# Biological inter-dependencies in 3D printing:

## Larvae scaffold excavation of high filigree clay structures

A thesis submitted to the Victoria University of Wellington in fulfilment of the
requirements of the degree of Master of Architecture

by

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# ABSTRACT

Ceramic 3D printing has emerged in recent years as a new method for working with age-old material, a blend of the digital and analog that breeds a new type of artisan. Working with clay in an FDM extrusion system presents a number of challenges due to the nature of the material, restricting the forms that can be produced to rudimentary levels of ornament and shape. This research tackles the issue of resolution and thickness when creating and designing shell structures from ceramic materials, notably when 3D printing is used for complex geometry. This research aims to navigate these material and technological constraints by designing a novel approach to support scaffolds using a secondary material. This secondary material serves as an organic encasement for the ceramic object, and nature is treated as a co-collaborator in the excavation and controlled curing of a high filigree clay structure. By introducing edible bio matter and/or cellulose solutions, this encourages a new relationship with nature as a tool and co-author, becoming a stakeholder in the final result. This research examines the relationship between human, machine, and nature in the design and manufacturing of products.

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# THESIS OVERVIEW

**Chapter 1 - Literature Review and Methodology.** This section will be dedicated to providing an extensive overview of where the different fields of this research are situated as well as specific examples via precedents and literature review

**Chapter 2 - Preliminary Desk Study.** This section documents an analysis of both potential partners for collaboration in the natural world and the ability to create new forms through agency in a digital environment.

**Chapter 3 - Physical Experimentation.** This section details the various inquires into both materials and biological organisms that are used as tools, via physical experiments in the real world. Additionally this section identifies the myriad of variables to be navigated as part of the proposition of this research.

**Chapter 4 - Design Synthesis.** This section discusses the potential use of the knowledge gained in the previous desk study and physical experimentation, and showcases the potential avenues for co-authorship and co-collaboration in the creation of high filigree structures.

## 1

# LITERATURE REVIEW

The purpose of this literature review is to develop a comprehensive understanding of biological systems, digital tools, and materials. In doing so, this research will investigate the potential for a bio-collaboration to create novel products and services, with the aim of employing this framework in subsequent design experiments. Precedent material is used to showcase how certain projects follow or potentially sit outside this framework, allowing for a clear evaluation criteria to be developed. Following this, the study of natural systems for design will extend into the digital realm, analysing the potential for digital environments to visualise organic assemblages and create form. While assessing current uses of clay as a digital material, this inquiry also aims to communicate the current state of ceramic 3D printing, by identifying the constraints of the material that serve as pitfalls for freedom in the design and fabrication of variable clay forms. In conclusion, these findings are summarised into key criteria and a proposition for the research is formulated.

# Bio Design

Biodesign is an emerging area of practice where the essential component is the inclusion of living organisms or ecosystems. These biological entities serve as core aspects of the design process and its output, "enhancing the function of the finished work", and creating a platform where the designer must surrender authorship or control to another species or lifeform (Myers, 2012, p. 8). This new form of collaboration ventures beyond biomimicry and the imitation of nature, to a true integration of living systems and their complexities, so that we might bridge between the natural and built environment (Myers, 2012).

Designing and negotiating with nature is a "timeless human ambition", to the point that we are even willing to surrender to her whim's (Carpo, 2012, p.104). Renewed alliances with nature are sought after, due to the ever present finiteness of the natural environment (Carpo, 2012). By taking advantage of and employing processes from the living world, we can create systems that "achieve near perfect economies of energy and materials" (p. 10). In this sense nature can be seen as a model for how the built environment can shift to achieve qualities that result in relatable, harmonious or familiar structures. By building interdependency, efficiency and adaptability through symbiotic design processes, we can encourage ecologically sound practices that go beyond subjective aesthetic quality or implied significance (Myers, 2012).

Wolfs (2014) claims there are a very limited number of commercial industrial products that invite that same collaboration with nature. Although in recent years, there are a range of projects from artists and designers that explore a relationship with nature in a contemporary context by making "functional collaborations" with nature as a partner (Wolfs, 2014, p.78).

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*Figure 0.01: Phillips Design - Microbial Home (Indoor beehive), 2011*

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*Figure 0.02: Thomas Libertiny - Endless Column, 2017*

One such example is the Microbial Home by Phillips Design, which explores creating a cyclical system for waste within the home, where the function of each appliance or piece of furniture outputs waste that can be used by another. The Microbial Home creates a novel relationship between the user and their biological waste, that encourages consideration for how sewage, effluent, rubbish and waste water can be repurposed which effectively transforms the home into its own closed ecosystem (Microbial Home by Philips Design, 2011). The concept even boasts an indoor beehive, accessed by bees through planters placed on the exterior side of the wall, the pre-existing honeycomb structure provides lodgings for their wax cells, see figure 1.1.

This process can also be seen in the work of Thomas Libertiny, which includes multiple collaborations with bees to build large honeycomb structures over time. By pre-defining geometries with plaster and PLA polymer, the bees natural affinity to cater to their environment is leveraged, resulting in, for the most part, controlled results, see figure 1.2. In a similar vein, Geoff Manaugh and John Becker have imagined the possibility of using genetically engineered bees to 3D print concrete. The aim is to use this new breed of bees to "3D-print sculptural forms and architectural ornament into existence through the help of geometric formwork." (Dan Howarth, 2014, para. 2). By placing the bees into moulds or scaffolds, the restricted environment encourages the bees to fill a controlled volume, similar to Libertiny's sculptures.

It is evident that nature's own 'organic' additive manufacturers already exist in the form of silkworms, spiders and bees. Domestication of these species allows for more controlled and creative purposes. By feeding silkworms 'green diets' of coloured mulberry leaves, researchers discovered the silkworm's ability to produce coloured silk (Nisal et al, 2014). This research revealed the potential to create new modes of production as well as new products using methods that circumvent potentially hazardous chemical dying processes. In a larger endeavour by MIT's Mediated Matter Lab, silkworms' natural tendencies are leveraged towards creating the 'Silk Pavilion', which explores using external stimuli such as food sources or pre-existing structures as guides or markers for fabrication and tool pathing. In this case, the collaborator or partner (silkworms) is given a task with a set of restricted parameters (geometry), but the end result is not fixed or entirely pre-determined due to the silkworms ability to freely navigate the underlying mesh structure as it sees fit. This autonomous tooling allows for new, unpredictable, or emergent (Johnson, 2012) qualities. By giving up control to another entity, the role of the human becomes that of an orchestrator, with the focus shifting towards that of partnership, co-collaboration, and interdependence between the digital and biological

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*Figure 0.03: John Becker and Geof Manaugh - Bees printing concrete, 2014*

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*Figure 0.04: MIT Mediated Matter group - Silk Pavilion, 2013*

# Digital Darwanism

Digital tools have rapidly become partners and collaborators in their own right, the reliance on which has been viewed as a potential dissolution of authorship in design, culminating in a new workflow dubbed 'digital emergence' (Carpo, 2012). Steven Johnson (2001) describes emergence as the process of self organisation from low level systems, as opposed to order derived from a hierarchy of information. In other words - the sum of the parts possessing intelligent behaviour beyond the capabilities of the single agent. As an example, the use of swarm intelligence to generate form establishes a relationship between the human and machine based on 'conversation' and a 'mediation' of ideas (Caranza & Coates, 2000). The visual representations created by the swarm are then interpreted by the human, so that meaning can be deduced, and an adjustment or selection made. "The swarm tends to 'understand' and 'agree' with the choices made by the person interacting with it, but it also seems to 'disagree' slightly, or at least to not fully understand the preferences of the user. It is only in this way that the conversation is possible, and the consensual domain formed" (Caranza & Coates, 2000, p.12). Here the swarm is personified, as are the agents acting within it.

