Designing with Mycelium

Utilising spatial printing to create scaffolds for mycelium growth

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Abstract

With increased awareness of the environmental impact of synthetic materials, there has been an increase in research investigating more sustainable manufacturing methods and materials. Making appropriate sustainable material choices for designs is becoming essential, whether it is using more durable or adaptable materials that will last an extended period or integrating sustainable bio-materials into short-term products. In addition, there are a number of research projects that use natural growing systems to produce materials with placement being defined by 3D printing or digitally fabricated moulds. These have been referred to as Hybrid Construction Systems, as both natural and manmade techniques are combined as a fabrication system. This research portfolio investigates the opportunities and constraints of using mycelium-based composites in combination with spatially printed structures to dictate the form, materiality and potential use.

Mycelium offers many unique material qualities, it is a naturally occurring resource that can perform as a structurally sound material when used correctly. One benefit of it beyond removing the use of synthetic materials is that it can be composted, when it is no longer needed, which could offer sustainable design alternative for short-term products or for large temporary structures.

There are a number of recent projects that have focused around the use of mycelium in an architectural context, one being Mycotree which created a load-bearing structure from mycelium composite blocks that were generated through 3D graphic software (Heisel et al., 2017). A common trait of these projects and others, is that the method of making used a process of growing the composite in engineered moulds and later assembled.

This research explored the creation of spatially printed 3D scaffolds and the synergies of materials, methods of growth and manipulation of mycelium based composites. Form, pattern, and structure of 3D printed objects were analysed along with application techniques to identify suitability for mycelium growth. Processes identified as successful were then applied to the design of large scale structures that highlighted the opportunities of the developed method.

The findings in this report provide evidence that spatial printing could offer a scaffold for mycelium composites to grow, defining form and strength, creating an alternative method and unique design opportunities to the traditional use of casting moulds. This research portfolio presents the possibility for innovative manufacturing methods that adopt a collaboration between digitally defined forms and bio-materials, exploiting the freedom and accuracy of digital design while using highly sustainable materials.

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Figure 1.01. (Right) Mycelium under a microscope (Aubor, 2020).

Introduction

This research project was built on knowledge gained when taking part in the Institute for Advanced Architecture of Catalonia (IAAC) Global Summer School in Melbourne. The workshop focused on using parametric design tools within Grasshopper, to create minimum material performance enhancing stuff forms. These were turned into pieces to create a mould, which was then filled with mycelium composite material. The workshop explored the potential for manufacturing, using both digital and organic tools.

Experience from this workshop gave an understanding of the fundamental properties of mycelium and also ideas about the way it could be integrated with digital technologies like 3D or spatial printing. These initial observations provided knowledge about the steps and processes involved to growing mycelium and a first-hand experience of using these systems.

Furthermore, integrating 3D printing, particularly spatial printing, has a number of benefits; less material to produce the mycelium scaffolds, faster 3D printing process in the creation of large structures, and the printing process also gives the designer greater control of the structure as each path of deposited material can be defined by the designer

Figure 1.02. Filling mould with mycelium composite at IAAC workshop (Author, 2020).

Key words

Although some words or terms may have alternative meanings within different contexts or industries. Each of these words or terms defined are in the context of this research project to provide clarity and understanding.

<i>Substrate</i>	The organic material used for growing mycelium which feeds it the nutrients the mycelium requires to grow.
<i>GM</i>	The straw supplied by the mushroom suppliers.
<i>Mycelium</i>	The vegetative part of fungus that appears as a network of fine white hyphae
<i>Mycelium Composite</i>	Substrate material inoculated by mycelium, bonding material together
<i>Incubator</i>	An enclosed space that creates a controlled environment.
<i>Composite</i>	Something made of multiple parts/ materials
<i>Foreign Mould</i>	Within this research paper the term foreign mould is referring to any mould growth identified that is not mycelium, and therefore not intended.
<i>Mould /mould making</i>	Within this paper mould will be used as a term for the use of a solid container used to dictate a shape of an object
<i>Desiccate</i>	The removal of moisture from something to cause it to become completely dry

<i>3DP</i>	3D Printing
<i>AM</i>	Additive manufacturing
<i>Spatial Printing</i>	Additive manufacturing that uses code to define the movement and deposition of extrudate with full control and ability to move in the xy and z, direction
<i>FFF</i>	Fused Filament Fabrication, often used interchangeably with FFF
<i>FDM</i>	Fused Deposition Modelling, often used interchangeably with FFF
<i>Filament</i>	The thin thermoplastic feedstock used in FDM/FFF printing
<i>Scaffold</i>	A term for the printed base structure that dictates the final shape and form acting as “bones” or caging
<i>CAD</i>	Computer- Aided Design
<i>Rhinoceros 3D Aka: Rhino</i>	CAD modelling software
<i>Grasshopper</i>	A parametric modelling plugin used within Rhinoseros 3D
<i>HAL</i>	Grasshopper plugin used to translate data from Grasshopper to code that instructs the robot arm
<i>Script</i>	In this research project this is referring what is input into Grasshopper to generate the definition for designed elements
<i>Extrudate</i>	Material that has been extruded through the printing nozzle
<i>Print</i>	In this context any reference to print is referring to either a 3D or spatially printed object/structure

Literature review

Sustainability

The need for sustainable design and development stems from the understanding that if the earth's resources are continuously being depleted and damaged, there will be a point where they run out and then in turn, compromise the quality and ability for life to persist (Portney, 2015). The Switch to a Circular Economy (CE) aims to drastically improve the efficiency of resources as it eliminates the concept of waste. In a shift away from the current take-make-waste consumption model (Despeisse et al., 2017). Disposal of waste is currently already the last resort for integrated waste management (Haggar, 2007). In a CE resources travel in a circular system reducing or potentially removing raw materials being used and end of the line items being either put to landfill or incineration, resources rotate within either a bio cycle for biomass or techno cycle for inorganic materials (Despeisse et al., 2017).

Haggar (2007) describes how current methods of pollution control, treatment and Environmental Protection can be expensive practices and therefore seen as though they impede development. A common perspective is that Environmental Protection cannot be achieved without hindering economic development or vice versa; however, according to Haggar that is a misconception (Haggar, 2007). The goal is to achieve sustainable development that promotes economic growth without compromising environmental resources. Any environmentally-focused practice needs to be able to suit both developed and developing countries in every aspect from economic, technological, environmental and social factors, or they would not be considered sustainable (Haggar, 2007).

The concept of sustainability emerged within the academic world in the mid-1980s and has since evolved substantially. In 1987 a definition of sustainability was presented by the World Commission on Environment and Development (now known as the Brundtland

Commission), outlining that sustainability is the economic development activity that can meet the needs for the present without jeopardising the ability to meet the needs of future generations (Portney, 2015). To be able to manage waste, there is currently a selection of techniques, management programs, and technologies called integrated waste management (IWM). IWM have a hierarchy of actions to carry out, being reduction, reuse, recycle, recovery/treatment, and finally disposal (Haggar, 2007).

Reducing: This is reducing the initial raw materials used at the source, either through cutting down materials used in the manufacturing process or reducing aspects such as packaging to the minimum (Haggar, 2007).

Reuse: This means reusing a product continually, either in its original state and intent or modified from or adapted application. This technique does not return products to the manufacturer or recycler but is instead a practice carried out by consumers (Haggar, 2007).

Recycling: Recycling is a process where waste materials are collected and transformed into raw materials that can be used to manufacture new products. Recycling often has to rely on consumer habits; however, it also depends on additional technical processes that can require capital investment (Haggar, 2007).

Recovery/treatment: The recovery process can take many forms to retrieve materials or energy from waste items. It is a limited practice worldwide, mainly focused on recovering energy by burning waste materials (Haggar, 2007).

Final Disposal: Final disposal is the end of the waste stream where waste that could not return to production cycle through previous stages are either put into a landfill or incinerated (Haggar, 2007).

One way to avoid the need for this system entirely is to remove the use of non-renewable materials. Ashby (2012) reports that 300 years ago humans used almost exclusively renewable materials such

as wood, stone, and natural fibres etc., and then occasionally non-renewable materials such as copper, iron, zinc, tin in small quantities for practical use. By the end of the 20th century, this changed to non-renewable materials displacing renewable, reaching a state of almost total dependence (Ashby, 2012).

The current model of consumption where humans make, use, and dispose of, is unsustainable as it drains resources while continually adding to waste. A circular economy is a more sustainable model, where products that reach the end of their current service are repaired, resourced, given upgrades or remanufactured parts, to be given an extended life, or the materials are recycled to create new resources Figure 1.03 (Stahel, 2016).

Figure 1.03. Circular economy diagram, modified from Stahel, 2016 (Author, 2020)

There has been some progress in achieving environmental, economic and health benefits through eco-efficiency; however, the current system of cradle to grave consumption is fundamentally destructive and therefore does not allow for sustainable development. Added responsibility also falls onto designers as a significant issue with attempting to avoid products becoming waste is that they are unable to be reused or recycled due to multiple materials involved. If designers plan for the reuse of products, it prevents waste from being generated (Haggar, 2007). To be able to design for a circular economy, materials should have the capability for modularity, disassembly and be repair friendly (Despeisse et al., 2017). With progress in manufacturing techniques, there is an opportunity to investigate the potential of 3D printing (3DP) contributing to a move towards a circular economy, attempting to move away from the current take-make-waste model through more resource efficiency and removing the concept of waste. 3DP has already presented itself as a tool that offers advantages when it comes to mass customisation, design freedom, innovation in business and collaborative-creation. Many types of 3DP already have an almost circular system with the option of recycling and reclaiming material waste. This is an added benefit to an already more material-efficient process, as the nature of additive manufacturing (AM) means it only uses materials where necessary (Despeisse et al., 2017).

Growing Design

One approach to sustainable design is to look at nature for inspiration, whether it is in methods of function and form, or materiality. Innovative technologies and materials are vital for progress, and one place of inspiration is from natural systems. Mimicking nature's method of growth rather than assembly as a building method is one way that researchers and designers have developed innovative methods of making. Vallas and Courard (2017) talk about how living architecture is not a new concept at all; it is present across cultures as a method of making. Through guiding the path of plants roots, people have been able to manipulate living structures to create the living architecture. A pioneer in achieving living architecture was John Krubsack who spent 11 years shaping 32 seedlings as they grew, until in 1914 he realised a "living chair" created purely from trees (Figure 1.04). His achievement inspired other tree shapers to adopt the method, such as Axel Erlandson who, after 20 years, opened his tree circus, which included over 70 tree sculptures that were made by shaping and manipulating growing trees (Figure 1.05) (Vallas & Courard, 2017).

In some ways similar to the long explored methods of manipulating living structures, designers are investigating what is called "Growing Design", an emerging practise, where living organisms such as algae, bacteria or fungi are being manipulated and used to grow materials (Karana et al., 2018). Dutch designers Maartje Dros and Eric Klarenbeek have managed to develop a 3D printable bioplastic made from algae (Figure 1.06), a product they believe could erase the need for synthetic plastics. Made from cultivated algae that then gets dried and processed into a material, the designers believe it could be used to manufacture everything from shampoo bottles to rubbish bins, hopefully wholly taking the place of plastics otherwise made from fossil fuels (Morris,

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Figure 1.04. John Krubsack with his living chair (Vallas & Courard, 2017)

Figure 1.05. Axel Erlandson's tree sculpture (Vallas & Courard, 2017)

Figure 1.06. Klarenbeek and Dros 3D prints from algae filament (Morris, 2017)

2017). The algae cultivated in the manufacturing process absorbs carbon dioxide through the process of photosynthesis (Morris, 2017). The designers are not limited to just researching the potential for algae plastics, they have also explored the possibility to use other organic matter to create alternative plastic biopolymers, including using cocoa bean shells, mycelium, and potato starch (Morris, 2017). Fungi have long been explored as a naturally occurring material with ways to manipulate it for industrial use and have been successfully used in the food and medical industries and more recently as a bio-material alternative within architecture and design (Karana et al.,

Figure 1.07. Structure of mushroom and mycelium (Author, 2020).

2018).

Mycelium is the root system of fungi. Mainly hidden within the soil, made up of hyphae which are a network of microfilaments (Figure 1.07). It can decompose matter by using digestive enzymes, making it a natural recycler (Henri, 2018). Mycelium has been primarily investigated in two main ways, the first being creating a composite with other substances, in which it interlocks within its network and the substrate to form a mycelium-based composite which can be a bulk material. Alternatively, by harvesting a liquid culture of mycelium, a material can be created, which is pure mycelium (Karana et al., 2018). The difference in approach of working with mycelium influences the materiality of the resulting substance, and therefore possible applications. A significant benefit of using a substrate to make a mycelium-based composite is that it can create a purpose for materials otherwise destined for waste, including wood sawdust, rice or wheat, straw and coffee grounds. The choice of substrate used will determine the outcome of the technical and experiential qualities of the final composite (Karana et al., 2018). However, the method of making can also influence these characteristics.

The process of working with pure mycelium is somewhat different as it is obtained from liquid culture. Dependant on how it is grown, processed and any additives combined, the resulting material can vary significantly. The output could resemble plastic, leather, or paper in a range of visual qualities such as the stiffness, translucency and colour (Karana et al., 2018) each would offer widely different possibilities of industrial use.

One company which has harnessed the unique qualities of mycelium in both growing methods is "Ecovative Design" which has developed a range of products. Ecovative Design has developed a patented process to turn 100% pure mycelium into a foam-like material suitable

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Figure 1.08. Mycoflex (Ecovative Design, n.d.), Figure 1.09. MycoComposite (Ecovative Design, n.d.)

for both textiles and skincare (Figure 1.08)(Ecovative Design, n.d.). The more common method of using mycelium-based composites in design is to create objects or parts using moulds to define the final form. This is used in Ecovative Designs' Mycelium-based composites stream, "MycoComposite" (Figure 1.09), which according to their website, is their "patented biomaterials platform utilising mycelium as a self-assembling biological binder for agricultural by products." (Ecovative Design, n.d.). Within which they offer mushroom packaging as an alternative to synthetic foam packaging which can either be ordered in standard shapes or moulded to custom forms. They also sell make-your-own supplies under the brand grow.bio™ that offers the sale of everything required to grow mycelium from home (Grow.Bio, n.d.).

This method of construction is also demonstrated in The MycoTree project, in which the designers paired the mould making process with 3D graphic statics to create a load-bearing structure (Figure 1.10). The goal of the project was to present an alternative to traditional building materials that put a strain on the earth, to offer a method of achieving sustainability within the construction industry. Using

just bamboo and mycelium, it also presents proof that traditionally weaker material, if used correctly, can be structurally sound and safe (Heisel et al., 2017). Using sugar cane and cassava root, in a range of recipes, compressive tests were done to find the most favourable mix. And to make sure the connections between each mycelium component were clean and had an even load transfer, bamboo plates were used to compact and cap the pieces. One main reason to use mycelium as a construction material is that it offers ecological advantages; however, it does mean it has lower structural strength than engineered materials. To overcome this, it is vital to use geometry to achieve stability; in the case of Mycotree, they used 3D graphic statics which is a method developed by ETH Zurich's Block Research Group. The technique generates polyhedral forms which are beneficial once coming to fabrication, as the pattern for the moulds for each node can be laser cut from recycled sheet material.

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Figure 1.10. Mycotree (Heisel et al., 2017)

These moulds are then compacted incrementally until full (Heisel et al., 2017).

While some of the different groups that either research or sell mycelium products at a commercial level have patented methods of their processes, the base structure for creating designs from mycelium-based composite would usually follow a simple process shown in Figure 1.11.

The process can remain somewhat constant, although the output can portray a range of material qualities. It is highly dependant on the substrate used, whether it is a pure sugar solution used within a laboratory, or includes agricultural waste, which would be more suited towards mushroom production (Henri, 2018). The choice of substrate can be driven by motives of the project, whether it is primarily an investigation on mycelium itself, trying to find a use for waste materials, or having an end goal of specific materiality wanting to replicate. Henri (2018) reported that additives and nutrients have been said to influence composites, including calcium or gypsum, may aid mycelium growth. Carbohydrates have the potential to increase mechanical properties, and higher sugar concentrations could reduce stiffness as less chitin being produced within the hyphae walls (Henri, 2018).

While moulding is the most commonly seen approach to working with mycelium composites, there has been some research into the use of mycelium composite as an extrudable material for 3D printing. Noticing the limitations in the complexity of shapes able to be produced through a moulding process, a group of researchers explored the creation of mycelium-bound composites for extrusion (Soh et al., 2020). Using *Ganoderma lucidum* (*G. lucidum*), otherwise known as Lingzhi mushroom, bamboo and chitosan, and material testing they were able to produce an extrudable material with promising potential for 3D printing (Soh et al., 2020).

Figure 1.11. Mycelium composite making process (Author, 2020).

Additive Manufacturing

While there is a limited understanding of the extent to which 3D printing may influence and impact society and production chains, its characteristics are promising as they do align well with sustainability and circularity principles. Material selection is influential during a design period, as different material qualities can give benefit an object during its use or also offer sustainable disposal or upcycle methods (Despeisse et al., 2017). While most current printing materials cannot achieve biological growth, 3D printing has been referred to by some as manufacturing by growth rather than assembly; this concept promotes synergy between using growing materials alongside 3DP. Additive manufacturing (AM), also referred to as 3D printing (3DP), is used to create physical models of digital 3-dimensional models. AM is opposite to traditional machining, where the final part is obtained by removing material, which can be referred to as subtractive manufacturing (Chaunier et al., 2017).

Initially created in the 1980s as a method of rapid prototyping, additive manufacturing is now being considered as its own method of manufacture. For polymers, the most common form of AM is material extrusion, which is the deposition of a molten thermoplastic polymer through a small nozzle, built up layer by layer on top of a solid plate. The thermoplastic material enters the process as a filament which is fed into the 3D printer and is heated to allow extrusion, the deposited material needs to solidify quickly to retain the shape and support the next layer (Chaunier et al., 2017). This process is known as Fused Filament Fabrication (FFF) or Fused Deposition Modelling (FDM); it is a prevalent method of 3DP that is used both by hobbyist and professionals, primarily for prototyping.

This method has limited control in the vertical axis as it is based on layers of deposited material building on top of each other, often referred to as 2½D printing as the layers have a limited increase in height in the vertical axis.

