolpath.

From this point, the progression of work to follow was to increase the complexity of the definition in order to provide mastery of Grasshopper to later have better control of the extrusion toolpath for freeform printing. The experimentation developed as follows:

- Develop an advanced knowledge of how to parametrically manipulate an orthogonal lattice structure; adding more or less geometry in the X, Y, Z directions, or changing the scale of the overall form.
- Create a logic that would enable the toolpath to instantly adapt to more complex geometries.
- Create a logic that will analyse the structural members of the desired form, and thus parametrically adjust members to match the structural requirements of the finite analysis.

6.5.1

REFLECTION CONT.

Parallel to learning the methods to create toolpath definitions in Grasshopper was the control and understanding of HAL inputs to create the logic for the robot arm. After learning the logic of Grasshopper, understanding the intricacies of HAL was easier. The process began with a simple, base template provided with the plugin and then components were added as needed to control robot speed, orientation and signal communication.

In conclusion, this was a simple process that gave visual feedback to the programming process. Toolpaths could be displayed through an image to compare the Grasshopper programming to the actual machine output. The process was invaluable to the learning process and did not rely on any physical material – making it a waste-free, limitless process.

REAL-LIFE PRODUCTION

7

7.1

SMALL SCALE
EXPERIMENTS

With basic programming and robot control mastered, the tests continued by adding a custom-made plastic extruder. The extruder was created in collaboration with an industrial design master's student, Liam Gilbertson, whom I intend to continue to work with to further advance the manufacturing capabilities of this freeform 3D printing process. The extruder had a limitation in that it could not be directly controlled through the robot programming. Extruder instructions had to be set prior to the start of robot movement and run as parallel but separate processes. Because of the disconnection between robot and extruder, testing the system as a whole was tedious and resulted in multiple steps. The means of operating this system are as follows:

1. Turning robot arm on and attaching the extruder to the gripper.
2. Turning on the extruder and setting up chosen filament.
3. Loading of the print file developed in Grasshopper into the robot arm.
4. Start toolpath at the robot.
5. From a separate Grasshopper file, send through required extruder instructions.
6. Supervise the process to ensure output is correct.

The initial tests were run in the manner described above. It is not the ideal process of operations, as it is not a fully automated. Steps 4 and 5 need to merge into one single streamlined system in order to automate the process once the process has commenced, the robot arm and extruder must be able to communicate with one another. A logic must be created that informs the extruder when to print, how much too print, and how fast to print. Only then can this system can be considered as having the potential for 'mass manufacturing'. A second extruder is currently under development to further the system for future research.

01

Squares 24/07/17

These tests are directed towards to creating a perfect square by only changing one variable (filament length). The first three tests are the result of not extruding enough filament. More was progressively added to each test until the full square was complete. Because the filament thickness is 1.75mm, the distance between the working surface and toolpath is set at 1mm. If set at 1.75mm or more, the filament will not stick to the surface. Anything less will ensure the filament sticks to the surface.

- 1
FILAMENT
LENGTH
(mm)
- 2
EXTRUSION
RATE
(mm/min)
- 3
ROBOT
SPEED
(mm/s)
- 4
SURFACE
- LINE
(mm)

02

Circles 24/07/17

These circular tests are investigating an identical result as in the 'Square Tests', however the variable being changed is robot speed, not filament length. Increasing the robot speed completed the circle, however it does effect the thickness of the line, hence the extrusion rate should also be increased when increasing the robot speed. Beading occurred because the plane the extruder printed at was set 1mm higher than the 'Square Tests', thus the material wasn't properly sticking onto the surface.

03

Freeform Lines 28/07/17

In succeeding with 2D shapes, 3D freeform lines became the logical next step. The key factor for these is the cooling fan ducts, thus enabling cool air to freeze the filament. Previous tests without the fan ducts resulted in sagging. The material couldn't harden fast enough for the speed at which it was extruding. However the inclusion of the fans created straight lines. The robot speed was decreased to ensure the material could harden adequately whilst moving against gravity.