Russell and Norvig (2003) describe an 'agent' as having the ability to perceive its environment and act according to it. Systems that involve multiple agents, are thus referred to as "multi agent systems (MAS), where passive data objects turn into the active agents, and the agents act according to the available data" (Agirbas, 2017, p.141). The process of agents navigating digital environments and the information it contains can be viewed as an application of stigmergy, that being a "mechanism of indirect coordination in which the trace left by an action in a medium stimulates subsequent actions" (Heylighen, 2016, p.1). When applied as a method for form-finding,

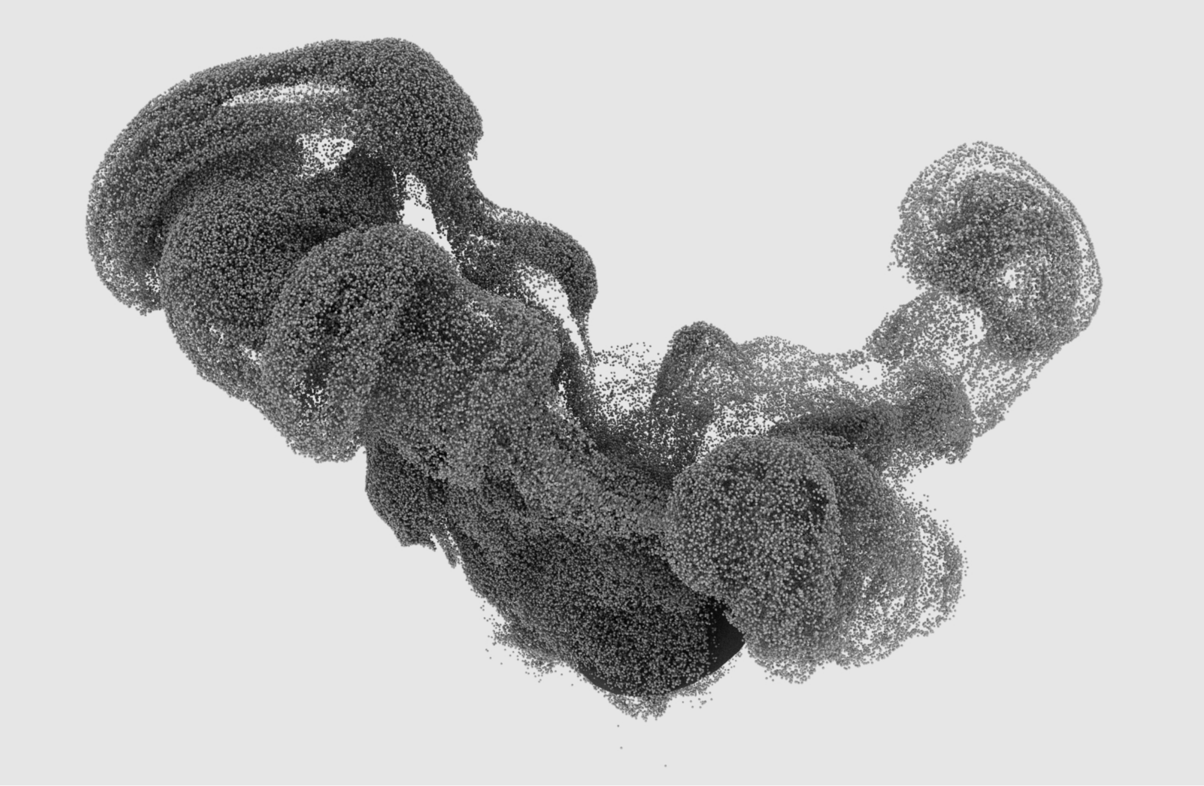

*Figure 0.05: Bifrost particle system*

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*Figure 0.06: Tommaso Casucci - Turbulent structures, 2017*

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*Figure 0.07: Michael Hansmeyer - Digital Grotesque II, 2017*

the resulting geometries are also variable and potentially even unpredictable, as they are driven by collective behaviours tied to digital parameters.

Michael Hansmeyer describes this process when discussing ‘Digital Grotesque II’, a large-scale 3D-printed grotto premiered at Centre Pompidou’s Imprimer le Monde exhibition. Through the use of computer algorithms to generate these high filigree structures, “the role of the designer becomes one of a curator, steering the process and defining the appropriate design goals” (Michael Hansmeyer - Digital Grotesque II, 2017) see figure 1.7. Hansmeyer (2017) argues that this new human-computer interaction builds on the designers creativity and imagination, because of a removal from the prevailing archetypical and categorical approach (2017). Neil Leach (2002) agrees, stating that “at a most radical level, the computer has redefined the role of the architect. No longer is the architect the demiurgic form-maker of the past. The architect has been recast as the controller of processes, who oversees the ‘formation’ of architecture” (p. 9). Finally, Carpo (2012) argues that this trend is also a “diminished form of authorship in design” (p.97).

This research examines the notion that this is instead a transfer of authorship between human and digital partners. With similarities to Biodesign and its collaborations with real-world natural systems, this research aims to create digital environments that enable a new form of collaboration and agency of digital tools. These ‘agents’ will act on the information found in their digital environment to design the output, thus creating forms that are “a far cry from the polished, smoothness, elegant curvilinearity and delicate intricacy that authorial parametricism has engendered and nurtured so far” (Carpo, 2012, p.104). This elicits the conversation and mediation between machine and human authors, a co-collaboration and interdependence that is seldom sought after within digital design methods.

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*Figure 0.08: TURBULENTARCH - Olympthings, 2014*

# Clay as a digital material

In contrast, both additive (deposition of material) and subtractive (removal of material) manufacturing are industries built on precision, efficiency and consistency, where concepts can be realised through computer-numerically-controlled (CNC) processes. Machinery is driven by a specific set of instructions to create an object, specified by the designers’ pre-conceived ideas and their ability to visualise them digitally beforehand. A new relationship is cultivated between the designer and the tools used to conceptualise, ideate and realise these ideas within a modern context. The ‘digital craftsmen’ uses new CAD-CAM technologies “as an extension of the mind and body” (Carpo, 2012, p.101), a union that breeds new forms of tacit knowledge, not unlike those that a ‘traditional’ craftsmen cultivates with real-world materials.

When referring to the output as a result of this ideation, Gursoy (2018) argues that we should be ‘making for’ the material within this digital to physical workflow. With reference to 3D printing with clay, Gursoy (2018, p.22) states “uncertainty in the processing of the matter is valued over the control and accuracy in the processing of information”. Because of the materials nature to sag due to weight and gravity while wet, designing or making for clay restricts potential geometry and degrees of complexity. This challenge can be viewed as either a feature or defect in the final result, but within the framework presented by Gursoy and his work, this is a necessary component of the material attributes that needs to be traversed as part of designing ‘for’ digitally extruded clay.