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Figure 1.12. Designed deposition print vs standard FDM prints (Molloy, 2017)

As a research thesis, Isabella Molloy (2017) investigated freeform printing as an alternative to the common FDM (Fused Deposition Modelling) through informed material deposition. This method defines the exact path of material deposition to create more precise structures and reduce support material; it does, however, require a high level of specialised knowledge and equipment to use their method of deposition, making it much harder than traditional FDM printing (Molloy, 2017). Molloy (2017) does also state that the freeform process offers a significant reduction on the material and energy usage, meaning that it is much more sustainable in the use of materials. Due to less material used, there is a significant reduction in printer motions, hence faster printing time, and less post-processing, due to lack of support material needing to be removed. By adopting spatial printing as a method for fabrication, compared to traditional 2½D printing, it eliminates the support material required, increases

the speed of prints, and any other waste or need for post-processing is eliminated. Research projects have been successful in showing spatial printing is a sustainable approach to introducing additive manufacturing and digital fabrication to manufacturing (Oxman et al., 2013).

Branch Technology is a company that is home to the largest freeform 3D printers in the world. They have developed algorithms capable of turning digital geometries into printable robotic code for spatial printing. They offer design, engineering, manufacturing, and installation services for their signature style of intricate designs. Geometries can either be supplied from a range of software's or can be developed with in-house designers, these are then converted to spatial printing CNC code (Branch Technology, n.d.).

A similar method of designed deposition was used by Ilgun & Ayres (2016) in a project that explored the possibility of a 3D printed scaffold offering as a base for construction by bees, forming a hybrid artefact intended to support activities for both bees and humans. By using 3D printing for the initial structure, they were able to create a porous yet robust model Figure 1.13.

Rather than relying on automated 3D printing translators, they used design data to manipulate the g-code which instructed the machines toolpath (Ilgun & Ayres, 2016). While the above project shows there was still limited control in the vertical axis, the ability to use a fully defined toolpath increased opportunities for unique aesthetic qualities to be achieved. Changes to speed, temperature, toolpath and flow rate were controlled, and external elements such as gravity exploited as shown in Figure 1.13 (Ilgun & Ayres, 2016). The project aimed to highlight the connection, and interdependence humans have to flora and fauna. It also more directly sought to portray the opportunity to couple designed construction alongside self-organised construction, opening the possibility of architecture to exhibit continuous adaptation seen in Figure 1.14 (Ilgun & Ayres, 2016). Despite architecture being a method of separation from the

outside world, throughout history, architects and designers have looked at natural systems for inspiration in form, function and symbolism. Rather than using the familiar concept of bio-inspiration for design, Ilgun & Ayres' project directly couples architecture with biological systems (Ilgun & Ayres, 2016) which has the potential to offer alternative more sustainable methods of construction.

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Figure 1.13. 3D printed scaffold from fully defined toolpath (Ilgun & Ayres, 2016)

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Figure 1.14. Hybrid construction combining 3D printed artifact and self-organised deposition of bee-comb (Ilgun & Ayres, 2016)

In nature, material systems are created from composites that have grown and adapted from one system, not made through an assembly of different parts. It is not restricted to and does not follow defined paths or planes; it instead reacts to external stimuli and spreads out through space (Oxman et al., 2013). The use of additive manufacturing opens up the option of using composite materials in the production of products or prototypes; this can be the reduction of virgin materials used in the use of recycled plastic or using biopolymers that offer other benefits (Horta et al., 2018). Currently, the most common materials used for Material Extrusion (ME) is acrylonitrile butadiene styrene (ABS) and Polylactic acid (PLA), with PLA having a significant advantage of being bio-based and biodegradable, offering a more environmentally conscious option. There are other options for biopolymers that could be used to formulate material extrusion suitable filaments; this includes

other bio-polyesters such as polyhydroxyalkanoates, and other melt-processable natural biopolymers (Chaunier et al., 2018). Biopolymers such as zein; a maize storage protein, are good options to create 3D printed parts as it offers unique qualities like biodegradability or biocompatibility (Chaunier et al., 2017).

This also includes proteins and starch as they can be processed as thermoplastics materials using plasticisers. These are good candidates as they have the advantage of being edible as well as bio-compatible and available from natural resources. These added abilities open up a wider field of application of AM, as it could be used in pharmaceutical, bio-medical and food sectors (Chaunier et al., 2018).

For the use of alternative additive manufacturing materials become more common in industry, there needs to be more testing, particularly on sustainable materials. Without effort made to test alternative composites, there can be little movement towards the industrial application of biopolymers (Horta et al., 2018). While small scale 3D printing has been a common practice for a while now, and one that has had a large amount of research into, large scale additive manufacturing is a much less researched field (Barnett & Gosselin, 2015). There are noticeable benefits in using additive manufacturing as opposed to traditional manufacturing techniques, as it offers fewer restrictions on 3D geometry, a streamlined process of design to construction, and elevated automation in part construction. These advantages are still present once scaled up; however, it also introduces new challenges. Most materials used for small or medium-scale additive manufacturing are expensive, making the use of them at a large scale impractical. Therefore, one obstacle that must be overcome is identifying a cost-effective material option (Barnett & Gosselin, 2015).

In recent years there has been a rapid evolution in the possibilities of 3D printing for the building and construction industry. This has produced new printable materials, alternative printing systems, and opportunities for commercialisation (Zhang et al., 2018). The

limitations to the potential scale of printed structures is a significant hurdle in any process using additive manufacturing. Since most existing 3D printers are based on a stand, its bed size limits the scale of any model produced. Robot-arm based systems offer more freedom in scale; however, it is still limited to the reach of the arm. One way to combat these limitations is to print smaller sections and assemble them; however, that does create additional design and production work, which may also reduce structural integrity (Zhang et al., 2018). Further investigation on the opportunities of spatial printing is needed to fully explore the limits of where it has industrial application abilities. This could be increasing the scale of the robotic arm, or a fully autonomous system that transports materials to locations, or can transport itself to print on-site (Oxman et al., 2013). Keating et al., (2017) exemplified this concept in their creation of an automated construction system, the Digital Construction Platform (DCP). Using a tracked mobile platform to carrying a hydraulic and robotic arm, they were able to construct a 14.6m diameter, 3.7m tall open dome structure with a fabrication time of under 13.5 hours on-site (Keating et al., 2017).

Direction

From the literature review, a clear frame of the current area of knowledge was formed. There has been a range of investigations into the use of mycelium in architectural and design contexts, ranging from speculative and artistic applications like Eric Klarenbeeks mycelium and 3D printed chair Figure 1.15 (Fairs, 2013), to Ecovative's range of mycelium-based products (Ecovative Design, n.d.). A notable area of investigation is Klarenbeeks combination of using a 3D printed bioplastic to encase a printed straw and mycelium centre (Fairs, 2013). The symbiosis between digital technologies and organic growth is similar to that of Illgun and Ayres hybrid construction of a 3D printed scaffold for bees to construct honeycomb around (2016). These projects offered inspiration for the concept of using spatially printed structures as a scaffold for mycelium composite to take on the form and grow. It is not just within design and architecture; the medical industry has adopted the use of 3D printing various biological and tissue scaffold materials as a possible way of creating biomimetic tissues and organs (Yoo & Polio, 2010). "By constructing an artificial tissue from an assembly of cells and biomaterials, tissue engineering techniques can offer 3D cellular environments that mimic the natural physiological/geometrical architecture of a biological tissue... Traditionally, the cells-of-interest are embedded in or coated on biocompatible materials that serve as temporary scaffolds to support their integration into the existing physiological environment" (Yoo & Polio, 2010, p.4).

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Figure 1.15 Eric Klarenbeeks mycelium chair (Fairs, 2013)

The decision to pair mycelium composite with a spatially printed scaffold as opposed to print with mycelium or a mycelium composite was directed by the current areas of research that were found. Multiple groups such as Soh et al (2020) and Co-de-iT (2016) have been developing extrudable mycelium-bound composites (Figure 1.16) and Eric Klarenbeek used straw to print for his mycelium chair. By looking to pair mycelium composites with more complex spatially printed scaffolds, the area of research differentiates itself. There are also spatial printing precedents that serve as inspiration for application, such as branch technology who use their spatial printed structures in combination with filled and milled composites to enhance existing structural capacities.

By researching the current field of knowledge of mycelium use in architecture and design, and spatial printing, this has formed the research question:

“What are the opportunities and limitations of using spatially printed structures to act as a scaffold for mycelium composite retention and growth, when considering application to contextual design opportunities?”

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Figure 1.16. *Bio Ex-Machina Research Project - 3D printed mycelium (Co-de-iT, 2016)*

Criteria throughout research

For the spatial printing step if a model is able to be printed, then it is successful even if there are some errors within the print such as missed points of contact between extrudate, or slight warping of the path. If these errors were significant enough to cause the overall form to be different than dictated, or cause continuous major errors, then it would be considered unsuccessful. If this occurred then it would be fixed either through changing the script, printing settings, or slight manual intervention.

When assessing the rate of growth across each experiment, if there were some irregularities in the mycelium growth such as lack of mycelium grown, or slight colour irregularities, these were left to continue growing. If there were any signs of green mould growing, the experiment was stopped or the contaminated test removed. Some moulds could grow white, making it difficult to distinguish from mycelium, so any white growth was allowed to continue growing and later identified, if made obvious it was not mycelium. If it was decided that there was contamination present, the growing process would be considered unsuccessful. However, knowledge could still be gained about the relationship between the mycelium composite and a printed scaffold, so it would not render a whole experiment as unsuccessful.

The overall aim of each test was to understand the relationship between a printed scaffold and mycelium composite. As the goal is to use the least amount of non-organic material to create the form, then a highly successful experiment would use the least amount of filament to be able to retain the most mycelium composite possible.

Methodology

Aim 1: Investigate the opportunities of using biomaterials and digital manufacturing tools in the field of architecture and design.

A critical step to establish a foundation of knowledge and position research focus within the design field is to use a literature review and conduct precedent research (Hanington & Martin, 2012). Through research into literature, an understanding of selected materials was developed by looking at their current use in design and architecture and properties they offer, with a focus on methods and practises adaptable to 3D printing.

By conducting a literature review, assessing case studies and material guides, an understanding of specific areas of knowledge with insights into the materials was formed. Using knowledge from a range of projects, established a base understanding of the research topic to begin educated decision-making when developing the research direction. By analysis and comparing projects that use bio-materials in a range of ways, each project provided inspiration and critique into what success could look like, and also what areas need to be explored further.

Promising material qualities identified from precedents gave inspiration to the direction of this research project. Experiments to understand how to control the chosen bio-material; mycelium, were carried out to develop a method of working with it. Variables that altered how the mycelium grew were identified, which helped to gain the understanding of how to use the material. From this understanding of the material, opportunities for application became clear. Criteria of what was wanted to be achieved were defined, what would need to be able to be controlled, and how it would affect the end output was formed from research and experiments.

Findings from previous research and experiments guided the decision of how to use mycelium most appropriately. Based on the knowledge collected from previous observations, criteria was formed to dictate what qualities the mycelium would need to possess to

pursue experimentation with additive manufacturing. From this understanding of mycelium as a material for 3D printing, options on the processing were identified. Using the information found in the literature and precedent review to inform where a gap in knowledge is within the design domain, an approach was chosen to pursue.

Aim 2: explore opportunities presented by the combining of mycelium with spatial printing, develop a context and sample designs that exemplify the design potential of the process.

Focusing on a varying pattern and the distance between filament strands, initial experiments indicated if it was possible to combine the materials, and how variations could change what was possible to create.

The formation of the printed object influenced the ability to retain mycelium composite and its growth. Conclusions drawn from the results of those experiments suggested how spatially printed scaffolds may also behave alongside mycelium.

Knowledge gained from previous experiments guided the focus for spatial prints with varying parameters. Spatial printing experiments used extruder settings defined in previous students' master's projects that were known to be successful. This meant experiments could focus on how the structural differences altered the ability to work with mycelium, rather than testing the spatial printing process itself.

Material options for spatial printing were identified and explored both through primary and secondary research. By understanding how the materials behave throughout the process, a good idea of what would be suitable output was established.

Spatial prints were assessed on the printability and capacity to retain composite material to refine what parameters were needed for designed structures suitable to a context.

At each stage of experimentation, the parameters that appeared to

work the most successfully to fulfil the criteria set, were identified and carried into the next step. A context suitable for the materials and method used was identified. Concepts fitting the specified context were created as a way of identifying the opportunities and limitations any output would have. Designs were focused on demonstrating the opportunities presented through the manufacturing method and materials used.

Using primarily digital tools such as Rhinoceros (Rhino) and Grasshopper, a range of forms were designed and converted to printable structures. Using the defined context as a driving force for design and opportunities and limitations as the success criteria.

CAD and rendering tools were then used to generate further developed concepts that would otherwise not be achievable within this research project due to time and the scale of resources.

Methodology

Frayling (1994) introduced the idea of describing types of design research under three different definitions; research into design, research for design and research through design. Frankel & Racine (n.d.) relates each of these titles to basic, clinical and applied research. Basic: research into design

The most straightforward and common being research into art and design, which can be historical, aesthetic or perceptual research, research into a range of theoretical perspectives on art and design. Research into design has countless models that provide an example of the rules and procedures (Frayling, 1994).

Clinical: Research for Design

Frayling (1994) first describes research for design as where the output would be an artefact that exemplifies the thinking. Research for design can label research that once carried out, is used to inform a way of designing that the designer wants to approach a project. Alternatively, it could be called research to enable design (Downton, 2003).

Applied: Research through Design

According to Frayling (1994), research through design can range from materials research, to development work such as custom technology, or innovation in a process, and the documentation of results. Action research uses step by step documentation of the process of practical experiments, which then communicate the results, differentiating research produced from a collection of resource material (Frayling, 1994).

From these definitions the research in this thesis fits under research for design as the knowledge collected throughout the experiments informs the next stage of experimentation, ultimately creating a guide for how to implement the process for future designs. The later stages of concepts and experiments fall under research through design as by applying previous knowledge to designs the opportunities and limitations could be further identified. This relationship between aims, objectives, methods and methodology are shown in figure X.

Aim	Objective	Methods	Methodologies
<i>Aim 1: Investigate the opportunities of using biomaterials and digital manufacturing tools in the field of architecture and design</i>	Establish a foundation of knowledge and position research focus within the design field	Literature review, Secondary research (Hanington & Martin, 2012)	Research for design
	Promising material qualities identified from precedents gave inspiration to the direction of this research project. Experiments to understand how to control the chosen bio-material; mycelium, were carried out to develop a method of working with it.	Evidence based design (Hanington & Martin, 2012)	Research for design
	Criteria was formed to dictate what qualities the mycelium would need to possess to pursue experimentation with additive manufacturing	Criteria based design (Hanington & Martin, 2012)	Research for design
<i>Aim 2: explore opportunities presented by the combining of mycelium with spatial printing, develop a context and sample designs that exemplify the design potential of the process.</i>	Knowledge gained from previous experiments guided the focus for spatial prints with varying parameters.	Evidence based design (Hanington & Martin, 2012)	Research for design
	At each stage of experimentation, the parameters that appeared to work the most successfully to fulfil the criteria set, were identified and carried into the next step. A context suitable for the materials and method used was identified.	Criteria based design, Concept mapping (Rodríguez Ramírez, 2017) (Hanington & Martin, 2012)	Research through design
	Using primarily digital tools such as Rhinoceros (Rhino) and Grasshopper, a range of forms were designed and converted to printable structures. Using the defined context as a driving force for design and opportunities and limitations as the success criteria.	Prototyping (Hanington & Martin, 2012)	Research through design

Materials

The choice of substrates was determined by identifying commonly used materials in mycelium products, such as woodchips, as well as consideration to what could be readily availability.

While being readily available, coffee grounds were also used as they were able to be sourced from local cafes allowing for up-cycling of a material. Another benefit is the pasteurisation which occurs during the brewing process, meaning it should be free from contaminants. This also contributed a variety in the material consistency from the straw while introducing the potential for contextualised designs in a café setting.

Flour was chosen to be tested as an additive due to online recommendations. However, being an edible product, this would be a waste of a food source and therefore not ideal as the primary substrate.

The upcycling of various materials offers an excellent sustainability value and doesn't target virgin material. The opportunity of using sustainable materials within this process was considered throughout the research; however, availability and consistency of substrates were made a priority within this research paper. Bags of straw could be purchased ready to use alongside the mycelium spawn, so were chosen to be used due to availability. Straw also offered variety in the composite texture and size, which benefitted the application process to printed structures.

Subsequent experiments used a range of substrate materials to explore material opportunities, one being wood chips or sawdust as it offers similar variety in texture and could be an upcycled material collected from the building or forestry industries. Sawdust was introduced as a substrate material in later experiments, sourced in the form of wood pellets that were then hydrated to break into sawdust.

To inoculate the substrate materials, spawn was purchased from

online "grow your own" mushroom retailers. Grey oyster (*Pleurotus ostreatus*) was the strain chosen to use as it was recommended by these retailers for beginners. Alternate strains would offer variations in material qualities due to hyphae make-up, within this research oyster mushrooms were used throughout to keep a constant variable and reduce complications from less reliable strains

Figure 1.17. Spawn and Substrate materials with corresponding symbols used (Author, 2020).

Mycelium composite preparation process

The base process used to grow mycelium composites was based on a collective knowledge from practical experience gained from the attending IAAC Summer school workshop as well as guides from literature and the mushroom kit suppliers.

The substrate must be free from bacteria and mould that would cause contamination later on, this is typically done through pasteurisation or sterilization. Substrate and spawn are then combined and left to grow in dark, humid and warm conditions where the mycelium will grow. An alternative method is to source an already grown mycelium composite block or prepare one using the previously stated method, and then break this up and mix with substrate to inoculate.

Water is added to the mixture while combining, based on the substrate being used. One technique of finding the correct moisture level is to squeeze a handful and if there is a small drip then it is suitable.

Figure 1.18. Mycelium composite making process (Author, 2020).

In a sterile environment, combine chosen substrates, spawn and water

Place Composite mixture into a grow bag, in a dark, temperature controlled space.

Allow mycelium composite to grow over a few weeks, monitoring growth and any signs of contamination.

Chapter

2

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Understanding Mycelium Composites -
Creating a process for growing mycelium
composites and understanding how they
can relate to 3D printed scaffolds

Figure 2.01. Supported + Water application experiment (Author, 2020).

First Mycelium Composite Experiments

This experiment aimed to test the growing ability of substrates and how the mycelium responded. By altering combinations of flour, coffee grounds and straw, the experiment was to evaluate the best composition of the three. Early tests showed that flour and coffee grounds without straw resulted in mould. Initial findings within this experiment indicated that the composite benefits from having a significant proportion of straw as it controls the moisture content and allows more aeration. As the first practical experiments the aim was also to begin to develop a method of creating the mycelium composites, through method setup, combining and establishing the correct environment.