- 1
FILAMENT
LENGTH
(mm)
- 2
EXTRUSION
RATE
(mm/min)
- 3
ROBOT
SPEED
(mm/s)
- 4
SURFACE
- LINE
(mm)

04

Freeform Cubes 29/07/17

In succeeding with 3D freeform lines, 3D forms were next. The primary issue was the need for a longer nozzle for the extruder. This became apparent as whenever the extruder would have to move back toward the geometry (diagonal lines), the bulk of the extruder head would collide with the existing form. This would result in lines being dislodged from its correct position and misshapen line segments. The extrusion rate and robot speed are the key variables for these tests.

A

B

C

D

1	200	300	400	450
2	500	500	500	500
3	10	10	10	10
4	1	1	1	1

A

B

C

D

1	400	400	400	400
2	500	500	500	500
3	10	11	12	13
4	2	2	2	2

A

B

1	200	200
2	500	500
3	10	7
4	1	1

A

B

C

1	1000	1000	1500
2	500	400	450
3	7	7	7
4	1	1	1

05

Layered Cubes 07/08/17

These are the first tests to use 3mm filament, however the longer nozzle still wasn't available. The logical solution was to firstly test how it would perform as a layering process. This provided an initial understanding of the materials physical properties. Following this was to develop an understanding of appropriate extrusion rates and robot speeds for freeform geometry that could be achieved with the short nozzle.

- 1
FILAMENT
LENGTH
(mm)
- 2
EXTRUSION
RATE
(mm/min)
- 3
LINE
SPACING
(mm)
- 4
ROBOT
SPEED
(mm/s)

06

Freeform Cubes 09/08/17

These are the first tests to utilise the longer nozzle. The vertical/diagonal members are more rigid and are no longer being dislodged by the fan ducts. Because there are more fixed points compared to the previous geometry, an assumption was made the robot would be able to move faster. However whenever there is deformity of a line segment e.g. sagging, it is because the material doesn't have long enough to cool due to the robot moving too fast.

07

Freeform Cubes 16/08/17

These are the first tests to use 3mm filament, however the longer nozzle still wasn't available. The logical solution was to firstly test how it would perform as a layering process. This provided an initial understanding of the materials physical properties. Following this was to develop an understanding of appropriate extrusion rates and robot speeds for freeform geometry that could be achieved with the short nozzle.

- 1
FILAMENT
LENGTH
(mm)
- 2
EXTRUSION
RATE
(mm/min)
- 3
ROBOT
SPEED
(mm/s)
- 4
NODE
DELAY
(secs)

08

Freeform Cubes 17/08/17

These tests are a continuation of the previous, in that they are attempting to create a perfect cube. And in order to do so an 5th variable was added. Previously the top chord would float above the legs and not stick together. 'Chord Offset' was created to combat this. So that the top chord would sufficiently stick to the 4 vertical legs. In addition to this the previous 4 variables have been successively altered to further perfect the cube form.

1	15000	15000	2000	2000	3000	3500
2	500	500	500	500	500	500
3	10	10	10	10	10	10
4	1	1	1	1	1	1

1	2000	2000	2500	3000
2	500	450	400	400
3	5	5	5	3

1	3000	2500	2000	1800
2	250	200	230	200
3	2	2	3	2

1	2200	2200	1800	1900
2	160	160	160	160
3	1	1.5	1.3	1.4
4			2	4

9

Two Cubes 18/08/17

With the single cube perfected, concluding whether it could become a modular process was the next step. The result was that it indeed could. All that was required was for more filament to be sent through the extruder and the same result will always output as long as the environment remains consistent.

- 1
FILAMENT
LENGTH
(mm)
- 2
EXTRUSION
RATE
(mm/min)
- 3
ROBOT
SPEED
(mm/s)
- 4
NODE
DELAY
(secs)
- 5
CHORD
OFFSET
(mm)

10

Eight Cubes 10/09/17

In concluding modulation was a possibility, the next step was to simply add more modules to the overall form. Hence the output was one large cube consisting of eight smaller cubes. This created a much stronger structure, opposed to creating one large single cube. Given that all of the five variables were fully optimised, all of the nodes would adhere successfully and the line segments would be rigid.