Olivier van Herpt, a ceramic 3D printing pioneer in his own right, provides an interesting take on these same material attributes, by using sound as an additional variable that produces uncontrollable results. In a collaboration with sound designer Ricky van Broekhoven, the two mounted a speaker below the building platform, forcing the printed model to bounce and shake during the printing process, creating deviations and tectonics in an otherwise regular path (2015). The objects created using this process contain a new twist on the ‘mark of the maker’, as new emergent qualities are embedded into the object from the additional element; sound. This is hard to replicate with more traditional thermoset polymers in 3D printing, where the potential for error is much higher with each new variable added.

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*Figure 0.09: Olivier van Herpt - Solid Vibrations, 2015*

Clay as a building material provides opportunities to discover new surface qualities, texture and colour, but the ability to create highly variable and non-linear objects has not been fully explored beyond what could be viewed as ‘happy accidents’. The majority of the literature and precedent material available in relation to 3D printing with clay focuses on what is possible through the uncertainty and constraints of a ‘sloppy’ material, with objects usually being cylindrical in nature to help the form self-support as it builds. This self-supporting function is necessary because of clay’s tendency to slump and warp under its own weight in larger builds. Some efforts have been made to build support structures for clay 3D printing, notably by Tom Lauerman, who has documented using additional clay to create pillars that support steep overhangs of material (https://tomlauerman.com/process).

Potentially the nature of this ‘sloppy’ material could be shifted to that of something more controlled through alternative manufacturing approaches. Particle-bed 3D printing processes tackle this issue by using particles that are selectively fused together layer by layer. This method allows for the fabrication of large-scale freeform structures by utilising binding agents in conjunction with concrete, sandstone, plaster and other more ‘reactive’ particulates. These

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*Figure 0.10: The Bottery - 3D printed clay slumping, 2019*

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*Figure 0.11: Richard Horne - Sugar paste 3D printing, 2012*

machines operate on an expansive print area, some boasting up to 6 metres in width, as well as deploying 100s of print heads to solidify material, see figure #. The previously described Digital Grotesque installations from Michael Hansmeyer utilise this very same 3D-printing process, which "demonstrates how leaps in computation and fabrication technologies can make new architectural worlds tangible" (Lowke et al. 2018, p.62).

Binding agents in this workflow are predominantly chemical compounds, although in a recent project Enrico Dini explored the use of sand and an inorganic seawater binder to restore coral reefs and undersea structures, as seen in figure #. This approach allows for the construction of not only large-scale freeform structures, but place-based responses by using material from the environment where the structure is to be situated. In an additional effort to minimise the ecological impact of this process, a focus is placed on the re-use of non-bonded material so that it is fully recyclable (Lowke et al. 2018, p.52).

The use of particle support structures and organic materials in additive manufacturing is not a new revelation, and continues to develop as designers and artists attempt to find innovative ways to circumvent the use of industrial polymers or other chemical binding agents. Richard Horne (2012) has experimented and documented 3D printing with chocolate, masa harina (corn flour) and sugar pastes using RepRap's universal paste extruder. With similarities to wet clay these materials bring a number of challenges to be navigated before extruding and forming into consistent shapes, affecting the geometry that can be produced. A concept that has not been fully explored is the culmination of dual extruder 3D printing and organic materials, to create a support structure.

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*Figure 0.12: D-Shape - Undersea structure excavation, 2010*

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*Figure 0.13: D-Shape - 3D-printer (left) and print head (right), 2010*

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*Figure 0.14: D-Shape - Artificial reefs, 2010*

# Conclusion/Proposition

Through analysing literature and precedent projects, this research posits that there is a commonality among these potentially disparate practices warranting further investigation. Instead of a ‘dissolution’, a new approach that champions the exchange or transfer of authorship can allow for results that could not be realised within the constraints of a conventional parametric approach. By utilising digital software to simulate multi-agent systems, the generation of form can be steered toward a conversation between both human and machine authors. The results of which can no longer be governed by that same ‘authorial parametricism’ (Carpo, 2012) that inhibits truly organic geometry.

These geometries are difficult, if not impossible to reliably reproduce using conventional moulding and or other manufacturing techniques. But with a rapid and continuing development of 3D printing capabilities, this allows for the translation of organic geometries into real world objects. Although 3D printing with clay still remains in relative infancy, this research proposes that there is an opportunity to apply dual extruder printing processes with organic materials, to build what could serve as both a support structure and an encasement that controls curing.

Emergence is described by Steven Johnson as the result of low level rules moving into higher levels of sophistication (2012). In this scenario, emergence is sought through the sharing of authorship, to create forms and finishes that are designed and manufactured by interdependent parties. By utilising organic materials and partners, the ‘conversation’ between human and machine authors can also extend to the biological sphere, creating artefacts that move beyond mere biomimicry, and towards that of true ‘Biodesign’ (Myers, 2012). These biological authors could be guided and directed through an organic encasement via selective material deposition, creating a new form of tool pathing that slowly cures and unearths a clay body with care and control.

# METHODOLOGY

This investigation explores the intersection between biology, materials and automated (computer numerically controlled (CNC) machines and includes software. The methodology forefronts action and reflection/deduction as highlighted below; as a combination of both action research and reflective practice. Archer (1995) describes action research as a calculated investigation carried out through practical experimentation, the goal being to communicate knowledge via testing new ideas in the real world (p.11).

It is both situational and emergent therefore: reflective practice is treated as a ‘reflective conversation with the situation’. Where constraints are identified within a problem, attempts are made to reach a solution, and the results are constantly evaluated (Valkenburg & Dorst, 1998, p.251). The ‘tacit knowledge’ (Friedman, 2008) gained through this process of inquiry helps to develop solutions to problems that were once only theoretically planned for, as part of the overarching method of research through design (Frankel & Racine, 2010).

The research will test the notion of the ‘solution’ as a temporal condition, (Kwinter & Davidson, 2008) prioritising differentiation and variability in the outputs as a necessary part of searching the space of materialisation (Delanda, 2015).

## 2

# PRELIMINARY DESK STUDY

This chapter is a summary of the desk research conducted to establish a grounded understanding of potential methods for both the design and fabrication of high filigree clay bodies, using a secondary encasement in conjunction with digital tools for concept ideation. As discussed earlier, this research aims to begin a discourse surrounding the use of biological and digital tools as agents and designers in their own right. To do so, preliminary studies involved locating viable ‘partners’ and materials for encasement based on a set of criteria. Additionally, digitally simulating how these agents may approach excavation of a highly filigree object, helped in visualising the possibilities for a novel, hybrid approach to manufacturing.

As part of this stage of the research, digital software is employed as a means of preliminary form-finding through the use of digital agents. By experimenting with attraction, repulsion and cohesion, these concepts aim to foster an understanding of how digital agents can be used to discover new aesthetic qualities, inspired by natural systems and their behaviour. Also, by digitally simulating how agents may approach excavation of these highly filigree objects, this helped in visualising the possibilities for a novel, hybrid approach to manufacturing.

## Nature as collaborator

This portion of the research is dedicated to finding potential partners and co-collaborators, with a hope of understanding the biological variables amongst different species that aid or hinder the ability to control excavation and curing of high filigree clay structures. This is an area where someone with a depth of knowledge in various species, such as a biologist or entomologist, would produce a highly meticulous and scientific summary of the myriad factors at play. To simplify this vast quantity of knowledge into the variables of significance, species were evaluated and selected using three key questions aimed at determining their feasibility and reliability:

Speed: How much food by weight does this species eat per day?