Figure 2.02. Setup equipment: (clockwise from top) heat mat set up below wire racks inside enclosed incubator space; grow bag; spray bottle of water; containers for mould experiments; heat mats with temperature controller (Author, 2020).

In the first set of experiments, the primary goal was to build upon the experience gained from the IAAC workshop to develop a successful method for growing mycelium for the research project. Based on experience and literature, the main factors that needed to be controlled during the growing process were temperature, moisture, light, and maintaining a sterile environment. The focus of these first experiments was to identify what substrate combination to use and if it needed to be sterilised before use to ensure growing a successful mycelium composite.

The ideal conditions for mycelium growth is a warm, dark and humid environment. The exact temperature recommended varies between different sources but sits around the range of 24°C to 27°C. Temperature is critical, as if it was too low, it would not grow efficiently, and if it were too high, it could kill the mycelium.

During the growing process, mycelium produces heat, so as well as close monitoring, the ability to have the heating source adapt to any increase in temperature is essential. Moisture content was controlled by adding water until reaching a point where, when squeezing a handful of composite, it would slightly drip. Using this method as opposed to a measurement of water is more suitable as different substrates absorb it at a different rate. The squeezing created a controlled measure of overall moisture; therefore, constant volume-based measurements of water could not be used.

An incubator was built to create a controlled environment for the mycelium to grow, using a heating mat and plastic sheeting to block out light. This created an easily adjustable enclosed area that could open up for monitoring the progress of mycelium growth. Ensuring the space was enclosed meant temperature and light were controlled. The heating mat had a thermostat to adjust based on the detected temperature. Being set to produce a reading of 27°C, the thermostat sat under a bag of composite which was positioned, raised over the mat.

Figure 2.03. Spawn and substrates (coffee grounds and straw) used for first experiments (Author, 2020).

Each Mycelium composite combination used the same process in preparation. The composite mixture was placed inside plastic grow bags which have a patch that allows for air exchange pictured in Figure 2.02 .

In these first experiments, the process was to measure substrates into grow bags, add spawn (which is a grain inoculated with mycelium), and then add water until desired moisture content. The combinations tested were as followed

Icon	Combination	Mixture	Dry Weight
Straw	2 Cups Straw 1/3 Cup Spawn	160g
Coffee	2 Cups Coffee Grounds 1/3 Cup Spawn	414g
Straw + Coffee	1 Cup Straw 1 Cup Coffee Grounds 1/3 Cup Spawn	288g
Straw + Flour	1 1/3 Cup Straw 2/3 Cup Flour 1/3 Cup Spawn	259g
Coffee + Flour	1 1/3 Cup Coffee Grounds 2/3 Cup Flour 1/3 Cup Spawn	429g
Straw + Coffee + Flour	2/3 Cup Straw 2/3 Cup Coffee Grounds 2/3 Cup Flour 1/3 Cup Spawn	259g

Figure 2.04. Preparing of mycelium composite inside grow bag (Author, 2020).

Figure 2.05. Temperature reading of batch of mycelium composite experiments (Author, 2020).

Figure 2.06. Photos documenting mycelium composite growth over 18 days (Author, 2020).

The above figures show the development of growth of each mycelium composite. Monitoring the growth of each mycelium composite bag involved regular photography and inspections to assess if there were any signs of foreign bacteria growth. This was all done without opening the bags as not to risk contaminating the composite. Any composite with an indication of foreign mould growing was photographed and then disposed of as identified as identified above in figures X, X and X.

Figure 2.07. Photos documenting mycelium composite growth over 18 days (Author, 2020).

Of the three bags that had foreign mould growing, each appeared to have a much higher water content despite using the same process of adding water to all combinations. This failure is likely because the flour in two of the bags retained more water due to smaller particles of material; this would be similar to the coffee bag. The straw in the other bags appears to have a positive effect on the growth of the bags as it allows air to penetrate the surface of the mixture.

Second Mycelium Composite Experiments

In the first experiment, the spawn was added to the grow bags first, then substrate, then water and shaken to mix. This was not the most effective method as it meant dry substrate surrounded the spawn for some time, potentially drying it up.

It also meant that mixing the substrate with spawn was less thorough and more challenging to reach a consistent level of moisture, as well as spreading the mixture around the sides of the bag, later making visibility difficult when growth started.

Going forward, water was added before the spawn to improve on this technique. The preparation of each composite was also done in an external container, and then added to the grow bag this time to create a cleaner bag.

One variable tested in this phase of experiments, was the need to sterilise substrate materials. The straw was supplied from mushroomgourmet.co.nz, and is sold as “ready to mix for mushroom growth”. The instructions for growth did not include a sterilisation process; this indicated that there was no need for sterilisation or pasteurisation before use.

These sets of experiments tested the need for sterilising the coffee grounds. This may not be necessary as the coffee grounds are effectively pasteurised during the brewing process. However, there was some mould growth on composites containing coffee grounds in the first set of experiments, so doing this provides information on whether or not there needs to be secondary sterilising, or if the brewing process is enough.

Another factor to consider is that the coffee grounds used in the first experiment were a few days old, which is not ideal and could be a reason for failure. Moving forward, less water will be added and only freshly source coffee grounds were used to reduce the chances of contamination.

Another variable tested within this experiment was the ratio of materials used for each composite. Each bag contained a different substrate, a variation in the combination of substrates, or tested proportions of each part.

Five of the composite bags were aimed at testing how the substrate would promote mycelium growth. This included testing straw and coffee grounds both combined and separately, making one set of experiments using the sterilised coffee grounds and one set using fresh grounds, thus being able to establish if it influences the rate of mycelium or contaminant growth.

The four other bags were testing two different ratios between the coffee grounds, straw and spawn, once again using both sterilised and fresh coffee grounds to compare the need of sterilising.

To sterilise half of the coffee grounds, they were placed in an oven bag, in a pot containing water heated between 65-75°C for one hour. The process to create each mixture was first to measure out substrate material with cup measurements and then weigh. Water was then introduced slowly while mixing until reaching a point where a small amount of water would drip when a handful of the substrate was squeezed, and then once again weighed. Spawn was then added to the mixture. The total weight was then measured before folding the bags closed with a clip.

	Label on bag	Mixture	Dry substrate weight	Wet substrate weight	Weight with spawn	Water used
CF	2c Coffee Fresh ½c Spawn	328g	373g	454g	48ml
CS	2c Coffee Sterilized ½c Spawn	335g	382g	471g	53ml
GM	2c Straw ½c Spawn	78g	224g	311g	148ml
GM+CF	1c Straw 1c Coffee Fresh ½c Spawn	195g	251g	334g	58ml
GM+CS	1c Straw 1c Coffee Sterilized ½c Spawn	229g	332g	417g	103ml
1	1 1/3c Coffee Sterilized 2/3c Straw ½c Spawn	264g	331g	417g	67ml
2	1 1/3c Straw 2/3c Coffee Sterilized* ½c Spawn	181g	295g	382g	119ml
3	1c Straw ½c Coffee Sterilized 1c Spawn	139g	204g	365g	68ml
4	1c Coffee Sterilized* ½c Straw 1c Spawn	204g	258g	416g	58ml

Figure 2.08. Experiment 2, Photos documenting mycelium composite growth over 13 days (Author, 2020).

For this set of experiments, there were no signs of green mould growth in any bag, and each combination appeared to have the spawn inoculate the substrate effectively.

Figure 2.09. Experiment 2, Photos documenting mycelium composite growth over 13 days (Author, 2020).

For bags labelled GM, 2, 3, and 4 there appeared to be faster initial growth than the others, although all were growing successfully. By the third week, all bags, especially those labelled GM, GM+CF, GM+CS, 2, 3, and 4, had a significant amount of growth. No particular combination appeared to be an obvious choice as the most successful since there such subtle disparities between each composite. There was no visible difference between the fresh and sterilised coffee being used. This indicated that it was either the use of old coffee grounds or having too much moisture that caused the previous failure. From that point on, coffee grounds were only used the same day as being collected, and less water was used.

Introducing Mycelium to 3D prints

This project is exploring the possible relationship between the spatial printing of structures and using that as a scaffold for mycelium growth. There were three areas of consideration when approaching this research project; the growing of mycelium composite material, the printing of a scaffold structure, and then being able to control the relationship between the materials when combined. The application of these methods to designed object then assess the opportunities of these methods. This experiment introduced the testing of application and growth of mycelium composite with 3D printed structures. Successful composites grown in the previous experiments were used for this next stage of investigation first introducing it to 3D prints.

Spatial printing is a technique of using a robotic arm with an attached extruder to print structures that are not limited to building up layer upon layer in the vertical direction, but instead can deposit material where instructed. Creating code to instruct the robot arm for spatial printing is a different process than designing for a FDM printer. Designing the toolpath of printing takes time to develop a technique suitable for the model. The first set of application experiments used FDM printing to replicate spatial prints, this meant these experiments could be carried out without first needing to take time to develop the printing technique. The results of these experiments were then able to inform the approach to designing the toolpath for spatial printing, improving the chances of success.

To understand how mycelium would interact with a 3D printed scaffold, the first experiments needed to focus on the distance it could be held within, the pattern of the print strands, and application technique. The first set of prints to be tested concentrated on the distance and pattern and then the second focused on application.

Figure 2.10. FDM Printed scaffolds for experiment 3 (Author, 2020).

Figure 2.11. Line drawings of scaffolds used for experiment 3, with scale (Author, 2020).

Part 1: Distance + Pattern

Spatially printed forms are typically made from a set of defined points, with the extrudate deposited in straight lines between the points, this means that all of the patterns tested were based on this point to point construction method and no curvaceous lines were printed.

This set of experiments focused solely on the ability to hold composite material on a horizontal plane, this gave guidance to how volumetric spatial prints could be applied with composite material.

Design of tests

The lowest value choice of distances was based on using a minimum distance to give a very dense starting point but far enough that the strokes of filament did not create a solid plane next to each other. The distances increased to a value where it was expected not to be able to support a significant amount of mycelium composite. The pattern repeated in sets of five and then increased to the next value. This was done, so it was easy to identify a change in the amount of composite material captured at each distance.

Zig Zag patterns are often used for vertical walls in spatial printing, however, to get an idea of how the pattern affects retention, five patterns were tested. Each pattern varies in the amount of filament used, with the line pattern using the least, then Arrow and Zig Zag, and then the Grid, with Cross using the most. For a final proposed process, the less material used the better.

Application

This experiment used the Mycelium Composite from the previous experiment. Bags GM+CF and GM+CS were used as there was no visible difference between fresh and sterilised, indicating that as long as experiments are using fresh coffee grounds, the substrate can sustain mycelium growth without contamination.

As with preparing to mix mycelium composite the work area was sterilised with alcohol. The 3D prints were also cleaned with alcohol to ensure they did not contribute to contamination.

Starting by taking the composite block from each bag and breaking it up by hand to small pieces, ensuring it was broken down to pieces smaller than 20mm in diameter. One cup of straw and 1 cup of sterilised coffee grounds were mixed through.

To apply the mycelium composite to the 3D prints, an even amount of finely broken up growing material was sprinkled across the entire surface by hand. Enough material was sprinkled for approximately 10mm of coverage of 3D prints on a well-supported area, and then any unsupported material would fall between the gaps. This was kept constant as if more of the mycelium composite was applied; more could be retained by building upwards, even at some longer distances. This is shown in an illustration in Figure 2.13.

Figure 2.13. Potential build up of mycelium composite if continued application (Author, 2020).

*starting with 10% as 0% would be if no mycelium composite was present on the print (before combining process)

Figure 2.12. Diagram of percentage value given to each unit value (Author, 2020).

Analysis

A visual assessment was made, and a percentage value was assigned to each section based on how much coverage was achieved by the mycelium composite, this allowed for consistent assessment of the success of each section. The percentage related to how much material could be supported and grown on the printed form, Figure 2.12 displays the value each level of coverage would be assigned.

100% would mean that there were no visible gaps where the composite had fallen out or was unable to grow across, and 0% indicated there was no mycelium composite present at all. Since the entire prints were directly sprinkled with mycelium composite without any obstructions, even the most “unsuccessful” sections had a value of 10% as some traces would remain on the print.

In a spatially printed structure with a range of vertical branches, there may be sections that would not receive a direct application of Mycelium Composite so would remain with a value of 0%. In areas that growth extended farther than the composite material itself, it was noted and discussed as this would be an example of successful growth.

Figure 2.14. Mycelium composite blocks used for application experiments (Author, 2020).

This experiment used the Mycelium Composite from the previous experiment. Bags GM+CF and GM+CS were used as there was no visible difference between fresh and sterilised, proving that as long as experiments are using fresh coffee grounds, the substrate should contain no foreign bacteria that could grow harmful mould.

As with preparing to mix mycelium composite the work area was sterilised with alcohol. The 3D prints were also cleaned with alcohol to ensure they did not contribute to contamination.

Starting by taking the composite block from each bag and breaking it up by hand to small pieces, ensuring it was broken down to pieces smaller than 20mm in diameter. One cup of straw, and 1 cup of sterilised coffee grounds were mixed through.

In the process of application each print was sprayed with water, sprinkled with broken up mycelium composite while resting on a table, and then lifted to move. While moving some of the mycelium composite would fall off in areas where the distance was too great to retain it, mimicking what would happen to suspended spatial prints.

Figure 2.15. Process of breaking apart mycelium composite blocks to add new substrate for application experiments (Author, 2020).

Figure 2.16. Distance focused application experiments before growth (Author, 2020).

Figure 2.17. Application experiments in incubator (Author, 2020).

Line

Figure 2.18. (Above) Line Pattern experiments front, back and side angles (Author, 2020).

Figure 2.19. (Below) Line drawing of pattern type (Author, 2020).

Line 1a

$$L=2(dxX)+w(X+1)$$

Average	63.8%
4.5mm	100%
5mm	100%
7mm	100%
9mm	90%
11mm	50%
13mm	40%
24mm	10%
30mm	10%

The line pattern was the base structure that all pattern variations used as a base, each variation just introduced more printed strands bridging the gaps.

The three smallest distances proved to catch composite material at a high volume.

At 9mm gaps, there were a few small spaces, then dropped between 9 and 11mm and again with 13 and 24mm.

Figure 2.20. Close up of line pattern experiments (Aubor, 2020).

Grid

Figure 2.21. (Above) Grid Pattern experiments front, back and side angles (Author, 2020).

Figure 2.22. (Below) Line drawing of pattern type (Author, 2020).

Grid 1b

$$L=[(dxX)x(n+2)]+w(X+1)$$

Average	82.5%
4.5mm	100%
5mm	100%
7mm	100%
9mm	100%
11mm	90%
13mm	80%
24mm	50%
30mm	40%

The grid pattern appears to have a consistent decline in the amount of material captured as expected, with the distances between 4.5 and 13mm having a high amount of material captured

Figure 2.23. Close up of grid pattern experiments (Author, 2020).

Zig-Zag

Figure 2.24. (Above) Zig-Zag Pattern experiments front, back and side angle (Author, 2020).

Figure 2.25. (Below) Line drawing of pattern type (Author, 2020).

Zig Zag 1c

$$L=2(dxX)+w(X+1)+\sqrt{(d2+w2)}$$

Average	80%
4.5mm	100%
5mm	100%
7mm	100%
9mm	100%
11mm	90%
13mm	90%
24mm	30%
30mm	30%

The zig-zag and arrow pattern each use the same amount of filament to cover the same distance but differ in pattern slightly. The benefit to using the zig-zag pattern over arrow is that in printing, it could be a continuous line. This is why it is often used in spatial printing.

Both patterns appear to capture a similar amount of composite, with the zig-zag seeming to hold slightly more. Both retained a high amount of composite at distances lower than 13mm with a significant drop in material for the largest two spans of 24 and 30mm, although there is still some captured material in the tighter angles

Figure 2.26. Close up of zig-zag pattern experiments (Author, 2020).

Arrow

Figure 2.27. (Above) Arrow Pattern experiments front, back and side angle (Author, 2020).

Figure 2.28. (Below) Line drawing of pattern type (Author, 2020).

Arrow 1d

$$L=2(dxX)+w(X+1)+\sqrt{(d2+w2)}$$

Average	77.5%
4.5mm	100%
5mm	100%
7mm	100%
9mm	100%
11mm	90%
13mm	80%
24mm	30%
30mm	20%

While the arrow pattern has the same path length as the zig-zag, both were tested to identify if they would perform significantly different. The results were very similar, with just a slightly less amount of mycelium composite retention.

Figure 2.29. Close up of arrow pattern experiment (Author, 2020).

Cross

Figure 2.30. (Above) Cross Pattern experiments front, back and side angle (Author, 2020).

Figure 2.31. (Below) Line drawing of pattern type (Author, 2020).

Cross 1c

$$L=2(dxX)+w(X+1)+2(\sqrt{(d2+w2)})$$

Average	87.5%
4.5mm	100%
5mm	100%
7mm	100%
9mm	100%
11mm	100%
13mm	90%
24mm	60%
30mm	50%

As expected from using the most filament, the cross pattern had the highest average collection percentage. This meant even at the highest distance tested; there was still 50% collection.

Figure 2.32. Close up of cross pattern experiments (Author, 2020).

Figure 2.34. Distance and pattern experiments during growth (Author, 2020).

By appointing a percentage value to the results of this experiment, a correlation between distance, pattern and mycelium composite capture was identified to make analysis of the experiment clear. The results were as expected with smaller distances able to retain a majority of the mycelium composite, forming a substantial amount of coverage. At the larger distances there was a significant drop in composite retention. However, there were some signs of mycelium growth reaching across gaps or in-between composite material which is an interesting quality. Since the PLA filament used is not an organic material a successful design would use the least amount of filament possible to retain the maximum amount of mycelium composite. For the majority of applications this would require the mycelium to be completely retained in a solid body, however the use of spatial printing could give opportunity to using the materials for sparse coverage or varying densities.

Figure 2.33. Graph showing rate of mycelium composite retention for each pattern and distance value (Author, 2020).

Part 2: Application Method Experiments

The first tests were primarily testing the path and pattern of the 3D printed structures, assessing the effect of distances between strands of extrudate in its ability to retain mycelium composite and grow. The secondary tests focused on evaluating the method of applying growing medium to 3D prints. To design for material capture in suspension is different from when there is a supportive surface below. To conduct these tests, a square sample print was designed containing four variations of patterns; this provided the ability to assess each application method more accurately.