11

Arch 12/09/17

I then attempted to add a curved wall parameter to the code. This did work effectively to a degree, however this method could only be applied to very specific geometries and had many limitations to where the curvature could be applied without distorting the toolpath. Despite this, the modulation parameter still remained effective.

- 1
FILAMENT
LENGTH
(mm)
- 2
EXTRUSION
RATE
(mm/min)
- 3
ROBOT
SPEED
(mm/s)
- 4
NODE
DELAY
(secs)
- 5
CHORD
OFFSET
(mm)

12

Arch 14/09/17

In achieving modulation to a degree where I could duplicate a single cube as many times as necessary, the next step was to move away from modular cubes. This spawned research into arched forms. The reason this differs from modulation is because every line segment must behave differently in order to combat forces such as gravity, to achieve the desired form.

A

B

C

1

4000

4000

3200

2

160

135

130

3

1.3

1.3

1.3

4

3

2

5

4

4

1

4500

2

130

3

1.2

4

1

5

4

1

7000

2

130

3

1.2

4

1

5

4

7.2

REFLECTION

Each aspect that has been identified is the result of vigorous experimentation and testing as shown with the previous examples. The primary goal was to come to a conclusion of what the most efficient ratios where for the extrusion rate, robot speed, node delay and chord offset. Although the modifications that were made during this process may seem very minor, each adjustment made was an imperative step towards creating the most efficient extrusion process. Hence it was of extreme importance to document every single change made, thus ensuring that there were no steps being made in the wrong direction. The result of this process is a finely tuned extrusion method that is deemed acceptable to be applied to medium scale production.

A.P. 2017.
Pre-weight Test. 7.05.

PROOF OF CONCEPT

Figures 7.05 and 7.06 show the compressive strength capabilities of the ProHT filament combined with the test structure I have created. One ProHT plastic cube weighed 6 grams and could support up to 11kg, which is 1800x its own weight. Whereas a 12x12x12cm concrete slab would weigh 4kg and would be able to support 4500kg, which is 1000x its own weight (DeWolf, 2005).

A.P. 2017.
Post-weight Test. 7.06.

PRELIMINARY PROBLEM SOLVING

01

'Squiggly' Diagonal Line

The issue of the 'squiggly' line (fig 7.07) is the result of extruding too much filament for how the fast robot is moving. To mitigate this from happening, the perfect ratio must be concluded for the extrusion rate and the robot speed. The ideal result should consist of a perfectly straight line. This was solved by reducing the amount of filament being extruded. The robot speed had to remain the same, as making the robot move faster would cause sagging due to the filament not being able to solidify quick enough.

A.P. 2017.
Problem 1. 7.07.

02

Top Chord Not Sticking

The issue of the top chord not sticking (fig 7.08) is the result of a few factors. The first is the top of each vertical member is shortened because the extruder drags the filament down a few millimetres to continue the diagonal line in the downward direction. Hence when the top chord is printed, it can't press against the top knob of the vertical member due to this shortening. This was solved by implementing a chord offset parameter which moves the top chord down a few millimetres to compensate for the lost millimetres at the top of each vertical member.

A.P. 2017.
Problem 2. 7.08.

03

Nozzle Sticking to Node

The issue of the nozzle sticking to the node (fig) is caused by the filament not being able to cool fast enough whilst the nozzle is moving into the following diagonal member. Hence the nozzle sticks to the top of the vertical member and slowly drags it down. This was solved by implementing a parameter which rotates the extruder so that the nozzle is always perpendicular to the diagonal lines, opposed to only ever being vertical. The introduction of this parameter will ensure the nozzle never sticks to a previous member, thus always producing straight lines.

A.P. 2017.
Problem 3. 7.09.