Attraction: What food sources are they attracted to?

Gestation: How quickly can they reproduce or what are their gestation periods?

By answering these questions and assigning a rating system, appropriate ‘candidates’ for both species and materials are determined. Possible encasements will be evaluated and selected on their ability to be obtained organically, whether they can be extruded and selectively deposited, and any other information that can be ascertained before physical experimentation.

Figure 1.01: Mealworm larvae, 2010

Figure 1.02: Mealworms in polystyrene, 2015

| | | | |
|---|---|---|---|
| **Speed** | 🟦 | **Attraction** | 🟦🟦 |
| **Gestation** | 🟦🟦🟦 | **Extrudability** | 🟦🟦🟦🟦 |

Mealworms present an interesting option because of their documented ability to consume polystyrene under conditions where no other food is available. Although this is quite a miraculous proposition, the rate that this can be done is quite slow, with 1kg of mealworms able to consume roughly 20g/day (Yang et al., 2015)

Figure 1.03: Tiger worms, 2020

Figure 1.04: Organic food waste, 2019

| | | | |
|---|---|---|---|
| **Speed** | 🟦🟦 | **Attraction** | 🟦🟦🟦 |
| **Gestation** | 🟦🟦🟦 | **Extrudability** | 🟦 |

Tiger worms are used in compost bins to process ‘green matter’ resulting from food waste. It can take some time to establish a functioning colony and they can eat up to their full body weight per day, but the rate at which it can process food is limited due to not being able to ingest rotten and decaying matter.

Figure 1.05: House Sparrow, 2011

Figure 1.06: DIY Bird Suet, 2017

| | | | |
|---|---|---|---|
| **Speed** | 🟦🟦🟦 | **Attraction** | 🟦🟦🟦🟦 |
| **Gestation** | 🟦 | **Extrudability** | 🟦 |

Birds could be used to process a large amount of material quickly, with 1/4 to 1/2 of their body weight possible depending on the species and availability of alternatives within the immediate environment.

Figure 1.07: Maggots, 2017

Figure 1.08: Fish heads, 2016

| | | | |
|---|---|---|---|
| **Speed** | 🟦🟦🟦🟦🟦 | **Attraction** | 🟦🟦🟦🟦🟦 |
| **Gestation** | 🟦🟦🟦🟦🟦 | **Extrudability** | 🟦🟦 |

Maggots present the most compelling possibility, with the ability to consume 2x their body weight every 4 hours. An estimation based on median size would place this excavation rate at 2.64g per day, per maggot. They are also very quick to breed an propogate, allowing for incrementally fast capability.

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*Figure 1.09: White-footed ants, 2017*

*Figure 1.10: Sugar, 2017*

| | | | |
|---|---|---|---|
| **Speed** | ■ ■ ■ | **Attraction** | ■ ■ ■ |
| **Gestation** | ■ ■ ■ ■ | **Extrudability** | ■ ■ ■ |

Ants can eat up to 1/3 of their body weight each day, that being roughly 2 milligrams. For example a 10,000 strong ant colony could consume around 20 grams a day. Diet's are quite omnivorous but can be targeted with sugars in the case of common house varieties such as white footed ants.

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*Figure 1.11: Termites, 2020*

*Figure 1.12: Wood, 2018*

| | | | |
|---|---|---|---|
| **Speed** | ■ | **Attraction** | ■ ■ ■ ■ |
| **Gestation** | ■ ■ | **Extrudability** | ■ ■ ■ |

Termites feed on cellulose structures within wood, though the rate this this happens is very very slow. The largest subterranian termite colonies in the world are noted to be able to process 'about a pound of wood per day' (Termite Facts - How Fast Do Termites Eat Wood?, n.d.), though cultivating this would be out of the scope of this project.

# Reflection and Analysis

This preliminary research indicates that there are some clear frontrunners for excavation of organic material, but it is at this point that consideration must be made for what else this concept for fabrication encourages, if it were to be realised at a large scale.

Using maggots as an example, these could be quite easily cultivated and used to consume decaying and necrotic flesh, but given where this research sits in creating a grassroots and accessible method for fabrication, there is a necessity to question what other problems this could invite. Predatory and invasive species create situations where the production of these objects will need to be in highly controlled environments, not unlike a science lab in strict quarantine conditions.

The same could be said for using birds as tools for excavation. To be able to access and make use of local inhabitants, an apparatus or environment would have to be designed that can encourage birds to access the full surface area of the object, but in a way that those same predatory species will not be able to use it as an equal opportunity to eat. Hanging a bird feeder from a branch with a small suet cake is easily attainable, although, when considering producing objects that will no doubt move into the range of kilograms, this becomes difficult to navigate.

The 'extrudability' of the material is an additional variable that must be considered while selective deposition by a 3D printer extruder system is the end goal. When going through an extruder setup, any inconsistencies and variation in the material will create clogging and eventual damage to the machine. That being said, this can potentially be circumvented by reprocessing into a much finer pulp or paste, as is seen in the smaller syringe-driven setups discussed earlier.

# Machine as designer

The objective of this portion of the research is to analyse the capability of software to emulate natural systems and forces, in a way that form can be created (generated) in a reactive environment as opposed to being methodically planned and executed (Caranza & Coates, 2000). With points and lines serving as agents, form will be discovered through slight changes in variables and environmental conditions within a digital simulation. This method of form finding through emergence is not without direction or intent, as this experimentation hopes to set a base level of knowledge of these digital processes, with the intent of applying it to observed natural processes as part of the following portion of research.

Digital simulations are based on attraction and repulsion, centering around the ability for the 'agent'(s) (in these cases the particles or curves) to navigate these factors and contribute towards an output. By applying additional variables such as turbulence, vortexes, flocking, collisions, and other dynamic attributes, these experiments showcase the potential to use multi-agent systems and simulated physics for form-finding.

To begin, an nParticle system in Autodesk Maya is used to drive a form based on a predefined path. This path also acts as a moving anchor for the fields that the agents must navigate while reacting to the digital environment. The movement of the agents within this space is captured, and the resulting curves are used to generate a mesh that is smoothed and averaged based on its surrounding geometry. Depicted in figure 1.13, turbulence within the digital simulation is reconfigured through magnitude and noise levels to create progressively more erratic yet controlled results.