The primary focus of these tests was to identify how the growth medium can be captured to then grow onto 3D prints, and how a different method of this application alter the results.

The methods being tested were sprinkling growing medium over a suspended print, sprinkling mycelium composite over a print that has a plastic sheet under, and compressing it onto a print that has a plastic sheet underneath.

Another variable tested was glucose powder, when mixed with water creating a glucose solution, would it affect the growth of the mycelium or its ability to assist adhesion?

Symbols associated with each of these variables are used to identify what each experiment was testing.

Water

Glucose

Compressed

Supported

Raised

Figure 2.35. Symbols used to identify variables used within each experiment (Author, 2020).

Moulded Tests

Figure 2.36. Moulded experiments during growth (Author, 2020).

While carrying out these application method tests on 3d prints, moulded tests were done to be able to compare between the use of traditional mould making, and the suggested method of using spatial prints as a scaffold.

Four tests were done to compare the variables of water against glucose and compression versus leaving at rest. Each test was filled in the container to the same level, this meant that more mycelium composite was used for the compressed tests. While filling each container it was either sprayed with water or a solution of 1 part glucose powder and to 4 parts water

All experiments successfully grew mycelium with slight variations due to the application method. Water with compression appeared to have the most consistent white coverage across the model and extremely defined edges.

Glucose with compression also grew very effectively, although it did not produce as white of a coverage in growth.

Both of the non-compressed experiments grew similarly to each other although water had a greater amount of white growth spread across the top, which formed a network of fibrous mycelium.

The glucose non-compressed test had slightly more white mycelium growth visible on the under-side but less on the top than the water variation.

As would be expected, the non-compressed tests had much more variation in the surface texture, this created a significantly more porous materiality.

Figure 2.37. Water, non-compressed experiment after growth and desiccation (Author, 2020).

Figure 2.38. Water, compressed experiment after growth and desiccation (Author, 2020).

Figure 2.39. Glucose, non-compressed experiment after growth and desiccation (Author, 2020).

Figure 2.40. Glucose, compressed experiment after growth and desiccation (Author, 2020).

Raised + Water

Figure 2.41. Raised with water experiment after mycelium growth (Author, 2020).

This application process was done by raising the print off of the table onto a rim of a container to be suspended away from a support surface, this allowed any material that the print itself could not support to fall below. The print was then sprayed with water to assist with the bonding capabilities and then sprinkled with mycelium composite across it evenly. While sprinkling and once done, water was then resprayed. Areas where there was little printed structure to support the growth medium, were much more likely to have the bulk

Figure 2.42. Raised with water experiment after mycelium growth, close up (Author, 2020).

Raised + Water ~ Desiccated

Figure 2.43. Raised with water experiment after desiccation (Author, 2020).

of the material fall through, as seen in the distance print experiments.

Mycelium grew across some of the composite material, with a section even reaching outwards or bridging across small gaps between the scaffold. While the mycelium composite was securely connected to the 3D print enough to remain secured while moving, pieces could be broken off if met with force. There was one focused area of growth which when desiccated contracted in size and turned into created more of a webbing form.

Figure 2.44. Raised with water experiment after desiccation, close up (Author, 2020).

Raised + Glucose

Figure 2.45. Raised with glucose experiment after mycelium growth (Author, 2020).

Same as the previous test, the print was suspended, then this time sprayed with a glucose and water solution. While applying and after it was resprayed with the solution. The use of glucose did appear to have a positive effect on aiding in adhesion and collection between the growth medium and printed structure. While it did not make a significant difference in the collection of larger pieces.

Figure 2.46. Raised with glucose experiment after mycelium growth, close up (Author, 2020).

Raised + Glucose - Desiccated

Figure 2.47. Raised with glucose experiment after desiccation (Author, 2020).

Similar to the previous results there was a focused area of significant growth and spanned over a few gaps. The glucose did help with more mycelium composite to stick to the strands of the scaffold however this not show significant signs of growth.

Figure 2.48. Raised with glucose experiment after desiccation (Author, 2020).

Supported

Figure 2.49. Supported with water experiment after mycelium growth (Author, 2020).

For this experiment, instead of being suspended, the print was placed on a plastic sheet on a flat surface. Then similarly to the first test, sprayed with water before, during, and after application of mycelium composite. As expected, the plastic supported the mycelium composite while sprinkling it over the print. There was some variety in the size of mycelium composite pieces as with the other tests.

Like the suspended tests there was a good amount of mycelium growth across the 3D print and composite material

Figure 2.50. Supported with water experiment after mycelium growth, close up (Author, 2020).

Supported - Desiccated

Figure 2.51. Supported with water experiment after desiccation (Author, 2020).

but this time had much more mycelium composite between the scaffold gaps as it was supported. The mycelium bonded the substrate materials effectively connecting it across gaps between the printed strands, however with too much force some parts could break off. This test did also have two focused areas of growth which then flattened out once desiccated.

Figure 2.52. Supported with water experiment after desiccation, close up (Author, 2020).

Supported + Compressed

Figure 2.53. Supported and compressed with water experiment after mycelium growth (Author, 2020).

Identical to the previous test, the print was placed on a plastic sheet on a flat surface, sprayed with water, then applied with mycelium composite and sprayed again. Once the mycelium composite was applied, it was compressed by hand.

Almost all mycelium composite remained on and between the print strands due to either the print or the base under

Figure 2.54. Supported and compressed with water experiment after mycelium growth, close up (Author, 2020).

Supported + Compressed ~ Desiccated

Figure 2.55. Supported and compressed with water experiment after desiccation (Author, 2020).

it. By compressing it down, this helped even the surface across and allowed it to surround each print strand. As with the other tests there was a good amount of growth, since it had been compressed it was more secure when moving the print around. This was the only test that did not have a focused area of growth but instead showed more white mycelium growth across the surface.

Figure 2.56. Supported and compressed with water experiment after desiccation, close up (Author, 2020).

Supported + Compressed + Glucose

Figure 2.57. Supported and compressed with glucose experiment after mycelium growth (Author, 2020).

Using the same process as the previous test but with the glucose solution rather than water being sprayed. Then once again manually compressing the mycelium composite.

Application of the growing medium was identical to just using water. There appeared to be some benefits to aiding in the adhesion of collected growth medium but not to the extent of making a significant difference.

Similar to the previous results there was a good amount of growth that secured the mycelium composite onto the

Figure 2.58. Supported and compressed with glucose experiment after mycelium growth, close up (Author, 2020).

Supported + Compressed + Glucose - Desiccated

Figure 2.59. Supported and compressed with glucose experiment after desiccation (Author, 2020).

scaffold. This test did also have a the focused area of intense mycelium growth but also had a significant amount of visible mycelium grown across the surface.

Figure 2.60. Supported and compressed with glucose experiment after desiccation, close up (Author, 2020).

Application tests reflection

These first experiments which explored the potential application of mycelium composite to a 3D print proved to have varying degrees of success. All experiments grew effectively with some reach?? between composite material and between print strand gaps, however this was not across large distances and had variety in rates of growth. Based on these experiments, if a printed structure had no support below the base then it would require the distance between strands to be 13mm or less to be able to easily retain the mycelium composite. Another option however, could be to not break down the mycelium composite as finely, so larger pieces could bridge across the printed strands.

The most effective way to combine mycelium composite to a 3D print would be to have it rest on a flat surface for application and growing, for extra bonding, compression could be applied. This is as expected as it is comparable to using a mould to shape the form. Another observation is that there was no difference to the growth of the mycelium due to glucose powder + water mix being applied compared to just using water. It did however help slightly with some mycelium composite adhesion to the print during application.

Figure 2.61. Under side of supported and compressed with glucose experiment after desiccation, close up (Author, 2020)

Chapter reflection

From the first phase of experiments, an understanding of how to prepare and create mycelium composites was formed. The investigation into the relationship between substrates and success of growing mycelium quickly and without contamination was identified. This knowledge was used going forward to create mycelium composite for subsequent experiments. Subsequent experiments used a combination of straw, coffee grounds and spawn to grow mycelium composites, although this was adapted again upon further experimentation.

Through introducing the mycelium composite to 3d prints, there was a variety of visual and material qualities achieved. In part one of tests a relationship between the distance of printed strands, pattern, and ability to retain mycelium composite was identified. As expected, printed forms with less distance between the strands could retain more mycelium composite. What was uncertain, was if mycelium could be retained between the printed structures' gaps, and if it would grow outwards at all. While there was not a consistent occurrence of this outwards growth across all of the mycelium composite, it did occur on a range of prints to different degrees.

Part two of the application test which looked into how the application of the mycelium composite effected the resulting growth showed how different the end result could be with the same printed structure. These showed how there was little difference in the use of glucose, but a significant difference on if the printed structure was raised, supported, or supported and compressed. While the print being able to support mycelium composite raised would be the best, as it removes the need for a separate support board, it did retain a significantly less amount of mycelium composite. A successful observation was that even once removing the print from the support beneath, it retained the connection to the mycelium composite, forming almost full coverage of the scaffold. The supported tests that were done under compression had a very strong bond to the printed framework.

Alongside the experiments focused on applying mycelium composite

to the printed structures, containers were used as moulds to create samples that replicated the more traditional approach of forming mycelium composite objects. These were important to make to be able to identify first-hand the benefits and limitations of the process. These each had a much more consistent coverage of white mycelium growth than the printed structure tests. This would be a goal in later volumetric tests using printed scaffolds, however it was likely not achieved in this set of experiments because of how thin and sporadic the mycelium composite was.

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Volumetric Exploration -
Generating volumetric spatial
prints and exploring their ability
to retain mycelium composite

*Figure 3.01. (Right) Surface of narrow angle curvilinear experiment after
desiccation (Author, 2020).*

Spatial Printing

A significant difference between FDM printing and spatial printing is in the design process. To design for FDM printing is relatively simple, typically a solid model needs to be designed through CAD and then exported as STL or OBJ file. The printing software then automatically slices the model into print layers and adds in any support material if required.

Spatial printing is different as the benefit of using it is being able to generate the exact points of material to be deposited. Exploiting the ability to move in the X, Y and Z-axis also means that it does not need to be built layer upon layer. CAD software Rhino and Grasshopper were used to generate the tool path points, and then HAL was used to translate it to the robot arm. The initial models used printing settings and structural patterns that had been refined by previous masters students; this meant the printing settings such as speed and temperature were known to print effectively and bond to extrudate at intersections (nodes), resulting in successful prints. By using this established knowledge to begin printing, there was little need for experiments focused on how to print. Instead, they focused on how the formation of the print could influence the synergy with mycelium composite. Each print was done with a focus of testing either unit size, construction of a print, or the overall geometry of the form.

Figure 3.02. (Above, left) Diagram of points dictating movement for toolpath (Author, 2020).

Figure 3.03. (Above, right) Diagram of what is referred to as one unit within printed structure (Author, 2020).

Using a print speed of 4mm per second and temperature set at 2V which translates to 235.1°C. For the first base layer it was advised to use a scraper to push down the extrudate while still hot to reduce the chance of the print lifting from the printer bed, which was a sheet of acrylic. For this first layer the fan that cools the extruded filament is turned to low to allow for the extrudate to cool slower.

The first set of spatial prints focused on setting up a script to make the desired forms. Using the base script from workshop technician, Hamish Morgan, it was then adjusted accordingly to the variations in patterns. To convert a digital model for spatial printing, points where the robot arm moves must be defined. The overall form was either generated in Grasshopper or Rhino, then divided into layers and units of a repeating pattern.

The first three prints tested the size of units making up the form. Values used were 30mm 40mm and 60mm. This was to examine the distance of units that could contain the mycelium composite

effectively. While the larger the unit size, the more material fallout is inevitable. The benefit of using a larger value for units is that it takes less time and material, so finding a balance between size and retention of mycelium composite was the goal of these experiments.

An error in the script was that the height value defined would act as a limit rather than a defined height; therefore each print ended up at different heights. This meant that when applying the mycelium, each one was filled to the lowest height to be able to compare the performance of mycelium composite retention effectively.

The lowest unit value tested was 30mm; this was used as it was the largest tested in the previous horizontal tests. The same pattern had 30% coverage in the horizontal tests, which would be too little for horizontal use however this was testing vertical walls, which were anticipated to support the mycelium composite at a higher rate.

The script was then adjusted to create models with internal structures which would be able to add strength and stability

Figure 3.04. HAL script provided by workshop technician Hamish Morgan (Author, 2020).

Fan Controls

Filament

Temperature ready indicator light

Flattening base layer against acrylic bed

Figure 3.05. (Above, left) Close up of extruder's filament feeder (Author, 2020).

Figure 3.06. (Above, middle) Extruder attachment on robot arm (Author, 2020).

Figure 3.07. (Above, right) Manual monitoring of first layer of printing, using a scraper to push against printing bed to assist adhesion (Author, 2020).

To prepare for the volumetric tests, new bags of mycelium composite were made. This time beginning with 2 bags of pre-mixed bags of straw and spawn sent from the supplier to speed up the process. One pre-mixed bag was mixed with equal parts coffee grounds, which resulted in two new bags of straw and coffee ground mycelium composite.

The supplier changed the type of straw to a much finer mixture, opposed to the more coarse and varied size previously supplied (figure X). Using the course leftover substrate from the previous experiments one bag was made up with equal parts coffee grounds and a cup of spawn. Another bag was made from the newer finely ground straw, equal parts coffee grounds, and one cup of spawn.

The resulting composite bags were as follows

1x pre-made straw bag,

2x straw + coffee grounds bags,

1x course straw with coffee grounds,

1x fine straw bags with coffee grounds.

These five bags were then left for a week to grow further.

For the rectangular volumetric tests all four of the composite mixtures were used apart from the pre-made straw bag.

To calculate the expected amount of mycelium composite needed to fill up each print, the volume was calculated. Since the prints were not the same height they were marked to be filled each to the same height of 180mm. Volume was calculate with

$$\begin{aligned} B \times H \times W &= 240 \times 180 \times 120 \\ &= 5,184,000 \text{mm}^3 \\ &= 5,184 \text{ml} \end{aligned}$$

$$1 \text{mm}^3 = 0.001 \text{ml}$$

From this calculation 5000ml was used as the base amount to be applied into the print. This was less than the calculated volume to make sure that it would not be overfilled, and give the potential for sparse filling of the structure while not overflowing.

$5,000,000 \text{mm}^3 = 5000 \text{ml}$ of mycelium composite was applied to the prints, then the falloff was measured to calculate the ratio of successfully captured vs fallout. This does not mean it would be directly the same for different geometries, but gave an indication of the relationship between grid size and mycelium composite retention. A measuring jug was used with millilitres marked on the side to track the amount of mycelium composite applied.

Figure 3.08. Side view of first 3 spatial prints, showing variation in height due to script error, left: 30mm, middle: 40mm, right: 60mm (Author, 2020).

Figure 3.09. (Above, left) Preparing mycelium composite by mixing coffee grounds, spawn, and a mix of straw and wood pellets that had been soaking in hydrated lime and water 24 hours early to cold water pasteurise (Author, 2020).

Figure 3.10. Substrates and spawn combined (Author, 2020).

External Wall Print 30mm x 30mm

This first script was made to create an initial volumetric form with no internal structure, just a base and walls. It was used for the initial 3 volumetric spatial prints, it then acted as a base for all future prints. There was one error in the script that made it print one unit less than the intended height of 240mm. This was adjusted in later scripts after these first spatial print experiments, the prints of varying heights were still used but marked at 180mm to make the experiments consistent.

Figure 3.11. Toolpath of 30mm x 30mm external wall spatial print (Author, 2020).

Figure 3.12. Script used for 30mm x 30mm external wall spatial print (Author; 2020).

To print using the robot arm, the Grasshopper script needed to be converted to code and exported to the robot arm controller. A plugin called HAL was used within Grasshopper to do this. The plugin script used, was one created by a previous masters student, Hamish Morgan, within his thesis, it worked for all prints with some minor adjustments for a few of a larger scale.

Figure 3.13. 30mm x 30mm external wall spatial print line sketch (Author: 2020).

Printing

Figure 3.14. Robot controller, monitoring early stage of print (Author, 2020).

Figure 3.15. First layer of vertical movements underway (Author, 2020).

Printed Scaffold

Figure 3.16. Close up of minor errors in 30mm x 30 mm external wall print (Author, 2020).

Figure 3.17. 30mm x 30mm external wall print (Author, 2020).

The first model printed without any issues first try, there were a couple of points where nodes did not fully connects although this had no effect on the overall form.

Mycelium Composite Application

Figure 3.18. Filling of 30mm x 30mm external wall print to black mark indicated (Author, 2020).

Figure 3.19. Filling of 30mm x 30mm external wall print (Author, 2020).

The process of applying the mycelium composite to the spatial print was as follows:

The print was cleaned with alcohol and placed on a plastic board the size and shape of the base, this acted as a support plane to retain material during application and growth, and was then removed before desiccation. The print and board were raised on supports in a bin to allow mycelium composite to fall out through the gaps but then be retained to measure falloff.

Once 5000ml of mycelium composite was sprinkled across the print, falloff material was measured to calculate ratio between retention and loss. More mycelium composite material was applied to the print in the same way until it reached the 180mm height level. This was done with more focused application to areas that were not level. The amount of material it took to reach full volume was recorded, this amount included falloff in secondary application.

For this structure, when the first 5000ml of mycelium composite was applied there was 450ml falloff. This meant a high retention rate of the material, as would be expected, due to the lowest value of 30x30mm being used per unit.

30x30mm
5000ml applied
450ml falloff
250ml to fill

h = 210mm

weight of print (m) = 124g

Growing

Figure 3.20. Close up of growth after two weeks of growth (Author, 2020).

Figure 3.21. Growth after two weeks of growth (Author, 2020).

All volumetric tests were placed inside a clear bin in the incubator to grow. The growth was regularly monitored and photographed, without removal from the growing bin, to not disturb the growth or contaminate the structures. Extra water from condensation within the one bin pooled to the bottom, this was removed during monitoring as it was a sign of too much moisture present.

Results After Growth

Figure 3.22. 30mm x 30mm filled experiment after four weeks of growth (Author, 2020).

This test, along with others in this group of experiments did not grow mycelium as desired and was not considered successful. There were some regions with signs of mycelium growth, and then many regions with signs of growth that was not mycelium and therefore a sign of contamination.

Figure 3.23. 30mm x 30mm filled experiment after four weeks of growth (Author, 2020).