04

Horizontal Line Sagging

The issue of the horizontal lines sagging (fig) is a result of the fan not cooling the line segment fast enough in relation to the robot speed. The most effective solution would be to install a stronger fan, however, this wasn't available at the time. The next viable solution was identical to the 'squiggly' diagonal line issue; to find a more suitable extrusion rate and robot speed ratio. The resulting solution was to reduce the extrusion rate, thus allowing the filament to cool as form a straight line. The importance of this is to create a more rigid spaceframe.

A.P. 2017.
Problem 4. 7.10.

FUTURE EXTRUDER DEVELOPMENTS

A.P. 2017.
Development 1. 7.11.

Aligned Extruder Movements

- Extrusions need to be precisely aligned with the robots movements.
- Need for a feedback loop for temperature control, extrusion movement, cooling speed.

Proposed Developments:

- Install cabling onto robot that facilitates digital/analog communication.
- Configure extruder to communicate directly with robotic control software and hardware instead of using parallelised processes.

A.P. 2017.
Development 2. 7.12.

Variable Print Speeds

- Need for variable robot speeds and extrusion rates accounting for gravitational deflection.

- Addition of software: controlled pauses and travel movements.

Proposed Developments:

- Write Grasshopper scripting that allows for pauses and accelerations.
- Write Grasshopper scripting that interprets and modifies toolpaths based on deflection values from empirical testing

A.P. 2017.
Development 3. 7.13.

Faster Printing

- Extruded materials need to be cooled quicker

- Materials need to be extruded quicker

Proposed Developments:

- Develop hardware that cools the extruded material at the tip of the print nozzle using compressed air.
- Trials of materials with lower extrusion temperatures/lower specific heat.
- Trials of different shaped nozzles to increase surface area of extruded bead (e.g. star shaped nozzle)

A.P. 2017.
Development 4. 7.14.

Multi-Process Manufacture

- Call for multiple materials and processes within the same print (e.g. incorporating co-extrusion into the robotic process)

- Need to improve versatility of 3D printing by incorporated automated cutting/milling/extrusion actions.

Proposed Developments:

- Development of a universal tool changing system into robotic arm.
- Programming of an industrial microcontroller for a universal use with different tools for the robotic arm including extruder.

FUTURE EXTRUDER DEVELOPMENTS

A.P. 2017.
Development 5. 7.15.

Improved Form Factor

- Need to improve resolution of prints using a “sharper” extruder that will not collide with printed geometries.

- Need for a shorter extruder to improve positional accuracy of robot and enable advanced alignment of the extruder with respect to extrusion direction.

Proposed Developments:

- Development of a new extruder hardware with a focus on small size and narrow shape.

A.P. 2017.
Development 6. 7.16.

Support for Co-Extrusion Filament

- Hardware needs to be configured to work specifically with co-extruded filaments.

- Fibres inside filament need to be cut at the end of extrusion movements to allow the nozzle to travel.

Proposed Developments:

- Make nozzles for co-extruded filaments that help prevent jamming
- Design a filament cutting solution for the tip of the extruder nozzle that can be activated through the robot control software.

7.3

MEDIUM SCALE
EXPERIMENTS

The experiments in the following section mark the beginning of medium-sized freeform prints. Acknowledging that small-scale cubic form had been successful, the next logical goal was to advance the computational logic to be applicable to larger geometries. These experiments explored the capabilities of Grasshopper in creating a parametric system that adapted to a printing toolpath to any structurally applicable 3D form.

Another goal was to acquire full control of the robot arm. This entailed creating a logic that allowed the robot arm to rotate in accordance with the requirements of each line segment to ensure it's printed as accurately as possible.