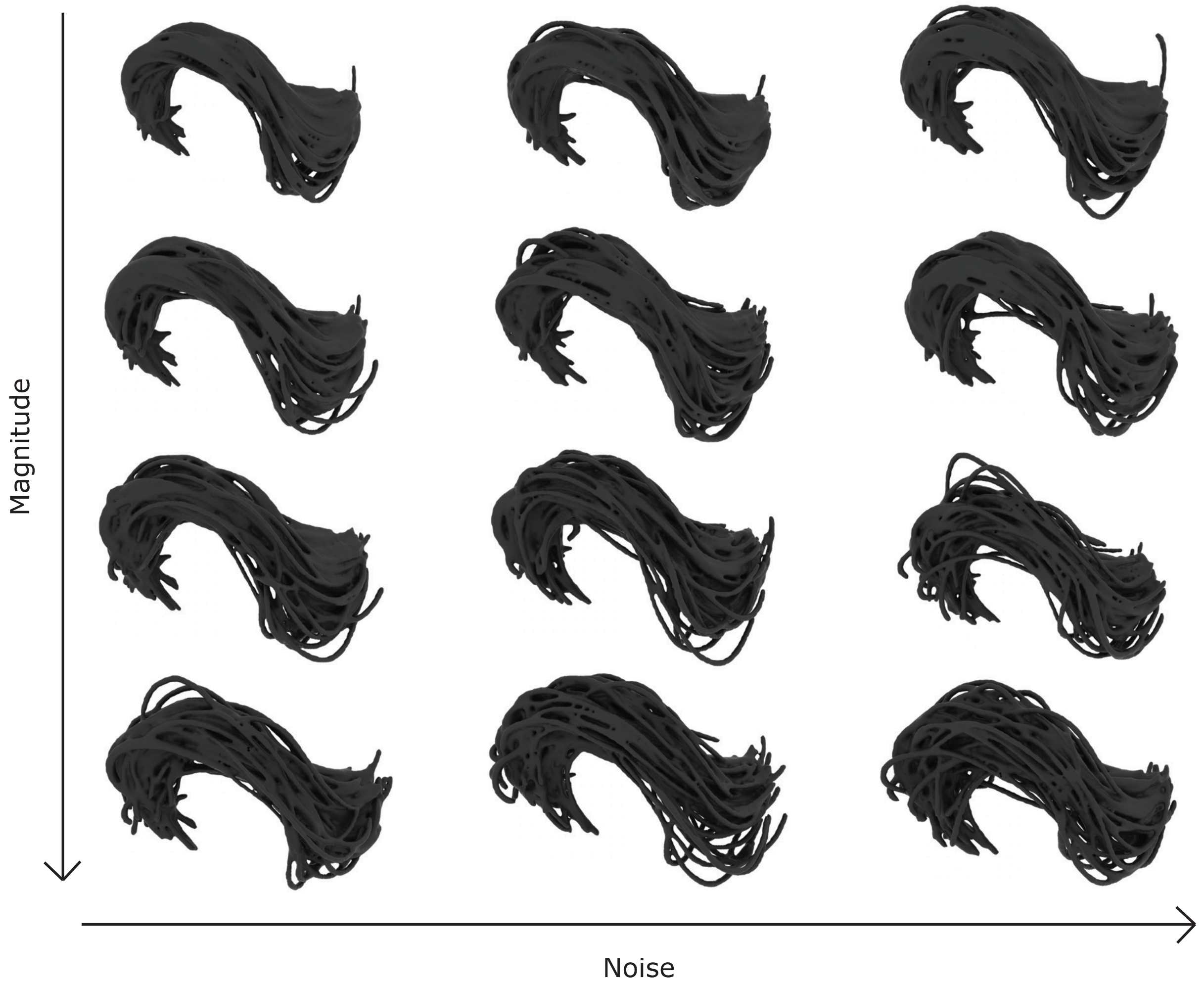

*Figure 1.13: Gen1 - Turbulence and noise*

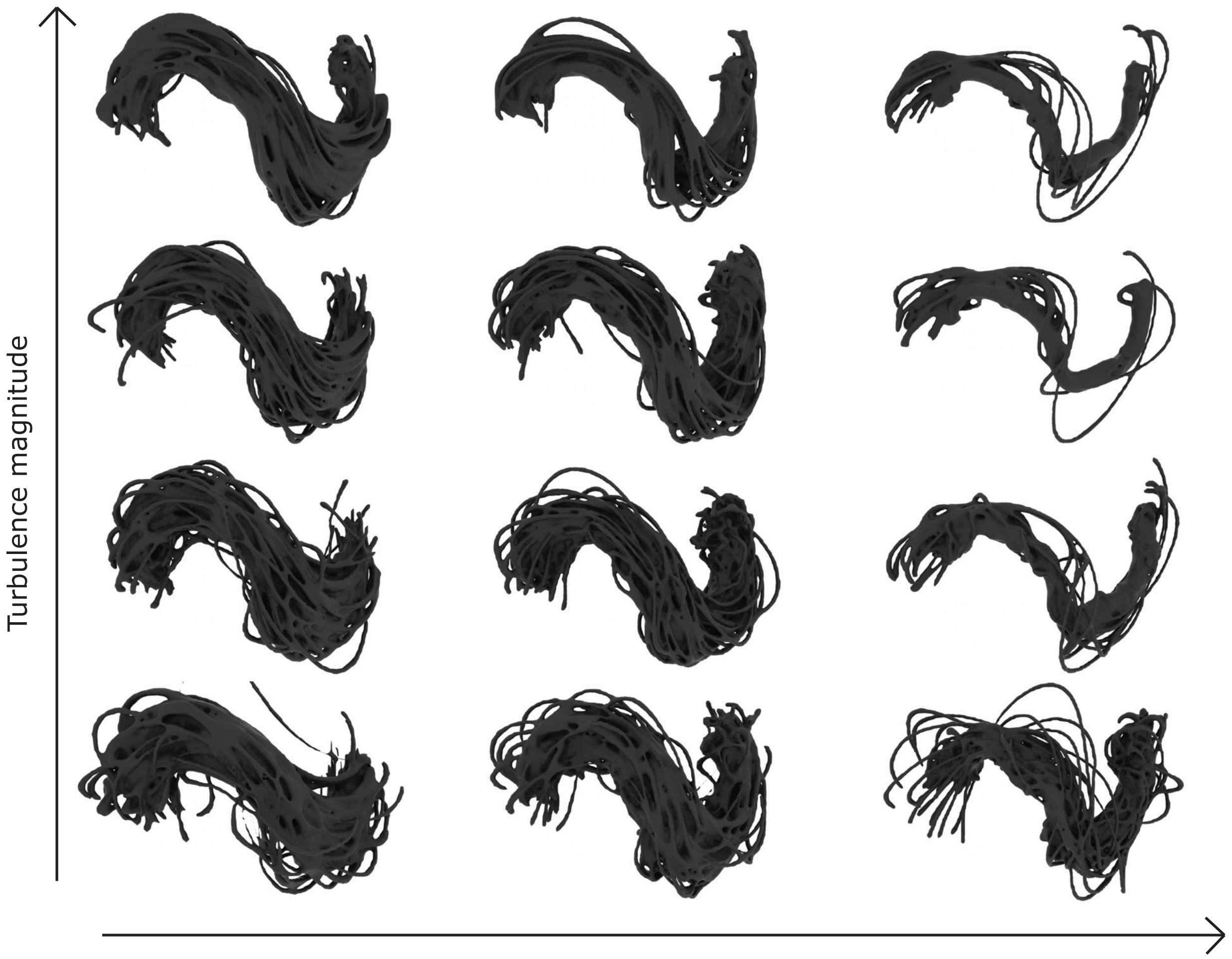

*Figure 1.14: Gen2 - Turbulence and newton strength*

Additionally, nHair systems can be used to generate forms based on a series of lines and curves, which are then manipulated by competing forces. In one series of experiments (Fig 1.15), the curves that make up the geometry of a sphere are extracted and converted into curves, before being subjected to turbulence over a series of frames. The resulting form slowly evolves from it’s starting configuration over time, creating an exponentially volatile response. In an effort to control this response, the magnitude of the turbulence can be altered, but with no real assurances as to what forms will be generated.