While the results after growth were deemed unsuccessful, the application of the mycelium composite to the spatially printed scaffold was successful. With the dimensions of units in this test being 30x30mm there was efficient retention of the composite material during application. Less than 10% of the initially applied material fell through the gaps of the printed structure.

External Wall Print 40mm x 40mm

This script was identical as the one used for the previous volumetric spatial print with the unit size adjusted from 30mm to 40mm.

Note that the generated path is five units high with the units being 40mm, thus the total height was 200mm instead of the intended 240mm due to the fault in the script of the top row.

Figure 3.24. 40mm x 40mm external wall spatial print line sketch (Author, 2020).

Figure 3.25. Script used for 40mm x 40mm external wall spatial print (Author, 2020).

Printed Scaffold

Figure 3.26. 40mm x 40mm external wall spatial print (Author, 2020).

As with the last spatial print there were no significant errors, just a few nodes that did not connect fully.

Figure 3.27. Close up of minor errors in 40mm x 40mm external wall spatial print (Author, 2020).

Mycelium Composite Application

Figure 3.28. Filling of 40mm x 40mm external wall print to black mark indicated (Author, 2020).

Using the same process as with the 30mm print, the volumetric print was cleaned, placed on a plastic board, raised within a bin and applied with 5000ml of mycelium composite. This resulted in 600ml of falloff and then took 500ml to fill to the 180mm mark. This was only 150ml more falloff than then previous 30x30mm print and took twice the amount of further mycelium composite to be applied to reach the 180mm mark. Though there was an increase in falloff due to the larger unit size, the printed structure was still able to hold the majority of mycelium composite and fill in the structures form without secondary support.

40x40mm	h = 200mm	m = 89g
5000ml applied		
600ml falloff		
500ml to fill		

Growing

Figure 3.29. Close up of growth after two weeks of growth (Author, 2020).

Figure 3.30. Growth after two weeks of growth (Author, 2020).

Results After Growth

Figure 3.31. 40mm x 40mm filled experiment after four weeks of growth (Author, 2020).

The same batch of mycelium composite was used in this structure as the previous and showed the same type of growth patterns, with some regions of mycelium composite showing signs of white mycelium growth, areas of no obvious growth, and areas of contamination.

Figure 3.32. 40mm x 40mm filled experiment after four weeks of growth (Author, 2020).

External Wall Print 60mm x 60mm

The same script was used as previously with the unit size adjusted to 60.

Figure 3.33. 60mm x 60mm external wall spatial print line sketch (Author, 2020).

Figure 3.34. Script used for 60mm x 60mm external wall spatial print (Author, 2020).

Printed Scaffold

Figure 3.35. First attempt of 60mm x 60mm external wall spatial print, errors caused print to be stopped (Author, 2020).

Figure 3.36. 60mm x 60mm external wall spatial print, some breakage of base when scraping off of bed (Author, 2020).

While this spatial print used the same script as the previous two there were some issues not faced previously.

In the first attempt at printing, the first corner of vertical movements did not stick to the base and then could not create the path changing directions in the corner of the print structure. To fix this, the robot was instructed to return to begin the vertical values and then it was paused manually to ensure enough material was extruded to bond with the base layer.

This appeared to happen because the first base layer was noticeably thin, meaning that the height of it was not high enough for sufficient contact.

This print then had errors again with the second level of the path, as the base path did not meet with the previous points correctly and then the next set of vertical movements did not connect properly. The tip of the vertical points appeared to have too much of a curve to them which made for an incorrect height for the next layer to meet with.

This was likely due to incorrect TCP (Tool Centre Point) so that was recalibrated. The maximum angle was also adjusted from 30° to 40°, just to give the best chance of fixing the problem.

After these changes were made there were no further issues.

Mycelium Composite Application

Figure 3.37. Filling of 60mm x 60mm external wall print (Author, 2020).

Using the same method as previously, this print was applied with 5000ml of mycelium composite. There was however, a significant increase in the amount of material falloff. It then took 4000ml to be applied to reach the height of 180mm. This was significantly less efficient than prints that contained smaller unit size. The mycelium composite would easily build up in a mound in the centre of the structure, creating a hill shape where newly added composite would roll down and through the gaps in the print. This meant that it reached a point where the contained mycelium composite was not building in volume, but instead, only falling out.

60x60mm	h = 180mm	m = 58g
5000ml applied		
1700ml falloff		
4000ml to fill *		
1000ml to fill manually *this is just how much was then added on top to reach the height of 180mm, some of this did then fallout		

Growing

Figure 3.38. Close up of growth after two weeks of growth (Author, 2020).

Figure 3.39. Growth after two weeks of growth (Author, 2020).

Results After Growth

Figure 3.40. 60mm x 60mm filled experiment after four weeks of growth (Author, 2020).

This print experiment grew the same as previously discussed, with regions ranging between no growth, mycelium growth and contamination growth.

Figure 3.41. 60mm x 60mm filled experiment after four weeks of growth (Author, 2020).

Internal Cross Strands 60mm x 60mm

Using the previously used script as a starting point for this script, it was then adjusted to identify opposite walls of the model and connect points between the walls.

Figure 3.42. 60mm x 60mm internal strands spatial print sketch (Author. 2020).

Figure 3.43. Script used for 60mm x 60mm internal strands spatial print (Author, 2020).

Printed Scaffold

Figure 3.44. Close up of minor errors in 60mm x 60mm internal strands spatial print (Author, 2020).

Figure 3.45. 60mm x 60mm internal strands spatial print (Author, 2020).

Mycelium Composite Application

Figure 3.46. Filling of 60mm x 60mm internal strands spatial print (Author, 2020).

Applying the mycelium composite, using the same method of sprinkling 5000ml over the structure as previously. At first the internal strands made no impact on the dispersal of mycelium composite, although the strands did create pockets where the growth medium would build up in some areas and then slide out in others. Because of this, some manual placement of material was needed in the second round of application.

60x60mm
5000ml applied *
2050ml falloff
4000ml to fill *this is just how much was then added on top to reach the height of 180mm, some of this did then fallout

h = 180mm (m) = 72g

Growing

Figure 3.47. Growth after two weeks of growth (Author, 2020).

Results After Growth

Figure 3.48. 60mm x 60mm internal strands filled experiment after four weeks of growth (Author, 2020).

As with the previous structures the mycelium was contaminated in some areas, grew mycelium in other and had little change in others. The internal strands had no visible effect on any of the growing process when compared to the 60x60 walls print.

Figure 3.49. 60mm x 60mm internal strands filled experiment after four weeks of growth (Author, 2020).

Double wall 40mm x 40mm

This script was testing how using a double wall system would affect the strength of the structure as well as how the mycelium composite could be applied. If mycelium composite was applied to different regions of the print it would be able to achieve very different results all from the same script.

As previously this script used the basis of the original script, however to achieve the internal offset wall it took some adjustments.

Figure 3.50. 40mm x 40mm double wall spatial print sketch (Author: 2020).

40x40mm

Figure 3.51. Script used for 40mm x 40mm double wall spatial print (Author, 2020).

Figure 3.52. Toolpath of 40mm x 40mm double wall spatial print (Author, 2020).

Figure 3.53. Robot Arm printing double wall volumetric model (Author, 2020).

Printed Scaffold

Figure 3.54. Partially printed 40mm x 40mm double wall spatial print (Author, 2020).

Figure 3.55. Close up of minor errors in 40mm x 40mm double wall spatial print (Author, 2020).

The first attempt with printing this model had some errors in on of the corners, it did appear as though it could regain control if left to continue but was stopped and restarted as it was caught early on and there was time to restart. This flawed print was kept and used to test an alternative approach to filling the script. The second attempt of printing was successful with only minor errors.

This print felt much stronger when applying weight to it or picking up as it did contain the highest amount of filament for the volume. While it did use up more filament the stability it created in the structure would be effective for the application into certain designs

Figure 3.56. 40mm x 40mm double wall spatial print (Author, 2020).

Figure 3.57. 40mm x 40mm double wall spatial print (Author, 2020).

Mycelium Composite Application

Figure 3.58. Filling of 40mm x 40mm double wall spatial print (Author, 2020).

Filling this print was very different to the previous experiments as it quickly filled the centre section but then the exterior section needed more targeted application, which did hold effectively when less randomly applied.

Instead of randomly sprinkled the partial print was packed with mycelium composite by hand which worked effectively. This time only applying to the outer section of the print.

40x40mm
178g

$h = 200\text{mm}$

$(m) =$

5000ml applied *this was more difficult fill compared to other types as the double wall would hold it in the different sections
800ml falloff

Growing

Figure 3.59. Growth of partial 40mm x 40mm double wall filled print after two weeks of growth (Author, 2020).

Figure 3.60. Growth of 40mm x 40mm double wall filled print after two weeks of growth (Author, 2020).

Results After Growth

Figure 3.62. Partial 40mm x 40mm double wall filled experiment after four weeks of growth (Author, 2020).

Figure 3.61. 40mm x 40mm double wall filled experiment after four weeks of growth (Author, 2020).

Both the full size and partial print were unsuccessful at growing mycelium, there was a small amount of white mycelium growth on the full print but extremely inconsistent. There were sections showing signs of contamination, particularly on the partial print.

Figure 3.63. 40mm x 40mm double wall filled experiment after four weeks of growth (Author, 2020).

96 Figure 3.64. Close up of visible green contamination on 40mm x 40mm external wall filled experiment (Author, 2020).

Reflection

All of the models within this set of experiments used the same batch of mycelium composite, and all of which had signs of contamination during and after growing. The appearance of each model had extreme inconsistencies in the mycelium growth, with regions of white mycelium growing as would be expected, and then darkened composite or green mould grown.

Figure 3.65. Close up of variations in growth across rectilinear volumetric experiments showing evidence of contamination (Author, 2020).

For any designed object that may use this method it would most likely not just be made up of straight lines and right angles so the next set of prints were looking at adapting scripts to forms with curves and angled walls. The previous set of volumetric spatial prints used a script that created the form within Grasshopper, this experiment tested how a solid model within rhino could be adapted for printing.

Figure 3.66. Preparing mycelium composite for curvilinear experiments using a pre-mixed bag of fine straw with spawn that been growing for 1 week (Author, 2020).

Curvilinear 40mm x 40mm

So far, geometric forms had been printed. However, curved forms were also required to be explored, so the following set of prints were looking at adapting scripts to forms with curved and angled walls. The previous set of volumetric spatial prints used a script that created the form within Grasshopper, this experiment tested how a solid model within Rhino could be used to dictate form by adapting for printing. The aim of this set of experiments was to assess the ability to make a script that could be adapted to be dictated by a rhino model with curves and angles instead of a rectilinear form dictated in Grasshopper.

These experiments also aimed to assess if curved and angled walls of a model would change its ability to be able to retain mycelium composite and take on the form.

This script used a model created in rhino to dictate the form. The script from the first three volumetric prints, was adapted to be able to work with the rhino model. Each form used the same shape for the base of the form to be able to compare the results. This also meant that the two models could be stacked on top of each other to replicate the possibility of creating sections of a larger form. The value of 40mm x 40mm, was selected to use as “one unit”; being the distance between each horizontal and vertical point of movement. This was based on the previous set of experiments, as this distance achieved the best retention of mycelium composite while still using the minimal amount of material. The vertical value was reduced to 30mm to be able to improve the way the composition of units fit into the form.

Figure 3.67. Rhino models used to inform script (Author, 2020).

Figure 3.68. Script used for curvilinear volumetric experiments (Author, 2020).

Figure 3.69. Curvilinear angled in spatial print sketch (Author, 2020).

Figure 3.70. Curvilinear angled out spatial print sketch (Author, 2020).

Figure 3.71. Line sketch of potential arrangement of the curvilinear volumetric tests fitting together (Author, 2020).

Printed Scaffold

Figure 3.72. Minor errors down one edge of the angled out curvilinear volumetric print (Author, 2020).

There were some slight errors in the corners of both this print and the next, this was due to the script, not the extruder or robot arm. Other than that, the overall form printed well with no errors. Despite the minor errors in the corners, the overall form printed very well, there were no issues in the achieving the angled walls.

Figure 3.73. Angled out curvilinear volumetric print (Author, 2020).

Mycelium Composite Application

Figure 3.74. Filling of angled out curvilinear volumetric print (Author, 2020).

Despite the walls angling out at the top, this print was able to capture and retain the mycelium composite extremely well. This and the other curvilinear model were not as focused on the proportion of material retained versus falloff, as the previous set of experiments. The printed structure was filled with 5000ml of mycelium composite which almost perfectly fit to the top, some of the top edges were manually filled in to create a more complete fill.

30x40mm h = 160mm (m) =
 92g
 5000ml applied *filled perfectly with some edges done by hand
 450ml falloff

Growing

Figure 3.75. Filled models in plastic bin for growing period in incubator (Author, 2020).

Figure 3.76. Filled models after four days of growth, some signs of mycelium growth already present on curvilinear models (Author, 2020).

Figure 3.77. Filled models after two weeks of growth, significant difference between mycelium growth on double wall experiments to the curvilinear experiments (Author, 2020).

Within a few days there were signs of mycelium growth throughout the model. The mycelium composite then went on to grow white mycelium across almost the entire surface. This was an incredibly successful result, particularly when compared to the volumetric tests which were grown under the same settings but had a much less consistent and slower rate of growth, which then resulted in a large amount of contamination. The one face of this model that did not grow as effectively as the rest was the side near the volumetric tests, so it could be that the contamination from the other models was transferred to this model but contained to just one side.

Figure 3.78. Close up of angled out curvilinear volumetric model after two weeks of growth (Author, 2020).

Within a few days of incubation there was a significant amount of mycelium growth present and reasonably even across the whole surface apart from on end. The speed at which this growth was present was much faster than the volumetric set of experiments.

Figure 3.79. Side view of curvilinear volumetric model after two weeks of growth (Author, 2020).

Results After Growth

Figure 3.80. (Above, first row) Curvilinear volumetric model after four weeks of growth, signs of fruiting bodies begun to form but not fruited due to lack of light (Author, 2020).

Figure 3.81. (Above, middle row) Curvilinear volumetric print after four weeks of growth, signs of fruiting bodies remove for desiccation (Author, 2020).

Figure 3.82. (Above, bottom row) Close up of curvilinear volumetric print

Almost all of the model had a good amount of white mycelium growth covering the surface. There were also sections that showed the mycelium growth up and along the strands of the print, creating an interesting webbing effect.

Figure 3.83. Curvilinear Volumetric model after four weeks of growth (Author, 2020).

Figure 3.84. Extreme close up of curvilinear volumetric model after four weeks of growth (Author, 2020).

Results After Desiccation

Figure 3.85. *Curvilinear Volumetric model after desiccation (Author, 2020).*

Once dried the white mycelium growth created a skin-like surface across the model.

Figure 3.86. *Curvilinear Volumetric model after desiccation (Author, 2020).*

Figure 3.87. Extreme close up of curvilinear volumetric model after desiccation (Author, 2020).

Printed Scaffold

Figure 3.88. Minor errors on the angled in curvilinear volumetric print (Author, 2020).

This print used the same script but with an alternative rhino model dictating form.

As with the previous model there were some issues with the corner points of the model during printing, however this did not however affect the overall form.

Figure 3.89. Angled in curvilinear volumetric print (Author, 2020).

Mycelium Composite Application

Figure 3.90. Filling of angled in curvilinear volumetric print (Author, 2020).

The volume of this model was much smaller than previously test, this meant it only took 3000ml of mycelium composite to completely fill. There was little falloff material, mainly as a result of the small opening rather than escaping out of gaps in the wall the structures walls. This meant much more focus application was needed with some manual packing of the mycelium composite to be able to fill the structure.

30x40mm h = 160mm (m) = 80g
3000ml applied *filled perfectly applied strategically as the narrow opening meant it was difficult to simply pour into
650ml falloff

Figure 3.91. Close up of Filled of angled in curvilinear volumetric print (Author, 2020).

Growing

Figure 3.92. Close up of angled in curvilinear volumetric model after two weeks of growth (Author, 2020).

This model showed signs of growth very quickly as did the other curvilinear test, with a very consistent coverage of white mycelium growth.

Figure 3.93. Close up of angled in curvilinear volumetric model after two weeks of growth (Author, 2020).

Results After Growth

Figure 3.94. Angled in curvilinear volumetric model after four weeks of growth, signs of fruiting bodies begun to form but not fruited due to lack of light (Author, 2020).

Figure 3.95. Angled in curvilinear volumetric model after four weeks of growth (Author, 2020).

Figure 3.96. Extreme close up of angled in curvilinear volumetric model after four weeks of growth (Author, 2020).

Results After Desiccation

Figure 3.97. Angled in curvilinear volumetric model after 4 weeks of growth after desiccation (Author, 2020).

Figure 3.98. Angled in curvilinear volumetric model after desiccation (Author, 2020).

Figure 3.99. Extreme close up of angled in curvilinear volumetric model after desiccation (Author, 2020).

Figure 3.100. Curvilinear volumetric models after desiccation (Author, 2020).

Reflection

One observation from across all experiments within this chapter was that while printing, despite having some minor errors with the connection between points, the majority of the time it would be able to continue printing and recover without impacting the model further. Though even a slight error may be an issue for other applications, for the use of a scaffold for mycelium growth minor errors are not a concern. Using a unit size of 40mm proved to be able to retain a high proportion of mycelium composite while using minimal amounts of filament.

Figure 3.101. Curvilinear volumetric models after desiccation (Author, 2020).

Chapter

4

Material Investigation -
An investigation into possible
spatial printing materials and their
relationship to mycelium growth

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Figure 4.01. (Right) Close up of spatial print using Compost 3D filament (Author, 2020)

Plastic Sample Corrosion Tests

A new batch of mycelium composite was made using one part coffee grounds and one part straw, and one quarter parts spawn. 4 bags of mycelium composite were made. After 3 weeks incubating the bags appeared to have a significant amount of growth, two bags were used in plastic sample experiments, with the leftover material bagged, and the other two were left to continue growing.

Upon inspection 12 days later it was found that the plastic experiments, as well as newly mixed bags from leftovers, and two original bags, were all contaminated. The plastic sample tests had very significant and obvious contamination, however on the bags of mycelium composite the only signs of contamination were very small and on the under-side. There is a chance that due to the little amount of foreign mould visible that some of the content of the bags could have still been used, however seeing how much contamination could occur all over, it was best to dispose of these and start with new materials.

The plastic sample tests were documented as they still gave some insight on the interaction with mycelium, and photos were taken of the contaminated bags and then discarded.