CURVED WALL v1
13/10/17

Curved Wall v1 (fig 7.17) was the first attempt at adapting the printing toolpath to any created 3D form in Rhino. The initial thinking behind this was to generate a predetermined 3D form and have it be filled with the cubes that have successfully been printed in the previous section. However, in the process of trying to achieve this, a number of issues arose that would require a more refined approach. Firstly, the 3D form had simply been filled with modular cubes, and any cubes that reside outside of this 3D form would get cut off. This forced the toolpath to become disarranged in order for the cubes to effectively fit within the form. Stray and undesirable lines would be created as a by-product of this issue (fig 7.18,19). The ideal scenario would be for no cubes to be 'cut off', instead they would be compressed and manipulated to fit neatly within the 3D form. Secondly, it is aesthetically unpleasing. This does have the aesthetic of an architecturally applicable structure due to how messy and disjointed it appears. Achieving a higher level of form adaptation will be the primary focus of the following experiments.

A.P. 2017.
7.17.

A.P. 2017.
7.18.

TWISTED COLUMN v1 02/11/17

Twisted Column v1 (fig 7.21) is the first successful test to achieve a complete coding logic that allows the cubic forms to be manipulated to neatly fit within the created 3D form. Alongside this accomplishment, several other customisable parameters had been added.

The first was to create a logic in Grasshopper that would enable the printing toolpath to instantly adapt to the created 3D form when extra adjustments have been made to the 3D form. For example, Twisted Column v1 (fig 7.21) began as a simple vertical cuboid, however, a taper had been incorporated that had made the cuboid smaller towards the top, and a twist. Figure successfully shows these parameters in place, with the printing toolpath successfully adapting to these alterations.

The second was creating a logic in Grasshopper that enables the ability to separately customise the amount of modules/segments in the X, Y or Z direction. This enables a greater control over where segment density is to occur, thus enhancing structural performance by using more filament, or decreasing it, by reducing filament usage. For example, Twisted Column v1 (fig 7.22) is comprised of 2 modules in the X and Y directions, and 13 modules in the Z direction (fig 7.24).

One evident issue has arisen with the addition of these customisation parameters, in that not all of the nodes are connecting. Figure 7.23 shows some of the nodes missing their designated positions. This is due to every line being unique and angled in a different way, thus each line will respond differently to gravity. It may sag more or less due to these factors, thus resulting in latter segments not being able to connect properly. In the 'Top Chord not Sticking' in the 'Small Scale Experiments' section, chord offset was the viable option for nodes not connecting, however, due to every line being unique, other coding solutions will need to be investigated to mitigate this problem. The most viable solution is to adopt the way of thinking from the 'Nozzle Sticking to Node' test. This was a much simpler solution as every line segment was modular, however, with every line segment being unique, a more complex logic will need to be explored to enable the robot extruder to remain perfectly perpendicular to every unique line segment.

A.P. 2017.
7.21.

A.P. 2017.
7.22.

A.P. 2017.
7.23.

A.P. 2017.
7.24.

CURVED WALL v2
05/11/17

Curved Wall v2 (fig 7.25) was the most complex and structurally sound of the medium scale forms created. This test attempted to generally evolve from the previous, in terms of successfully reaching a larger scale (fig. 7.25), greater segment density (7.26), and greater control of the robot arm's rotational capabilities to improve printing accuracy. At this point, a greater knowledge over of the coding parameter had been gained, however correctly applying this control to successfully address the evident issues was still a concern. The major predicament lingers from the previous experiment, in that the nodes still aren't connecting properly. And the reason remains the same; the extruder is not rotated in the correct manner in relation to the way these specific line segments are being printed. For example, figure 7.27 shows a close up of the nodes, and although they may appear rigid, they are not completely connected. In many cases they are simply sitting on top of one another. It was assumed that minor adjustments could be made to mitigate this issue; the extrusion ratios for example. However, after continued failures, a conclusion was made that this specific issue must be addressed. The Grasshopper code must become more refined and move beyond a standardised rotation that applies to all segments. A more intricate logic needed to be created that can rotate the extruder to cater to each segments unique requirements, thus ensuring they are printed as straight as possible.

A.P. 2017.
7.25.

A.P. 2017.
7.26.

A.P. 2017.
7.27.