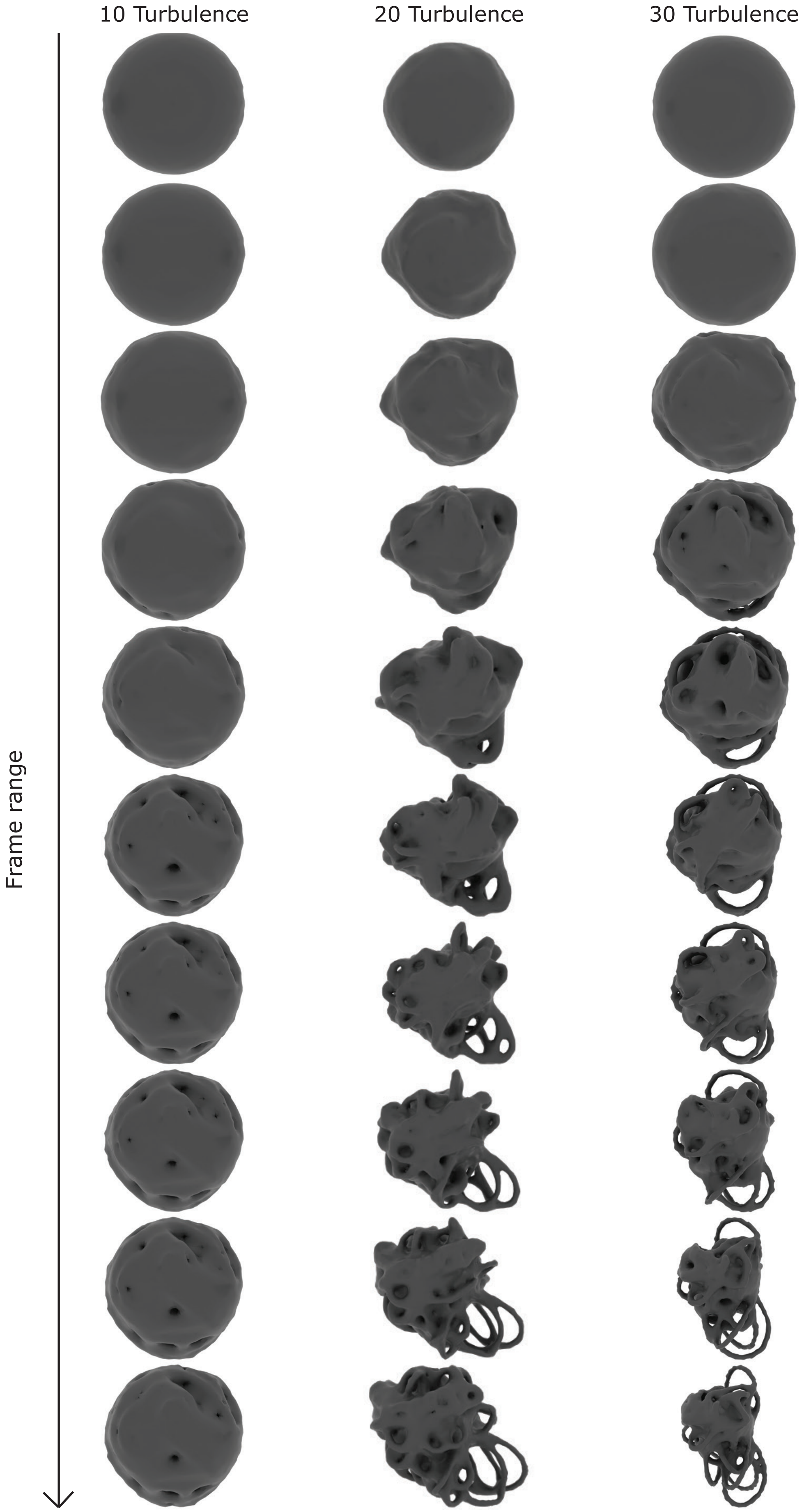

*Figure 1.15: Gen3 - nHair turbulence from sphere*

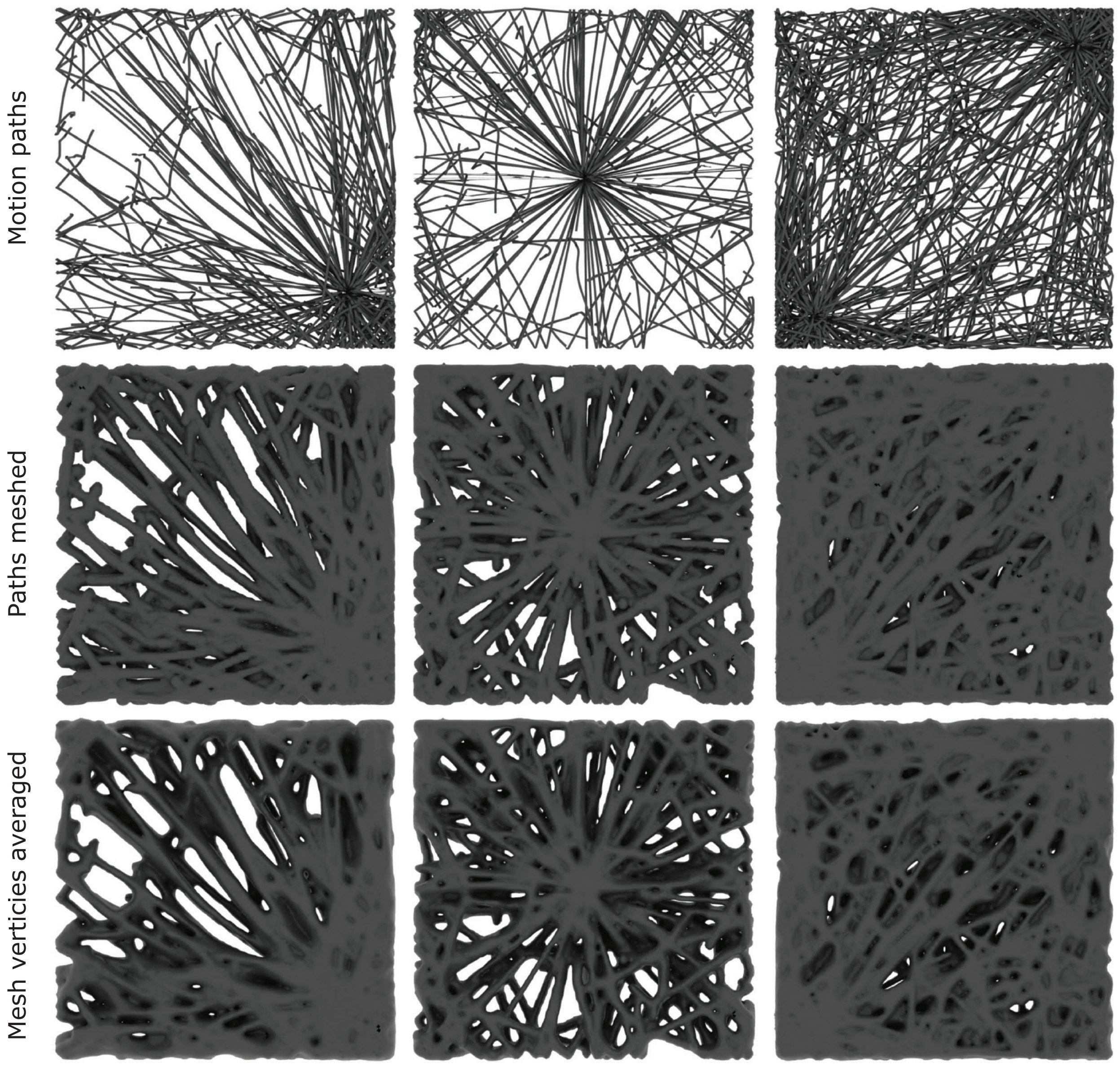

*Figure 1.16: Gen4 - Changing emitter start point inside container*

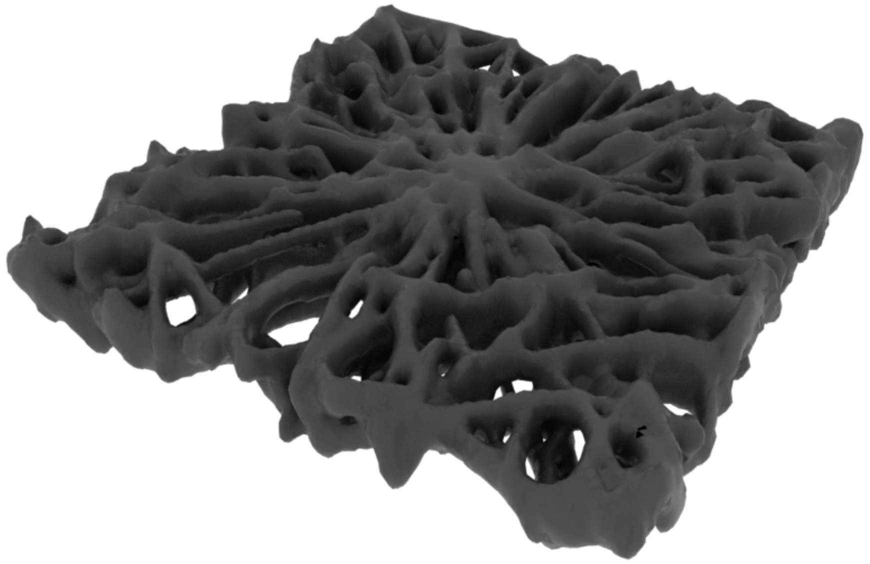

*Figure 1.17: Gen4 surface texture*

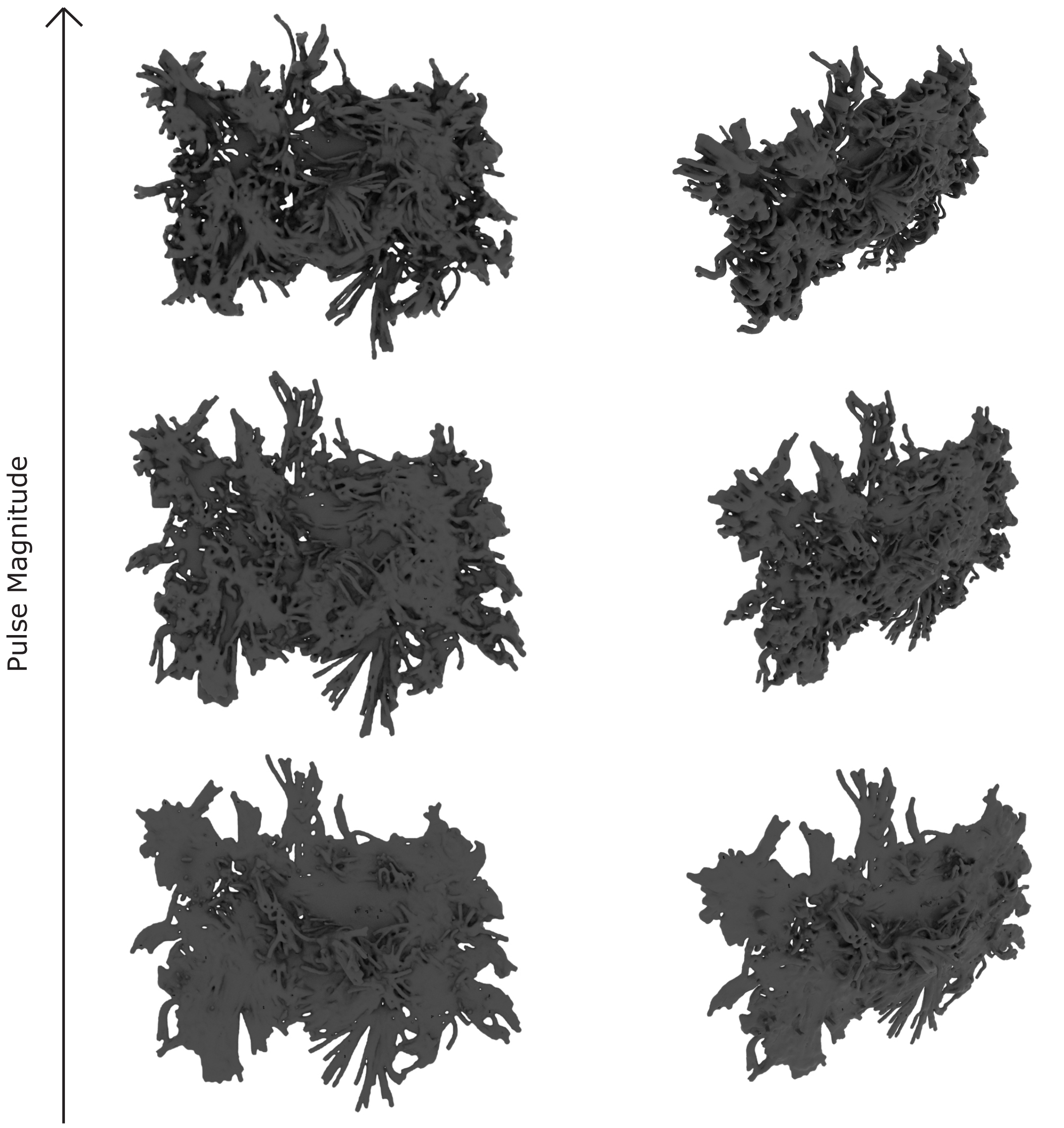

*Figure 1.18: Gen5 - Pulsing turbulence against surface to create filigree*

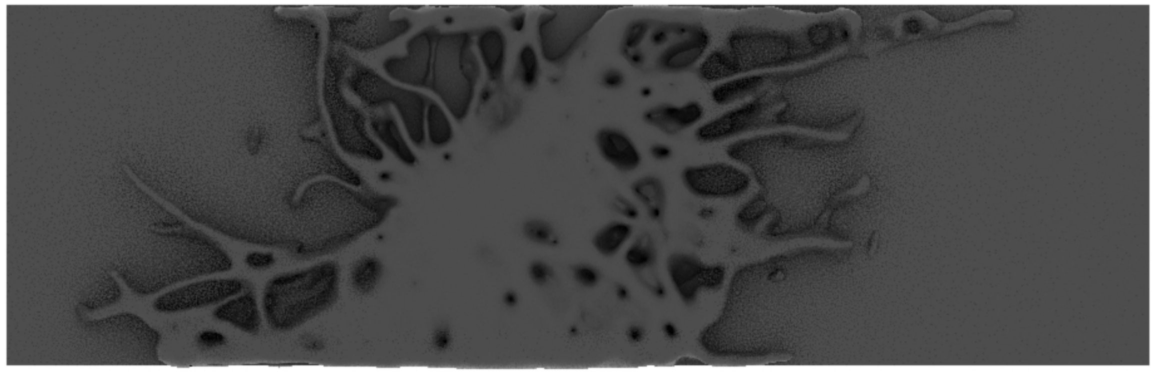

*Figure 1.19: Gen6 - Turbulence inside container to create filigree*

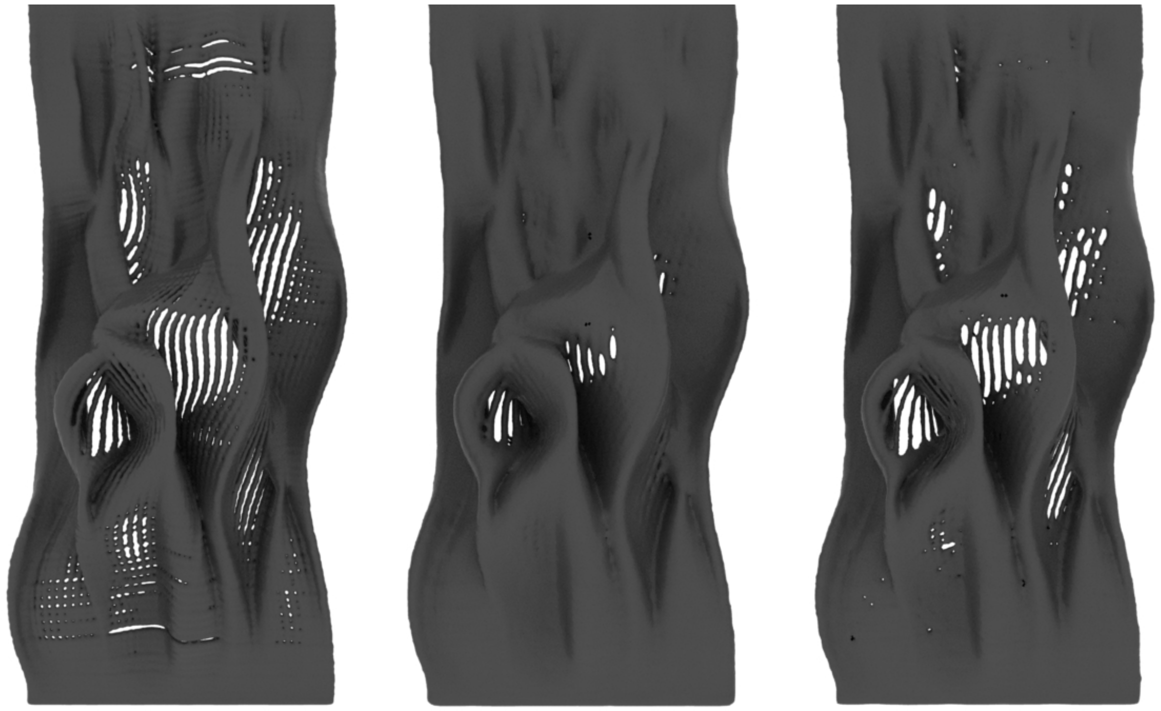

*Figure 1.20: Gen7 - Turbulence in nHair system to create filigree*

Snooks (2012) describes volatility as being 'predicated on resisting equilibrium'. By negotiating positive and negative feedback, this resistance allows for unique forms of order to emerge (Snooks, 