High temperature PLA (HTPLA) filament was used for the previous set of volumetric experiments, as it was what was known to print successfully and using the established printing settings. While the majority of experiments within this research project used this HTPLA it was important to understand how different materials may react with mycelium as this could be included in the design process for future concepts. Knowing if it would either break down or retain its integrity could be beneficial as it could be an intentionally designed quality. An understanding of how to create adhesion between the mycelium and printed scaffold to a desired point and then stopping growth would allow for more design opportunities.

To understand this reaction between materials, tests were conducted. The first set of experiments investigated the relationship of four variables on three material samples; water vs glucose solution, and sanded surface vs smooth.

The three material samples, supplied by Scion, were 100% PLA, 10% wood + 90% PLA, 30% wood + 70% Polybutylene Succinate (PBS). The 10% wood + 90% PLA was a composite of wood fibres with a PLA base, similarly the 30% wood + 70% PBS uses a PBS base combined with a higher ratio of wood fibres.

Half of the samples were lightly scratched to explore if surface texture would affect the results. While this wouldn't be possible to scratch the surface of a spatial print, some materials vary in texture after extrusion so this was used to simulate that effect.

Powdered glucose mixed with water was made into a glucose solution and applied to half the material samples. This solution was also tested in the first 3D print application tests and while it didn't appear to impact the growth, it aided in some initial adhesion, so it was important to assess if the mycelium growth would impact the printing material.

This resulted in 4 variations within each material sample; water, glucose, scratched + water, scratches + glucose. A sample of each material was also kept out as a control.

Figure 4.02. Material samples placed out on board before mycelium composite application, positioning of samples was changed before application (Author, 2020).

Figure 4.03. Material samples experiment, before growth, close up (Author, 2020).

Figure 4.04. Material samples experiment, before growth (Author, 2020).

Plastic Sample Corrosion Tests: Results after Growth

After leaving them for 12 days, the samples were inspected and there was a large amount of foreign green mould growing. While it could be seen across all of the mycelium composite, it was much more intense in the side where the glucose solution was applied.

Photo of full test

Upon closer inspection of the remaining batch of mycelium composite bags, there were traces of green mould within each bag. This suggests that while the glucose may have acted as a catalyst for the foreign growth, there was contamination within the initial composite mixture. To reduce the chance for further experiments to be effected with contamination remaining composite bags were all disposed of.

While the corrosion test plastic samples were contaminated they still illustrated how the mycelium would affect the plastic.

Figure 4.05. Close up of growth on material samples experiment (Author, 2020).

Figure 4.06. Material samples experiment, after growth, bottom half used glucose and showed signs of extreme contamination. (Author; 2020).

70% PBS 30% Wood

Figure 4.07. 70% PBS 30% Wood results (Top down), control - no mycelium composite applied, water, water and scratched, glucose solution, glucose solution and scratched (Author, 2020).

Each sample was placed on a plastic board, fully surrounded by mycelium composite, with just one end sticking out to identify it. When gently removing the samples, any residue of the mycelium composite remained attached to the sample was removed by wiping off with the finger to reveal the amount of erosion.

There was a noticeable difference in the appearance of the samples containing wood.

- The 70% PBS 30% wood sample had the most significant change in colour and surface texture. This change could be felt when removing the sample as it had a high amount of resistance when removing from mycelium composite and then wiping away residue.
- The 90% PLA 10% wood sample had an obvious change in colour and texture. There was some resistance when removing it from the mycelium composite however ultimately it came out clean.
- The clear PLA did not have any visible difference and was able to be removed and wiped clean very easily, leaving no trace of having been in contact with mycelium.

These observations were as expected, the more organic material (wood) in each sample, the more corrosion the mycelium had on the sample. By understanding this, if a design required the printed structure to remain intact throughout the growing process PLA would be a suitable choice. If a design would benefit from breaking down then a higher wood, or other organic material biopolymer would be more suitable. There is a potential to control the amount of corrosion to gain adhesion between the mycelium and the scaffold structure (extrudate).

90% PLA 10% Wood

Figure 4.08. 90% PLA 10% Wood results (Top down), control - no mycelium composite applied, water, water and scratched, glucose solution, glucose solution and scratched (Author, 2020).

Due to this set of experiments a few changes were made in subsequent experiments, firstly glucose was not used again as it accelerated foreign growth and had no visible improvement to mycelium growth. Going forward the straw substrate was also only used once pasteurised with dehydrate lime. Wood pellets were also introduced as a substrate material as it could be easily sourced and pasteurised with dehydrated lime. By pasteurising substrates before use the chance of contamination was reduced significantly.

Second Plastic Sample Corrosion Tests

Due to the contamination that occurred in the first plastic material tests further tests were carried out. Since it was visible that there was no obvious difference made by scratching the sample's surface, this was not repeated. Glucose was not used again as it acted as a catalyst for the foreign mould to grow without presenting as a benefit to mycelium growth.

Leftover mycelium composite from the curvilinear volume test was packed into small plastic containers. Plastic material samples were then inserted into the mycelium composite, with approximately half exposed above the surface. The same samples were used as previously; PLA, 10% wood+ 90% PLA, 30% wood+ 70% PBS, and then also extrudate and filament samples. A section of a failed print was used to test HTPLA and a length of compost 3D filament was bent in half and each of these were placed partially inside the mycelium composite.

These were then left for one month to grow before removal and photography. Like the curvilinear volume tests that grew mycelium very effectively which used the same mixture, so did these material samples. There was noticeable growth of the mycelium up each of the plastic samples beyond the surface of the composite. This was a promising observation as it showed that the mycelium growth was not limited to just occurring on the surface of the composite but could spread out over a printed scaffold if given the right variables.

Figure 4.09. Second material sample experiment after four days of growth (Author, 2020).

Figure 4.10. Second material sample experiment after four days of growth (Author, 2020).

30% Wood 70% PBS

Figure 4.11. 70% PBS 30% Wood in mycelium composite, grown for four weeks (Author, 2020).

Figure 4.12. 70% PBS 30% Wood removed from mycelium composite front and back (Author, 2020).

When placing the 30% wood + 70% PBS sample into the mycelium composite it broke, this is why it is shorter than the other samples. This was completely covered in mycelium after growth and then broke apart further within the mycelium composite when trying to remove it. This was similar in the previous contaminated tests where this material gave the most resistance to removal, signalling a good amount of adhesion between plastic sample and mycelium composite. However, since in this test, it completely broke apart due to adhesion, this showed an even stronger corrosive effect. This could be seen as both an opportunity or limitation when considering application to a design. If the intended design could benefit from the scaffold being removed through breaking down, then this material would be suitable if left to grow for an extended period of

Figure 4.13. 70% PBS 30% Wood sample before and after exposure to mycelium growth for four weeks (Author, 2020).

time. If adhesion between the materials was required but the scaffold needed to remain stable, then desiccating the structure at an earlier point would achieve that balance.

10% Wood 90% PLA

Figure 4.14. 90% PLA 10% Wood in mycelium composite, grown for four weeks (Author, 2020). Figure 4.15. 90% PLA 10% Wood removed from mycelium composite front and back (Author, 2020).

The 10% wood + 90% PLA had some growth up the plastic sample, extending from the mycelium composite itself. However, it was much less than the PBS + Wood sample which contained a higher wood percentage. This could indicate the difference in how PLA and PBS influence the mycelium growth, or this could suggest that because of the higher wood content it acted as not only as an effective scaffold but also as a substrate to encourage growth.

Figure 4.16. 90% PLA 10% Wood sample before and after exposure to mycelium growth for four weeks (Author, 2020).

PLA

Figure 4.17. PLA in mycelium composite, grown for four weeks (Author, 2020).

Figure 4.18. PLA removed from mycelium composite front and back (Author, 2020).

The 100% PLA sample acted the same as the previous contaminated set of experiments with no visible change to the material itself. It did have a similar amount of mycelium growing up the sample as the PLA + Wood sample, however, had much less residue adhered to it once removed. Although it did have a small amount of mycelium grown over it, once wiped off there were no traces of any corrosion to the plastic.

HTPLA, Compost 3D

Figure 4.21. HTPLA sample in mycelium composite, grown for four weeks (Author, 2020).

Figure 4.22. HTPLA sample removed from mycelium composite front and back (Author, 2020).

Figure 4.19. Compost 3D sample in mycelium composite, grown for four weeks (Author, 2020).

Figure 4.20. Compost 3D sample removed from mycelium composite front and back (Author, 2020).

The HTPLA and Compost 3D behaved very similarly to each other and the PLA. There was more obvious mycelium growth upward of the samples than PLA although that is likely due to the shape. This growth across the exposed filament and extrudate once again, supports the concept of using the printed structure as a scaffold for mycelium growth as well as to retain mycelium composite. There was some mycelium growth that stuck to the sample when removed from the mycelium composite, however, there was no visible corrosion or change in surface textures.

Spatial Printing with Compost3D

Figure 4.23. Development of spatial printing tests using Compost 3D (Author; 2020).

After conducting a range of tests on how plastic material samples would interact with mycelium composite and its growth, the next stage was to test how materials could be spatially printed. HTPLA was used for the majority of the prints in this study as there was expert understanding on using it for spatial printing available, it is a bioplastic so fits within the projects vision, and since it melts at a higher temperature there would be less warping while in the oven during desiccation than other plastics.

While PLA is a bioplastic and is biodegradable under the right conditions in industrial composting, it would not be considered compostable in itself. Because of the nature of mycelium and the intended application of this process, it would require the use of a compostable filament to make the entire design compostable. One brand has created a filament that claims to be entirely home compostable. This filament, Compost 3D was experimented with for spatial printing to explore the opportunity for use. Although it was not used throughout all experiments the compostability of Compost 3D presents itself as the best material option when considering a sustainable approach.

The circumference of Compost 3D was measured at 3.04mm on one angle and 2.54mm at another, this was a significant variation, however, since the middle point was $2.79\text{mm} \pm 0.01$ compared to HTPLA which has a circumference of $2.78\text{mm} \pm 0.01$ it was decided to test regardless to identify if it would result in issues due to these inconsistencies. This variation could cause irregularities in how the filament is fed through the extruder, and there were some inconsistencies through the prints however it did not seem to cause a significant issue. This could change when increasing the scale as the robot arm would rotate as needed and filament could be fed at different angles from the spool.

Figure 4.24. Spatial printing using Compost 3D test 1 (Author, 2020).

Figure 4.25. Spatial printing using Compost 3D test 2 (Author, 2020).

Figure 4.26. Spatial printing using Compost 3D test 3 (Author, 2020).

Figure 4.27. Spatial print using Compost 3D test 1 (Author, 2020).

Figure 4.28. Spatial print using Compost 3D test 2 (Author, 2020).

Figure 4.29. Spatial print using Compost 3D test 3 (Author, 2020).

Compost 3D filament was put through the extruder on the robot arm to print test cubes. First test used the same settings as previously used for HTPLA other than temperature which was reduced from 2V, which translates to 235.1°C, to 0.3V, which translates to somewhere between 216.5°C and 222.2°C. While it did extrude as needed, the extrudate showed signs of being too hot. This overheating caused bubbling and loss of form as the extrudate was not consistent.

The second test cubes settings were adjusted down to 0V which equals around 216.5°C. This improved the print in consistency however still showed signs of overheating in the initial vertical movements, but then regulated itself.

For the third test the settings remained as prior, however, the fan used to cool the extrudate was turned to full power earlier than normal to allow the temperature to reduce before beginning vertical movements. This proved to help improve the extrudate consistency. There were still some inconsistencies in the size of extrudate, however, this did not affect the overall form from being constructed. There was some delay in the extrudate beginning to print in both of the first tests, to solve this the movements were paused at the first point until it began extruding and then restarted.

Spatial Printing with PLA + Fibre Composite

Figure 4.30. Development of spatial printing tests using PLA + Fibre composite (Author, 2020).

Another filament that was tested was supplied by the University of Waikato, although they could not identify the specific fibre used, as it was undocumented, it contained PLA with 10-20% natural fibre. This could be seen within the filament before and after extruding in variation of colour and texture. While the fibre was unknown, it was tested for spatial printing to assess how alternative materials could be introduced into the process. A PLA and 10% Harakeke filament was supplied and tested too, however, inconsistent filament diameter meant that it could not be extruded.

Figure 4.31. Spatial print using PLA + Fibre composite test 1 (Author, 2020).

Figure 4.32. Spatial print using PLA + Fibre composite test 2 (Author, 2020).

Figure 4.33. Spatial print using PLA + Fibre composite test 3 (Author, 2020).

Figure 4.34. Spatial print using PLA + Fibre composite test 4 (Author, 2020).

Figure 4.35. Spatial print using PLA + Fibre composite test 5 (Author, 2020).

Using the previous settings from the compost 3D test cubes, the settings were set to a temperature of 216.5°C (0V) for the first test. This lifted up from the acrylic printing bed after the first couple of vertical movements.

The same settings were used again for the second test, this time pushing down the base layer with a scraper, in the same way that was done with all other spatial prints in previous experiments. This still lifted after the first few vertical movements.

To remove the issue of lifting from the acrylic, PE tape was used to assist in adhesion between the base layer and the printer bed. The tape slightly melted when extrudate came into contact with it, causing it to stick enough to print without issue and then be peeled off after. This allowed for the whole cube to be printed without any major errors, however some of the nodes did not connect.

To slightly increase the temperature, the fan was not turned on as high in this next test. However, that meant that the extrudate could not cool fast enough to maintain its shape which resulted in warping. This also did not solve the bonding issue.

The extruding temperature was increased to 235.1°C 2V in an attempt to assist in bonding. This created slightly better bonding at nodes, however, there was draping of the extrudate due to the increased temperature. It is important to note that the printed extrudate had a wax-like feel to it which could be a cause of these bonding issues, so there could be a need for further experimentation with the material itself, or an alternative approach to the construction of spatial printing to be able to use this material.

While even the final test was not without any issues, these tests present the opportunity for the use of bio-composites in spatial printing. More options for these bio-composites, or totally compostable materials, would present a much wider variety in opportunities for the use of spatial printing both on its own and when combined with mycelium and other organic matter.

Thickness Tests

Figure 4.36. Rhino models used to define form (Author, 2020).

Figure 4.37. Script used for thickness test spatial print (Author, 2020).

Figure 4.38. Toolpath of thickness test spatial print (Author, 2020).

Following the volumetric and material experiments, further curvilinear tests were needed to assess how manual application of mycelium composite could influence aesthetic qualities. By reducing the width of the printed structure it could be possible to create a gradient in transparency through the structure.

This set of tests also looked into further variations in curvilinear forms in how to adjust the script for a successful print. It was printed in both HTPLA and Compost 3D to compare the performance of the materials.

Figure 4.39. Thickness test spatial print sketch (Author: 2020).

Printing Thickness Tests HTPLA

Figure 4.40. Failed thickness test print (Author, 2020).

Figure 4.41. Printing of thickness test print in HTPLA (Author, 2020).

Printing Thickness Tests Compost 3D

Figure 4.42. Printing of thickness test print in Compost 3D (Author, 2020).

Thickness Tests HTPLA

Figure 4.43. Thickness test print in HTPLA (Author, 2020).

Figure 4.44. Thickness test print in HTPLA (Author, 2020).

The HTPLA print was done first, this had some issues with the first layer of vertical movements which was caused by the curved middle section. Instead of making a vertical movement straight up and then an angled movement down, it went up at an angle and then straight down. This type of movement does not work as it drags the extrudate down with the nozzle by moving in the same path it is trying to print. This was adjusted by reducing the unit value to 37 than 40. This was then reprinted and was successful, it had a slight error in one corner but then recovered.

Thickness Tests Compost 3D

Figure 4.45. Thickness test print in Compost 3D (Author, 2020).

When printing with the compost 3D, the settings were adjusted to what had been defined by the cube tests. This print experienced some errors with adhesion at nodes. Though it did have issues at specific points each step up continued to be able to print the overall form successfully. Once completed, there was a significant difference between one side and the other, the side closest to the robot had failed to connect to the “base” path of each previous layer. Despite this, the base layer was still able to follow its path. If redone the script would be adjusted to either complete two rounds of the base path to thicken this base layer, or the vertical movement of each layer would be shifted slightly down to ensure bonding.

Figure 4.46. Thickness test print in Compost 3D (Author, 2020).

Applying Mycelium Composite HTPLA

Figure 4.47. Filling of HTPLA thickness test spatial print (Author, 2020).

Figure 4.48. Mycelium composite used for thickness test spatial prints (Author, 2020).

The filling of each model was almost identical. Due to the narrow hole at the top, mycelium composite would need to be either applied through the sides, or by pulling apart the opening. The Compost 3D was more flexible so could be pulled open more than the HTPLA.

As there were continuous contamination issues, coffee grounds were not used from this experiment on. While straw and wood chips could be cold water pasteurised, coffee grounds were more labour and resource intensive to sterilise. Although it would be beneficial to use coffee grounds in future development, this would be with an adjusted resource stream of either collecting the coffee grounds in a more sterile way, leaving less time between collection and use, or sterilising on a large scale.

This experiment used wood pellets that were cold water lime pasteurised. This is a process of using hydrated lime mixed with water to soak the substrate material for 12 – 24 hours which increases the PH rapidly to mould spores and bacteria. This hydrated lime was purchased alongside other materials from sporeshift.co.nz with instructions for use, which was 2g per litre of water.

Applying Mycelium Composite Compost 3D

The filling of each model was almost identical to each other. Due to the narrow hole at the top, mycelium composite would need to be either applied through the sides, or by pulling apart the opening. The Compost 3D was more flexible so could be pulled open more than the HTPLA.

As this test was focused on testing how the application process could be done in a targeted way for specific aesthetic qualities it was not filled completely, but instead had targeted regions that remained empty. The mycelium composite was not broken down as much as in previous experiments as a way to use the larger pieces to scatter in the narrow sections.

As each print had the same form, there was little to no difference in how this application process resulted. Despite the Compost3D structure having a significant amount of errors on one side of the middle section, it was still able to retain the mycelium composite effectively.

These tests were left for 3 weeks to grow before photography and desiccation.

Figure 4.49. Filling of Compost 3D thickness test spatial print (Author, 2020).

Results After Growth HTPLA

Figure 4.50. Filled HTPLA thickness test after 3 weeks of growth (Author, 2020).

Figure 4.51. Close up of filled HTPLA thickness test after 3 weeks of growth (Author, 2020).