A.P. 2017.
7.28.

7.4

LARGE SCALE
EXPERIMENTS

The experiments in the following section moved away from medium scale tests, and into large-scale production to establish this system's true potential toward an architectural application. However, due to the physical constraints of the current extruder, these tests did reach a size limitation of which is approximately 1m in height and 2m in length. This was due to the extruder being too long, thus whenever the robot would attempt to print out of this range, it would move beyond its reach due to axial limitations. A means of mitigating this issue is with the installation of a shorter extruder. This is something I wish to continue to develop with Liam Gilbertson (extruder designer) for future work. In doing so, the printing envelope would increase to approximately 2-3m in height.

The first goal of these tests was to conclude a means of solving the predominant issue from the medium scale experiments. To create a logic that parametrically rotates the extruder unique to each line segment's printing path, thus eliminating the issue of nodes not connecting. Once this had been perfected, and any print will be completed with zero errors, the structural optimisation component of this research can be implemented.

To view the vidoes please follow the following steps

- Hover smartphone camera over QR code.
- Notification will appear, open it.
- You will be taken to the respective video on YouTube.

TWISTED COLUMN v2
08/11/17

Twisted Column v2 (fig 7.29) is the first of the large-scale experiments. Through more testing of rotational capabilities and minor extrusion rate adjustments in Grasshopper, 100% node connection was achieved (fig 7.31). The collection of developments made over previous sections i.e. the ability to add extra customisaiton to the 3D form (twisting, tapering), larger scale of prints, greater segment density etc., had begun to convey this system's architectural application capability. The next step was to evolve this concept by incorporating the structural optimisation component of the research. This portion of the research was intentionally left out until a complete resolution of the system was achieved with the basic printing methodology. Doing so avoided having to constantly re-edit and update the structural optimisation logic to continuously match the standard printing technique. A basic workflow was established and deemed successful, allowing the structural optimisation portion to be included in the following experiments.

A.P. 2017.
7.29.

A.P. 2017.
7.30.

A.P. 2017.
7.31.

A.P. 2017.
7.32.

The arch structure (fig 7.33) explored the capabilities of the system in creating arched forms. The arch experiment was a major challenge because unlike all the other tests, this one was not self-supporting during its printing process. All of these experiments have to be printed from bottom to top to avoid collision with the extruder and material that is already placed. For all of the other experiments, they consisted of solid forms with no voids i.e. wall, column-like structures. Whereas this has a void in the centre, thus creating the arch. All the prints must be done from bottom to top, thus a large cantilever is created during the first layer of this print. And because there wasn't sufficient support anchoring the beginning of the first layer to the substrate, it would always fall over halfway through the first layer. The solution for this issue was to seamlessly integrate legs into the toolpath (see video below). This was an immense challenge as the toolpath had to remain as one continuous line. The integration of these legs meant the print was now self-supporting. Once the print was complete, the legs could be easily removed.

Despite having the leg support system in place, there was still a concern of the structure not being rigid enough, thus the nodes were at risk of not connecting. However, due to the stringent testing that occurred in previous tests for resolving the rotational capabilities of the robot, this was not an issue (fig 7.35).

A.P. 2017.
7.35.

A.P. 2017.
7.36.

8.1

COMPUTATIONAL
RESOLUTION

The purpose of this section is to clearly communicate the methodology of the developed building system. The following is the workflow that was successfully developed over the course of the research. Rhino, a 3D modelling application was used to create the overall form of the printed object, along with any additional alterations such as, tapering, twisting or scaling. It is important to note that this concluded system possess zero limitations in terms of what can be created and successfully analysed.

Grasshopper, a parametric modelling plug-in for Rhino was used to create the printing toolpaths and robot instructions as well as run Millipede, a plug-in for Grasshopper

Finally, Millipede a structural optimisation plug-in for Grasshopper allowed for the structural optimisation of the initial form created in Rhino. Millipede provided the information of where to place more or less material to create the final form.