Figure 4.52. Angled view of filled HTPLA thickness test after 3 weeks of growth (Author, 2020).

The filled models were monitored during growth and it was observed to grow significantly different to some previous experiments. While it was present that there was mycelium growth and no contamination, it did not present in the white fluffy coating that other successful composites did. On inspection it did have white mycelium growth between the visible sawdust pieces, but no covering layer. Water was applied through spraying the models as it did not appear to be very high in moisture, but there was no change in the subsequent days. While this was different to some previous experiments, it did not

Results After Growth Compost 3D

Figure 4.53. Angled view of filled Compost 3D thickness test after 3 weeks of growth (Author, 2020).

deem to be unsuccessful, but instead a variation in how it can present. This could be due to a range of environmental factors, such as the temperature or moisture level, or the strain of spawn used, as this was different from previous due to limited resources.

Figure 4.54. Close up of filled Compost 3D thickness test after 3 weeks of growth (Author, 2020).

Figure 4.55. Filled Compost 3D thickness test after 3 weeks of growth (Author, 2020).

Results After Desiccation HTPLA

Figure 4.56. Filled HTPLA thickness test after desiccation (Author, 2020).

Figure 4.57. Close up of filled HTPLA thickness test after desiccation (Author, 2020).

The Models were placed in the oven for 2 hours at 95degrees Celsius.

Upon inspecting both models after desiccation, they were initially very similar in appearance. However, the HTPLA test did have a formation of space between the mycelium composite and the print. It was expected that there could be some more deformation of the Compost3D than the HTPLA due to the lower melting temperature. It did have some signs of strands of extrudate bowing outward, however, it held the overall form even in the corners where there was minimal mycelium composite. It appeared to be that in some places where the mycelium composite did experience shrinkage, the printed form adjusted with the movement.

Since the type of mycelium growth was different on the surface than some previous experiments, it did not grow across the extrudate as would have been desired. Despite this, the sparse application of the composite material in the corners was able to achieve the visual quality of negative space and gradient that would not be able to be achieved in the traditional mould- making process.

Results After Desiccation Compost 3D

Figure 4.58. Close up of filled Compost 3D thickness test after desiccation (Author, 2020).

The contextual experiments were carried out using the HTPLA rather than the Compost 3D, this decision was made firstly as HTPLA printed more consistently with limited errors, as it had been experimented with and trouble-shooted more. A secondary reason is that since it is a higher temperature filament it would be expected that there would be less warping during desiccation. The results of the previous tests comparing both HTPLA and Compost3D were not concluded at the point of printing the larger models so it had not been seen that the compost 3D adjusted to the shape more than the HTPLA.

Figure 4.59. Filled Compost 3D thickness test after desiccation (Author, 2020).

Figure 4.60. Filled Compost 3D and HTPLA thickness tests after desiccation (Author, 2020).

Figure 4.61. Filled Compost 3D and HTPLA thickness tests after desiccation (Author, 2020).

Chapter

5

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Contextual Designs -
Large scale contextual designs to
assess the opportunities presented
through the research

Figure 5.01. (Right) External surface of grown stool (Author, 2020).

Identifying a Contextual Opportunity

The creation of contextual experiments presented an opportunity to apply what had been learnt in previous experiments. By giving it an applied context, the opportunities and limitations that were not already made obvious were presented.

Due to the nature of mycelium and its fast growth and ability to be composted, the identified context is to target the manufacture of short term custom designs. This could be the setting of a music festival, food shows, public exhibitions and more. Typically for these temporary events, there is a limit in how customised any design can be without being unsustainable, as it would always have a short life-span

This presents the idea of using digital tools to design and manufacture a printed scaffold of any structure, using minimal printing material, which will then define the final form. This print then acts as a scaffold to retain mycelium composite and guide mycelium growth.

Alongside contextual opportunities this method presents, it also removes the limitations brought by using a mould to define form. By using spatial printing, more complex forms with internal geometries can be achieved.

While these contextual experiments were on a larger scale than the previous prints, there was still the limitation for scale to continue the process beyond printing. The oven used to desiccate the models measured 550mm by 550mm by 470mm internally and required 30mm of clearance between any model and the oven walls. This restricted the options for designs in this set of experiments, but these tests would still inform the approach to creating even larger scale designs.

Figure 5.02. Design opportunities identified at local music festivals Bay Dreams and Rhythm and Vines (Author, 2020)

Preparing Mycelium Composite

In order to grow enough mycelium composite to fill these large scale prints within the limited time frame, a different approach was made. Previously spawn was mixed with substrate material, and left to grow into a mycelium block to then mix with further substrate for application. This is extremely time consuming, as it would take weeks for the initial blocks to grow. By reaching out to a company that sold both 'grow your own' bags and pre-harvested mushrooms, spent mushroom blocks were able to be sourced. These blocks had already yielded mushrooms that were harvested and sold and would typically become organic waste.

A risk of using these spent blocks to inoculate the substrate is that there could be contaminants present. To reduce this risk, the spent block was removed from the grow bag, lightly sprayed with alcohol and then the surface layer was cut off with a sanitised knife. The exterior layer of mycelium composite would be the most likely to have been exposed to external contaminant, so by removing this it was hoped to reduce the chance of contamination. The resulting mycelium composite showed no signs of contamination so this may have contributed to that success.

A day earlier, equal parts of wood pellets and straw had been put into hydrated lime and water to soak. The sanitised spent blocks were then broken down and combined with the prepared soaked mixture. These were left to grow for three and a half weeks while both contextual experiments were printed.

Figure 5.03. Process of preparing mycelium composite using spent mycelium composite blocks (Author, 2020).

Generating Stool Toolpath

Figure 5.04. Rhino model used to define form through Grasshopper, bounding lines indicate oven size to remain in scale (Author, 2020).

Figure 5.06. Script used to create stool printing toolpath (Author, 2020).

Figure 5.05. Wireframe sketches of toolpath generated from rhino (Author, 2020).

One opportunity of using a spatial print as opposed to a mould is the ability to create internal negative space without the need for allowing for draft angles or using multiple parts. To demonstrate this, a stool was designed and made. The stool was designed to be printed, filled and grown on a sideways orientation and then flipped upright once ready for use. This internal negative space was achieved using an adaptation of the double wall script from the volumetric tests. By printing in one orientation and rotating it for use, the hope was that it would remove the risk of breaking the nodes within the printed structure when under pressure.

The internal tube was designed to have a concave curve to it, this was partially to improve the strength, and also because it would not easily be achieved through using moulds.

The form was first designed as a volume in Rhino and then adapted for printing through a Grasshopper script. The script used the same principle as the double wall script from the volumetric tests, but instead of following a rectangular form generated within Grasshopper it referenced the rhino model.

In rhino the volume of each design was calculated and converted to mls to define the amount of mycelium composite to prepare for the final models.

The stools volume was 50517468.3mm^3 which then translated to just under 50.5L

Figure 5.07. Toolpath process with robot model (Author, 2020).

Printing Stool

Printing:

During the printing there were no issues with the script, however, when the roll of filament ran out and was replaced, it appeared to not be extruding enough filament. This was because the new roll had too much weight to easily spin to feed filament into the extruder. The print was cut back to before the issues started and then script restarted from there. From then on it printed as expected, with a few points of irregularity or weaker node connections, but nothing that would affect the overall form or function.

When removing the print from the print surface, it did not easily release and ended up breaking in areas. To reduce this impact on subsequent large scale prints there were always two layers of the base edge printed to thicken this layer, making for easy removal.

Figure 5.08. Errors in stool spatial print caused by extrusion issues (Author, 2020).

Figure 5.09. Stool errors removed before restarting print (Author, 2020).

Figure 5.10. Spatial printing of the stool (Author, 2020).

Printed Stool Scaffold

Figure 5.11. Close up view of internal cross strands that connect the inner and outer stool walls (Author, 2020).

Figure 5.12. Minor errors in spatially printed stool (Author, 2020).

Figure 5.13. Side view of spatially printed stool (Author, 2020).

Figure 5.14. Spatially printed stool (Author, 2020).

Preparing Mycelium Composite

Figure 5.15. Mycelium composite blocks grown from spent mycelium blocks (Author, 2020).

Figure 5.16. Process of breaking down Mycelium composite blocks to combine with new substrate to be able to apply to printed stool scaffold (Author, 2020).

After growing for three and a half weeks, the mycelium composite blocks created from the spent blocks were efficiently grown for use. They appeared to grow much faster and inoculate more effectively than any previous experiment using spawn. There were no signs of any contamination, so no blocks had to be disposed of.

Three blocks were broken up and combined with wood chips that had been cold water lime pasteurized. Working out to be approximately 3 parts mycelium composite to 2 parts wood chips, making just under 60L.

Applying Mycelium Composite

Figure 5.17. Filling of stool scaffold with mycelium composite (Author, 2020).

Working at a larger scale compared to previous experiments the printed structure could not be filled with the mycelium composite and then transported to the incubator, but instead, was filled in the incubator space. This proved to be challenging for reaching the far side of the stool. The internal strands of the print caused similar difficulties that were found in the volumetric experiments where it could cause pockets of material to not be as densely packed. The mycelium composite was also broken up very finely to ensure it could take on the form closely, however, this did make for more falloff than desired. Due to supply changes, there was also a much lower proportion of straw which could have aided in branching across the printed gaps.

Figure 5.18. Filled stool (Author, 2020).

Once the structure was filled, some of the falloff was pushed against the model to fill in even areas and the rest was wiped away. The whole structure was sprayed with water before covering with plastic.

Results After Growth

Within a few days there were visibly white patches beginning to appear all over the structure. After two weeks it was covered in white mycelium.

The model was removed from the incubator for photography and then moved to the oven for desiccation. The model was put into the oven in three periods of time; 4 hours, 7 hours, and then 3 hours. On the moisture reader there were still some areas that read as moist but once being aired out for a few days, fully dried out.

Figure 5.19. Stool after two weeks of growth (Author, 2020).

A distinct rectangle on one side of the stool remained brown rather than grow mycelium. This lined directly up to where the heating mat was placed on one of the incubator walls. It is a sign that it was too close and therefore too hot, killing the mycelium in that section before it could grow.

Figure 5.20. Section close to the heating mat did not experience any growth (Author, 2020).

Figure 5.21. Close up of mycelium growth across surface of stool (Author, 2020).

Final Stool

Figure 5.22. Full stool after desiccation (Author, 2020).

Figure 5.23. Details of exterior surface of stool after desiccation (Author, 2020).

Figure 5.24. Details of interior surface of stool after desiccation (Author, 2020).

Figure 5.25. Stool in use (Author, 2020).

Generating Spatial Divider Toolpath

Figure 5.26. Design iterations (Author, 2020).

The aim for the second contextual design was to show a different range of qualities than the stool did. The stool required the mycelium to add strength to the spatial print for it to be able to function and support a person. It was also a form that was filled with the mycelium composite in a constant way.

For this design the aim was to be able to assess if a spatial print could act as a scaffold to support the mycelium composite to be defined into stable forms, but then also show a gradient in visual qualities such as opacity.

A dynamic modular form was created as a section of a spatial divider. The form used a radical change in thickness of the form to manipulate the material qualities that the mycelium composite would contribute to the form.

Figure 5.27. Rhino model converted to toolpath, if all three parts were to be printed together and then separated (Author, 2020).

Figure 5.28. Script made for full three part toolpath (Author, 2020).

Figure 5.29. Script used for once section generated at a time (Author, 2020).

Figure 5.30. Full line sketch of spatial divider (Author, 2020).

Though the goal was to create a spatial divider of substantial size, there was still the limitation of scale due to the size and reach of the robot arm, the size of oven used to desiccate the structure, the amount of material needed to be prepared, and space required for growing. Because of this, the screen was divided into three sections to comply with the dimensional limitations but could be stacked to show the intended size proportions and applying the methods to create a larger scale design concept.

Figure 5.31. Three sections as rhino models (Author, 2020).

Figure 5.32. Three sections converted to toolpath for printing (Author, 2020).

Printing Spatial Divider

To be able to fit into the oven and be printed with minimal error the model was divided into 3 parts. Each with a base to support the material load and keep the form, otherwise just printing the external walls. Since it was difficult to remove the stool from the printing bed, this the script was adjusted to repeat the base outline path twice. Making for a stronger base which could “pop” off of the acrylic printing surface easily.

Figure 5.33. First layer of one section printing (Author, 2020).

Figure 5.34. Close up of printing of spatial divider (Author, 2020).

Printed Spatial Divider Scaffold

Figure 5.35. Repeated error across multiple levels of part three of the spatial divider (Author, 2020).

There were no issues with printing of the base and middle parts but then during the printing of the third top section there were some issues with nodes not quite connecting at the points. The base cross section was extremely thin to the point that the extruder nozzle almost hit into the already printed side when printing the opposite wall. It is uncertain if it was due to this narrow section but the result was, either weaker connections of nodes, or absolutely no join. This was not a major issue while printing as it was still able to print the overall form correctly, but later caused issues when filling with mycelium.

Figure 5.36. Part one, the base of the spatial divider (Author, 2020).

Figure 5.37. Part two, the middle section of the spatial divider (Author, 2020).

Figure 5.38. Part three, the top section of the spatial divider (Author, 2020).

Figure 5.39. Meeting points between printed sections (Author, 2020).

Figure 5.40. Full spatial divider when stacked together, rotating views (Author, 2020).

Preparing Mycelium Composite

Figure 5.41. Mycelium composite blocks grown from spent mycelium blocks (Author, 2020).

This model also used the spent mycelium blocks that were prepared by mixing with new substrate and left to grow further. This experiment used the same method as used for the stool, these grown bricks of mycelium composite were mixed with new substrate that had been pasteurised in hydrated lime. The mycelium composite blocks were broken down slightly less than when filling the stool as the centre of the third printed part was designed to be extremely narrow in the hope to create negative space within the final structure.

Figure 5.42. Mycelium composite block grown from spent mycelium blocks, view inside growing bag (Author, 2020).

Figure 5.43. Process of breaking down Mycelium composite blocks, to combine with new substrate, to then apply to spatial divider printed scaffold (Author, 2020).

Applying Mycelium Composite

Figure 5.44. Filling part one of spatial divider with mycelium composite, bottom middle image shows the use of part two to assess warping (Author, 2020).

Figure 5.45. Filling of part two of the spatial divider printed scaffold (Author, 2020).

Figure 5.46. Wire used to maintain form from warping (Author, 2020).

The first and second part were filled as normal, then leaving a small area at the very top of the centre piece to blend into the third parts empty space. Since the models were very thin and had no internal cross strands there was some warping that occurred from filling the model. The piece that sat on top of it was used as a guide to find what the shape of the perimeter of the top needed to be. Then a piece of wire was used to hold it together. Because of this it would be recommended that any future developments used just a few cross strands between walls to retain the overall geometry even when filled with mycelium composite.

The third piece had the most issues when applying the mycelium composite. Since there were areas of weak or no connection at the middle point that curved in, as soon as material was added, it started to bow outwards and, unfortunately, it broke. This was fixed by using wire to connect the opposite sides and join printed strands that were not connected. Because of this and the shape of the form it did however warp the form slightly, putting more weight on one side making it unbalanced. It was leant against a stable wall while growing

Figure S.47. All three sections of spatial divider filled and placed in incubator for growth (Author, 2020).

Results After Growth

Figure 5.48. Visible growth after one week (Author, 2020).

Figure 5.49. All three sections of spatial divider after three weeks of growth (Author, 2020).

Figure 5.50. Side surface of base section of spatial divider (Author, 2020).

All three parts then grew for two weeks. It was obvious within a few days that the type of growth was closer to the type of growth seen in the thickness test models than the type occurring on the stool. Once again there are a range of reasons as to why this may have happened, whether it was the strain, moisture levels, heat or nutrients in the substrate. Despite not having the white coating of mycelium growth on the surface, mycelium was found to have grown effectively and bonded the composite together. While growing it could be seen that each of the models had shrunk in size much more than in any previous experiment. At this point there was no simple way of reducing the impact of this.

Figure 5.51. Base section of spatial divider after three weeks of growth (Author, 2020).

Results After Growth

Figure 5.52. Top layer of middle section held in shape by wires (Author, 2020).

Figure 5.53. Middle section of spatial divider after three weeks of growth (Author, 2020).

Figure 5.54. Errors in top layer of top section of spatial divider, shrinkage visible from height difference between print and mycelium composite (Author, 2020).

Figure 5.55. Top section of spatial divider after three weeks of growth (Author, 2020).

Final Spatial Divider: Base Section

Figure 5.56. Base section of spatial divider after desiccation (Author, 2020).

Figure 5.57. Significant shrinkage in base section of spatial divider (Author, 2020).

After desiccation there was some warping of sections of the printed scaffold particularly in areas that were not connected with the mycelium composite. There was further shrinking of the mycelium composite, more significant on the base and top pieces than the middle. As each part could not be in the oven continuously to desiccate, mushrooms grew on the models before being able to achieve full desiccation. These mushrooms were allowed to grow as a way to explore an alternative design application and then removed for photography of the final form.

Final Spatial Divider: Middle Section

Figure 5.58. Middle section of spatial divider after desiccation, showing warping of the spatial print on one side (Author, 2020).

Figure 5.59. Some shrinkage of mycelium composite visible and warping of the spatial print (Author, 2020).

Final Spatial Divider: Top Section

Figure 5.60. Top section of spatial divider after desiccation (Author, 2020).

Figure 5.61. Significant shrinkage of mycelium composite away from spatial print (Author, 2020).

Figure 5.62. Assembly of spatial divider from three sections (Author, 2020).

Figure 5.64. Final large scale concepts with person for scale and context (Author, 2020).

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Discussion and Conclusion

Figure 6.01. (Right) Oyster mushrooms growing from base section of spatial divider (Author, 2020).

Discussion

This research was an investigation of the question:
What are the opportunities and limitations of using spatially printed structures to act as a scaffold for mycelium composite retention and growth, when considering application to contextual design opportunities?”

Through a series of experiments focused on growing mycelium, spatial printing scaffolds, combining the two processes together, and further material exploration, a relationship between spatially printed scaffolds and mycelium growth was established.

This research study was inspired by the use of mycelium within design and architecture and aimed to provide insight into an alternative method of defining geometries of mycelium composite products.

The first two phases of experiments gave insight into how to approach the next stage of experiments. Subsequent experiments were adjusted, based on observations of the results from the previous experiments; the first phase of experiments established a method of creating mycelium composite that would grow effectively.