I was able to link all of these programs in such a way that allowed them all to operate seamlessly together as one unified system. The overall aim of this system is to create the ability to be able to adapt a freeform printing toolpath to any 3D form, and critically analyse and reflect upon an initial design form, and make revised alterations based on the structural feedback.

Concluded Toolpath

As a theoretical example, the below toolpath (fig 8.16) is the chosen design by the client. The toolpath is to now undergo structural analysis to allow for further informed alterations based upon the weaknesses of the initial toolpath.

A.P. 2017.
Density in All Directions. 8.16.

Structural Analysis

The analysis shown below illustrates that revised alterations need to occur to both the wall's design, and to the segment density and dispersion (fig 8.17,18). The segment density is located at the bottom left, and there is minimal density at the right side. This initial design decision has drastically weakened the right side of the wall as the line segments show immense sagging (fig 8.18). A revised segment dispersion needs to be incorporated that will compliment the relatively symmetrical design of the wall. As of now, it does not achieve this.

In regards to the overall form, the slender dimensions of the base makes it very susceptible to collapsing in the Y direction. Hence further regard to the form's overall dimensions need to be re-considered to ensure a solid foundation.

A.P. 2017.
Finite Analysis Iso. 8.17.

A.P. 2017.
Finite Analysis Side. 8.18.

Original Analysis

With all of the customisation options displayed in steps 1 and 2, the revised structural analysis (fig 8.20) aims to address all of the issues raised in step 3. The most noticeable defect that requires resolution is the chosen segment dispersion from the initial design. It is assumed that the theoretical client chose this arrangement of segment dispersion to create a specific design aesthetic, however, in order to conclude a structurally coherent wall structure, alterations must occur. Upon completing the structural revisions, the result will be a much more structurally optimised form that can support much greater force.

A.P. 2017.
Finite Analysis Iso. 8.17.

A.P. 2017.
Finite Analysis Side. 8.18.

A.P. 2017.
Revised Analysis Iso. 8.19.

A.P. 2017.
Revised Analysis Side. 8.20.

Revised Analysis

Figures 8.19,20 are the result of analysing the previous form's structural defects and making an informed designed based upon the feedback. To summarise:

- The overall segment density has been increased. While this will use a much greater amount of plastic to complete the entire form, the structural benefits are necessary.
- The base has been made thicker to increase its rigidity, and to compensate for the smaller surface area at the bottom. This will improve the force transfer to the ground (fig 8.19).

- Evidently given the form of the initially designed form, having a asymmetrical dispersion of the segment density is not structurally advisable. Reflecting upon this feedback, segment density has been symmetrically designated to the two ends of the form to complete the wall's design (fig 8.20)

The combination of these informed alterations has created a complete, structurally optimised form ready to be printed.

CURVED WALL v3
20/11/17

Curved Wall v3 (fig 8.21) is the physical manifestation of the structural optimisation analysis that occurred in the previously illustrated steps. Upon printing this experiment, all defects that had proven troublesome in previous tests have been resolved. There were practically zero evident errors during the printing process of this form. Given the level of computational resolution achieved, I could simply install the code into robot, press play, leave for the duration of the print, and come back to find a complete freeform printed matrix.

Also, to prove the versatility of freeform 3D printing, post-print customisations have been made to create a more interesting geometry. A large portion of the centre was removed to create this central void, thus creating an archway structure. Using the structural optimisation feedback, I ensured that the positioning of this void in relation to the segment density was well informed, as positioning it incorrectly could result in jeopardising the structural integrity of the form. It was important to constantly refer back to and reflected upon step 3 and 4 to ensure minimal compressive strength was lost.

A.P. 2017.
8.23.

A.P. 2017.
8.24.