Phase two introduced the mycelium composites to 3D printed structures to provide evidence that the bonding between materials was possible and could be influenced by the method of application.

The third phase of experimentation developed a method for generating points through Grasshopper to define toolpath movement. By printing models with variations in unit size, design, and forms, an understanding of the most successful printing formation for type of application was generated.

The opportunity to use alternative printing materials to HTPLA was also investigated through material sample corrosion tests. These samples indicated that the presence of natural materials increased the adhesion between plastic and mycelium.

Alternative filament materials were also used to print, providing insight to see if they could be suitable for spatial printing. Compostable filaments would offer the greatest value to applied

designs as it would then be 100% compostable, making it suitable for custom designs anticipated to have a short lifespan. Large scale designs were used as the final phase of experimentation to act as proof of concepts while also presenting any opportunities or limitations of the methods that were not previously identified.

Implications

The knowledge gained from this research project offers an understanding of how digital and organic processes can be introduced to each other to create a functional output that expresses a symbiotic relationship between materials and processes. Digital tools were used to guide and dictate growth as a way of gaining control over a natural material that has an extensive amount of unique qualities.

A large variety of research is being done around the world on the use of mycelium in design and architectural applications, the knowledge gained within this research project fits within this sector in a way that has not as yet been focused on.

While designers and innovators are seeking out sustainable alternatives to synthetic materials, this proposed scaffold method for growth could be applied to not only the use of mycelium designs, but a range of organic materials.

Although an integral aspect of changing the way designers create sustainable products is to produce more durable and long lasting goods, there is also the need to identify the opportunity for embracing the design for decay, but only when done in a sustainable way.

Strengths

- Across almost every phase of experiments there was evidence that the mycelium would grow not just across the surface of the composite, but also outwards, guided by the strands of the printed form. This proves that beyond just retaining the mycelium to grow on the scaffold, it would grow around it in a symbiotic way.

- From the material experiments it is clear that the growth of mycelium around bio-plastic composites proved that the organic material can be used as a tool, both to reduce the amount of synthetic materials used, and ideally to eventually remove them. In addition, it showed the materials could be naturally broken down and that the mycelium would adhere to the print material through corrosion.

- Filament alternatives, both Compost 3D and a 10-20% natural fibre PLA composite, were able to be successfully spatially printed with little errors. This provided insight to the opportunities that future material developments could propose an array of design opportunities, in that, the printed scaffold itself could act as a substrate for the mycelium, or that it could remain intact until a designated point in time and then decompose.

- To spatially print a structure capable of supporting a load like a person's weight or more, it would require a greater amount of built-in strength than it would to just generate a framing scaffold, which is what has been used within this research. By creating strength through the spatial printing structure, it would take a greater amount of time and filament, than just generating the framework, therefore being more resource intensive and less sustainable. By adding strength in the structure through the use of mycelium composite reinforcement, it removes the need for excess filament use, reduces printing time, but can remain lightweight primarily organic material. Alongside how the mycelium composite adds strength to the spatial print, the printed structure can act as reinforcement to the mycelium composite.

- Though the final models experienced a higher rate of shrinking than anticipated, they each still provided valuable information for the future design opportunities and methods

of achieving them. Each experiment showed that the mycelium composite could take on the geometry dictated from the spatial print, even after shrinking. This increased rate of shrinkage could have been due to a range of reasons, including substrate mixture, environmental state, or application technique such as packing with compression versus lightly sprinkling. Further large-scale experiments would be able to refine the cause of this variation to be able to anticipate the exact physical changes throughout the whole process and design accordingly.

- By using a spatially printed scaffolds instead of a traditional mould to define the form, there was a wider scope of opportunities in the properties that could be achieved, as more complexity in geometry could be designed in fine detail through digital tools. A range of these opportunities can be seen through the final set of experiments.

The stool was used to illustrate the opportunity for under-cuts and internal negative space, by using a concave outer shape. With the internal negative space curving out, it would require a multi-piece mould to be able to achieve the same form through a mould-making technique. The internal strands of print also present the opportunity for cross beams to be designed within a structure adding strength.

The spatial divider was intended to show how, through the change in thickness of the printed form, materiality variations in transparency could be achieved in a gradient. This transparent quality was seen in the earlier horizontal application experiments (Figure X) and though it was not achieved as intended since the mycelium growth did not present in the white fluffy coating, it did still show signs of being a possible visual technique, if intended mycelium growth was achieved. The shrinking of the mycelium composite also presented an opportunity to use the shrinking as a way of creating transparency (figure X).

Figure 6.02. Mycelium growth spans across gaps between mycelium composite (Author, 2020).

Figure 6.03. Shrinking of mycelium composite created significant cracks of the composite giving a semi-transparent quality (Author, 2020).

Limitations

Earthquake strengthening resulted in limited access to the workshop which included the robot arm and oven. This delayed the process of carrying out experiments, hence, later experimentation was limited to a smaller window of time. Adjustments were made to minimise the impact, such as using the UPbox FDM printers to replicate spatially printed scaffolds. This provided an initial understanding of the opportunities of using mycelium composites alongside spatial prints.

Covid 19 caused a lockdown for over 5 weeks during this thesis, which meant there was no access to the university or its resources. Also, purchasing or sourcing any materials was not possible. It then had lasting affects for weeks, as there were knock-on effects while in different alert levels. This also interrupted experiments that were underway and needed to be halted or discarded. Upon returning to an alert level that experiments could be carried out, there was a significant delay in the sourcing of materials, some of which were sold out. To be able to source the high quantity supplies needed, multiple retailers were used.

This research topic was focused on investigating opportunities of medium to large scale structures, this was limited by the size of the oven available to desiccate any grown models.

This research was driven from industrial design knowledge and used research for, and through, design methodologies. This meant that it was not within the scope to always understand the results of experiments at a scientific or engineering level.

Since mycelium is a natural material there was always a chance of inconsistencies between each experiment. This was evident in the way the mycelium presented its growth between different experiments. There was always a chance of contamination too, which would render an experiment unsuccessful. From the large-scale models there was a significant amount of shrinkage compared to smaller tests. Some shrinkage was anticipated due to information gained from secondary research, however, the high rate of shrinkage that occurred was not anticipated. This could have been due to the substrate mix, environmental conditions, or needing to apply the composite material under compression to reduce later shrinkage. Further experiments at a large scale would be needed to be carried out to be able to identify this conclusively, however, designs could be adapted to embrace the shrinking for application. If the mycelium growth on the final larger scale experiments were closer to what was seen on the curvilinear volumetric experiments, more conclusive results could be drawn as this was the desired way mycelium growth would present.

Substrates were unable to be kept constant throughout research due to the Covid-19 lockdown, meaning successful mycelium blocks were disposed of which would have been used to inoculate subsequent mycelium composites. All new substrates and spawn required to create mycelium composite blocks after moving down the alert levels were purchased, however, at this point the suppliers were not offering the same type of straw and then moved to wood pellets weeks later. There was then a shortage of stock from the original suppliers so there was a need to use multiple companies to acquire the large quantity of materials needed for subsequent experiments. This inconsistency in substrates meant that results on mycelium growth varied across experiments and a conclusive reasoning could not be made.

Speculative Design directions in response to research findings

Figure 6.04. Conceptual large scale scaffold for outdoor area social spaces (Author, 2020).

Figure 6.05. Conceptual large scale scaffold for outdoor area social spaces (Author, 2020).

Reflecting on what was seen in the large scale designs there is much more research needed into the how to finely control the properties of the mycelium composite within the spatial print. There was a significant amount more shrinkage than previous tests had experienced, while this was an unfortunate occurrence in the models as it was not anticipated, it does not mean that there would not be a way of designing with intent to embrace this quality.

One way to design with the shrinkage rather than against it would be to use the cross beams intended for structural stability to help divide the mycelium into sections as it shrinks. In figure X it shows the triangular pattern of cross beams.

This structure would be intended as a large scale social area for outdoor events, while it could give some sectioning between groups the transparency gained by the shrinkage would aid in the open feel.

Figure 6.06. Mushrooms grown on spatial divider sections when only partially dried (Author, 2020).

Another observation was that when the spatial divider sections were out of incubation, but before fully dried out, they grew a large amount of mushrooms. This could be used as a way to combine architecture and cooking through a living wall at a restaurant, café, or food event. If scaffolds were in sections then once the mycelium was no longer fruiting it could either remain as an architectural piece or be replaced.

Future research

The knowledge gained in this research project provides an understanding of the opportunities of both spatial printing and mycelium composites and their ability to be used together to create complex forms

While spatial printing offers an immense amount of freedom in design and authorship, it is a complicated process to learn compared to traditional FDM printing. With more time and complexity of script, spatially printed scaffolds could have much more focused design for targeted applications. Rather than purely exploring if the mycelium composite could be retained and have the form defined by a scaffold, it could also focus on aesthetic properties like printed patterns, exploit gravity while extruding, or anticipating bending, warping, or even melting of the filament during the desiccation process.

This investigation has used an industrial design approach to the research question. A scientific approach would yield more information on specific variables that could influence the properties of the grown mycelium. This could then result in more consistent results and present a wider variety in design opportunities.

Recording of structural properties was beyond the scope of this research, any future research in this area should consider the targeted placement of the construction of the scaffold to create integrated strength to the structure. This considered placement should facilitate the synergy between the scaffold and mycelium composite growth, as identified in the material experiments of adhesion between printing materials and mycelium. Future research would benefit from an interdisciplinary approach from engineering, biology, and design to be able to advance the project further and quantify the results.

Conclusion

Spatial printing presents an opportunity to generate structures that are fully defined by the designer down to every motion of the toolpath during printing. This creates detailed design opportunities through complete toolpath control, compared to FDM printing, which opens up a unique opportunity to digitally control biological growth in a spatial manner.

Mycelium presents itself as an ideal organic material for this process as it can be easily retained by the spatially printed scaffold, is able to grow rapidly taking on the dictated form and can grow around the structure to form strong connections.

This combination of materials presents itself as a suitable way of creating objects at either a medium or larger scale that can be used for a range of contexts. One contextual opportunity is events which have a limited timeframe such as a music festival, food show, or sporting event. By using materials that are fully compostable, the temporary need for the object does not cause strain on resources but instead can almost fully come from and go back to the earth.

References

Figure 1.04. John Krubsack with his living chair. From “Using nature in architecture: Building a living house with mycelium and trees” by Vallas, T., & Courard, L. 2017. *Frontiers of Architectural Research*, 6, p.320.

Figure 1.05. Axel Erlandson's tree sculpture. From “Using nature in architecture: Building a living house with mycelium and trees” by Vallas, T., & Courard, L. 2017. *Frontiers of Architectural Research*, 6, p.320.

Figure 1.06. Klarenbeek, E & Dros, M. (2017). 3D Prints from Algae Filament. [Photograph]. Dezeen. <https://www.dezeen.com/2017/12/04/dutch-designers-eric-klarenbeek-maartje-dros-convert-algae-biopolymer-3d-printing-good-design-bad-world/>

Figure 1.08. Ecovative Design. (n.d.). Ecovative Design. [Mycoflex]. Ecovative Design. <https://ecovativedesign.com>

Figure 1.09. Ecovative Design. (n.d.). Ecovative Design. [MycoComposite]. Ecovative Design. <https://ecovativedesign.com>

Figure 1.10. Mycotree. From “Design of a load-bearing mycelium structure through informed structural engineering: The MycoTree at the 2017 Seoul Biennale of Architecture and Urbanism.” By Heisel, F., Schlesier, K., Lee, J., Rippmann, M., Saeidi, N., Javadian, A., Hebel, D., & Block, P., 2017.

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- Ashby, M. F. (2012). *Materials and the Environment: Eco-informed Material Choice*. Elsevier.
- Barnett, E., & Gosselin, C. (2015). Large-scale 3D printing with a cable-suspended robot. *Additive Manufacturing*, 7, 27–44. <https://doi.org/10.1016/j.addma.2015.05.001>
- Branch Technology. (n.d.). Branch Technology. Retrieved 5 October 2020, from <https://www.branch.technology>
- Chaunier, L., Guessasma, S., Belhabib, S., Della Valle, G., Lourdin, D., & Leroy, E. (2018). Material extrusion of plant biopolymers: Opportunities & challenges for 3D printing. *Additive Manufacturing*, 21, 220–233. <https://doi.org/10.1016/j.addma.2018.03.016>
- Chaunier, L., Leroy, E., Valle, G. D., Dalgarrondo, M., Bakan, B., Marion, D., Madec, B., & Lourdin, D. (2017). 3D printing of maize protein by fused deposition modeling. *AIP Conference Proceedings*, 1914(1), 190003. <https://doi.org/10.1063/1.5016792>
- Co-de-iT. (2016). BIO EX-MACHINA research project. <http://www.co-de-it.com/wordpress/bio-ex-machina-research-project.html>
- Despeisse, M., Baumer, M., Brown, P., Charnley, F., Ford, S. J., Garmulewicz, A., Knowles, S., Minshall, T. H. W., Mortara, L., Reed-Tsochas, F. P., & Rowley, J. (2017). Unlocking value for a circular economy through 3D printing: A research agenda. *Technological Forecasting and Social Change*, 115, 75–84. <https://doi.org/10.1016/j.techfore.2016.09.021>
- Downton, P. (2003). *Design Research*. RMIT Publishing.
- Ecovative Design. (n.d.). Ecovative Design. Retrieved 5 October 2020, from <https://ecovativedesign.com>
- Fairs, M. (2013, October 20). Mycelium Chair by Eric Klarenbeek is 3D-printed with living fungus. <https://www.dezeen.com/2013/10/20/mycelium-chair-by-eric-klarenbeek-is-3d-printed-with-living-fungus/>
- Frankel, L., & Racine, M. (n.d.). *The Complex Field of Research: For Design, through Design, and about Design*. 12.
- Frayling, C. (1994). *Research in Art and Design* (Royal College of Art Research Papers, Vol 1, No 1, 1993/4) [Monograph]. Royal College of Art. <https://researchonline.rca.ac.uk/384/>
- Grow.bio. (n.d.). GROW.Bio. Retrieved 5 October 2020, from <https://grow.bio/>
- Haggar, S. E. (2007). *Sustainable Industrial Design and Waste Management: Cradle-to-Cradle for Sustainable Development*. Elsevier Science & Technology. <http://ebookcentral.proquest.com/lib/vuw/detail.action?docID=307125>
- Hanington, B., & Martin, B. (2012). *Universal Methods of Design: 100 Ways to Explore Complex Problems, Develop Innovative*

Strategies, and Deliver Effective Design So. Quarto Publishing Group USA. <http://ebookcentral.proquest.com/lib/vuw/detail.action?docID=3399583>

Heisel, F., Schlesier, K., Lee, J., Rippmann, M., Saeidi, N., Javadian, A., Hebel, D., & Block, P. (2017, December 11). Design of a load-bearing mycelium structure through informed structural engineering: The MycoTree at the 2017 Seoul Biennale of Architecture and Urbanism.

Henri, R. (2018). Investigations on Mycelium-Based Composites.

Horta, J. F., Simões, F. J. P., & Mateus, A. (2018). Large scale additive manufacturing of eco-composites. *International Journal of Material Forming*, 11(3), 375–380. <https://doi.org/10.1007/s12289-017-1364-5>

Ilgun, A., & Ayres, P. (2016, January). Coupling Distinct Paradigms of Deposition-Based Construction for the Production of Co-occupied Boundaries. https://www.researchgate.net/publication/313772458_Coupling_Distinct_Paradigms_of_Deposition-Based_Construction_for_the_Production_of_Co-occupied_Boundaries

Karana, E., Blauwhoff, D., Hultink, E.-J., & Camere, S. (2018). When the Material Grows: A Case Study on Designing (with) Mycelium-based Materials. *International Journal of Design; Taipei*, 12(2), 119–136.

Keating, S., Leland, J., Cai, L., & Oxman, N. (2017). Toward site-

specific and self-sufficient robotic fabrication on architectural scales. ResearchGate. <https://doi.org/10.1126/scirobotics.aam8986>

Molloy, I. (2017). Designed Deposition—Freeform 3D Printing for Digitally Crafted Artefacts—Details. https://viewer.waireto.victoria.ac.nz/client/viewer/IE1029474/details?dps_dvs=1558347417486~337

Morgan, H. (2019). Optimised 3D Printed Structures.

Morris, A. (2017, December 4). Dutch designers convert algae into bioplastic for 3D printing. Dezeen. <https://www.dezeen.com/2017/12/04/dutch-designers-eric-klarenbeek-maartje-dros-convert-algae-biopolymer-3d-printing-good-design-bad-world/>

Oxman, N., Laucks, J., Kayser, M. A. R., Tsai, E., & Firstenberg, M. (2013). Freeform 3D printing: Towards a sustainable approach to additive manufacturing. <https://doi.org/10.1201/b15002-93>

Portney, K. E. (2015). Sustainability. MIT Press. <http://ebookcentral.proquest.com/lib/vuw/detail.action?docID=4397950>

Rodríguez Ramírez, E. (2017). A Postgraduate Thesis Model for Research through Design Based on Design Criteria. *The International Journal of Designed Objects*, 11(4), 11–27. <https://doi.org/10.18848/2325-1379/CGP/v11i04/11-27>

Soh, E., Chew, Z. Y., Saeidi, N., Javadian, A., Hebel, D., & Le Ferrand, H. (2020). Development of an extrudable paste to build mycelium-

bound composites. *Materials & Design*, 195, 109058. <https://doi.org/10.1016/j.matdes.2020.109058>

Stahel, W. R. (2016). Circular economy. *Nature; London*, 531(7595), 435–438. <http://dx.doi.org/helicon.vuw.ac.nz/10.1038/531435a>

Vallas, T., & Courard, L. (2017). Using nature in architecture: Building a living house with mycelium and trees. *Frontiers of Architectural Research*, 6(3), 318–328. <https://doi.org/10.1016/j.foar.2017.05.003>

Yoo, S.-S., & Polio, S. (2010). 3D On-Demand Bioprinting for the Creation of Engineered Tissues. In B. R. Ringeisen, B. J. Spargo, & P. K. Wu (Eds.), *Cell and Organ Printing* (pp. 3–19). Springer Netherlands. https://doi.org/10.1007/978-90-481-9145-1_1

Zhang, X., Li, M., Lim, J. H., Weng, Y., Tay, Y. W. D., Pham, H., & Pham, Q.-C. (2018). Large-scale 3D printing by a team of mobile robots. *Automation in Construction*, 95, 98–106. <https://doi.org/10.1016/j.autcon.2018.08.004>

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