CURVED WALL v4
11/12/17

Curved Wall v4 (fig 8.25) is another such example to successfully implement the structural optimisation component of the research. As with the previous example (Curved Wall v3), this revised wall design has been derived from the previously conducted structural analysis. The purpose of this example is to provide perspective as to how alternative resolution can be concluded. In this case, a different revised wall design had been produced by the theoretical client. The finite analysis feedback concluded that the weakest area of the wall was located at the 100mm thick centre, as it is thinner than the two 200mm thick ends of the form (fig 8.26). Hence greater segment density was added to the centre to compensate for this weakness (fig 8.25).

Also, to provide a new perspective on the versatility of freeform 3D printing, a different form of post-print customisation has been made. In using the finite analysis feedback, it was determined that the two ends did not require as much segment density due to them being 100mm thicker than the centre. Therefore the risk of reducing compressive strength is drastically lessened by trading less segment density for a thicker form. In acknowledging this informed analysis, two windows were positioned where they are less likely to cause structural issues (8.25,27).

A.P. 2017.
8.25.

A.P. 2017.
8.26.

A.P. 2017.
8.27.

A.P. 2017.
8.28.

LOOKING FORWARD

9

9.1

ENVISIONED
DEVELOPMENTS

The key strategies to further this research into a viable system are categorised as follows:

1. ROBOT & EXTRUDER

- Redesign the extruder to integrate programmatic control with robot movement.
- Alter build speeds (robot movement and extruder speed) for specific build properties (more or less material for structural support).
- Extruder cooler control through programming for faster printing or better adhesion of material.
- Multiple materials for specific structural conditions (tension vs. compression).
- The improved form factor of the extruder for tight build conditions.

2. MATERIALS

- Study alternative materials such as the biopolymers being developed by partner researcher.
- Use recycled plastics to form the filament for building with plastic.
- Test longevity and structural properties of materials once placed

While in the initial phases, this research has shown great promise and has created a solid foundation for further development of a sustainable building system using freeform 3D printing. Many failed tests were produced (fig 9.01), however, these failures are arguably one of the most important aspects of this research. They are what enabled the progression of work evident throughout this research portfolio to become a reality, and be manifested into the final resolved productions that have been created.

A.P. 2017.
9.01.

9.2

CONCLUSION

This field of research is very important for the development of the construction industry, as it is in a current state of unsustainability. And it will continue to remain that way unless construction alternatives are explored. Throughout this thesis I have learned an array of pragmatic skills that have enabled me to provide one such alternative. I have learned how to programme through Grasshopper, control an industrial robotic arm, learned introductory concepts of mass customisability, industrialisation, structural optimisation, and developed a potential new building methodology.

My research began with the question: “How can freeform 3D printing, combined with structural optimisation tools, provide a sustainable and efficient construction alternative?” Throughout this body of work I have undergone an in-depth analysis into existing precedents researching similar methodologies as mine. Established what they are doing, what their system strategies and methods are in comparison to my own. I have investigated existing conventional construction methods and why we need to explore alternatives. I have discussed and reflected upon the negative implications attributed to unsustainable construction methods i.e. unprecedented quantities of construction waste. Have proposed a potential system solution through the form of pre-fabricated freeform printed modules, and the potential material solution through the form of recyclable plastic filaments. Have undergone vigorous computational testing to create a seamless and efficient structurally optimisable and mass customisable freeform printing toolpath system. Have undergone equally as vigorous physical experimentation (fig 9.01), and have incrementally produced a series of scale tests that have grown from simple 50x50mm cubes to complex 1mx1m walls, archways and columns.

With the collation of these research components, I have concluded a fully operational freeform printing system, capable of mass customisation and the innovative structural optimisation. Combining these elements presents endless sustainable opportunity that needs to be utilised now and in the future. The only evident limitation was the current technology available to me i.e. the extruder and programs. I aim to remove these limitations by furthering this research to develop the applied technologies, my own knowledge regarding the intricacies of this field of research, and of course the freeform printing system itself.

In summary, New Zealand has a paramount opportunity to redefine the built environment through emerging technologies such as freeform 3D printing, mass customisation, robot arms and structural optimisation systems. And I want to be the one to lead this evolution of industry.

10.1

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10.2

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