2012, p.57). This method of design is discussed by Neal Leach (2002) as "An approach that focuses on process rather than representation, on formation rather than form" (p.5). While parametric design engenders controllable, malleable and predictable form, generative (emergent) strategies produce that which is not limited by convention, and is difficult to conceive of outside the realms of the natural world. The resulting geometries are novel, complex, and difficult to reproduce with conventional methods let alone conventional materials.

It is this complexity that 3D printing as a manufacturing method is well suited for, fabricating geometries that would otherwise be impossible with traditional mold-making techniques. Thermoset polymers allow for these geometries to be built with removable scaffolding, and simulating this printing process with slicing software shows the amount of support required to produce forms of this nature. This would be even more cumbersome with a clay extrusion setup, slumping material and inconsistent curing restricting what can be produced from a digitally generated file.

To mitigate this problem, an organic encasement that is fed through an auger-extruder setup (which at this stage is the intended delivery system) would need to be progressively layered with no overhangs to create no slumping. Although this will be explored further in the next chapter, these diagrams theorise how this encasement could be generated digitally based on the thickness of the clay structures - to slow down and speed up curing.

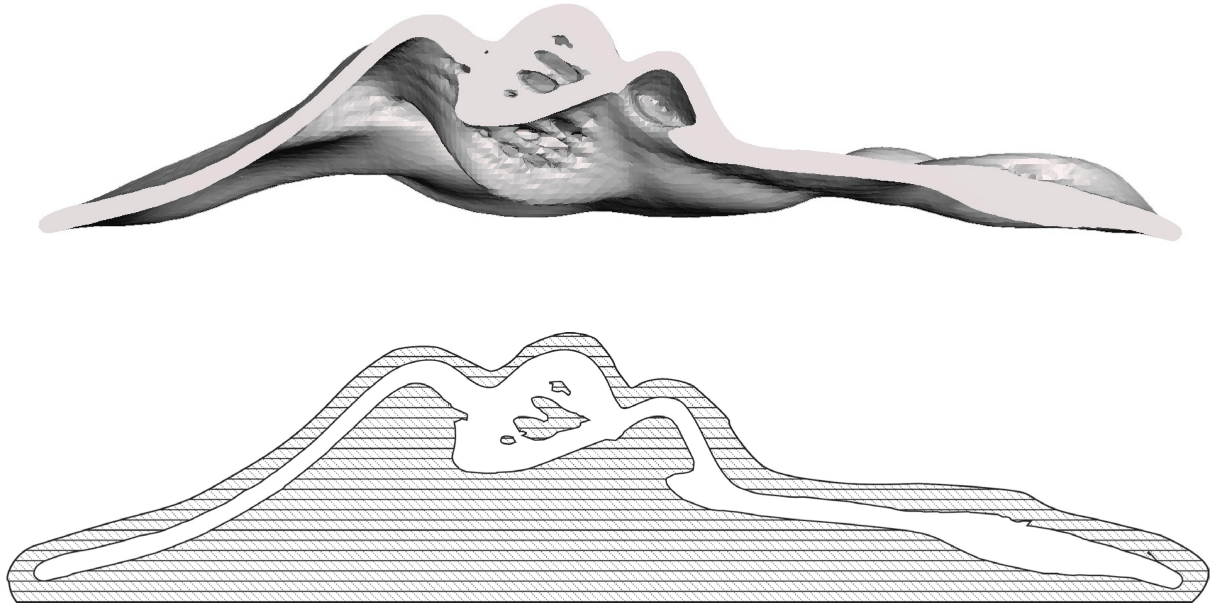

*Figure 1.21: Gen7 sectioned with encasement example*

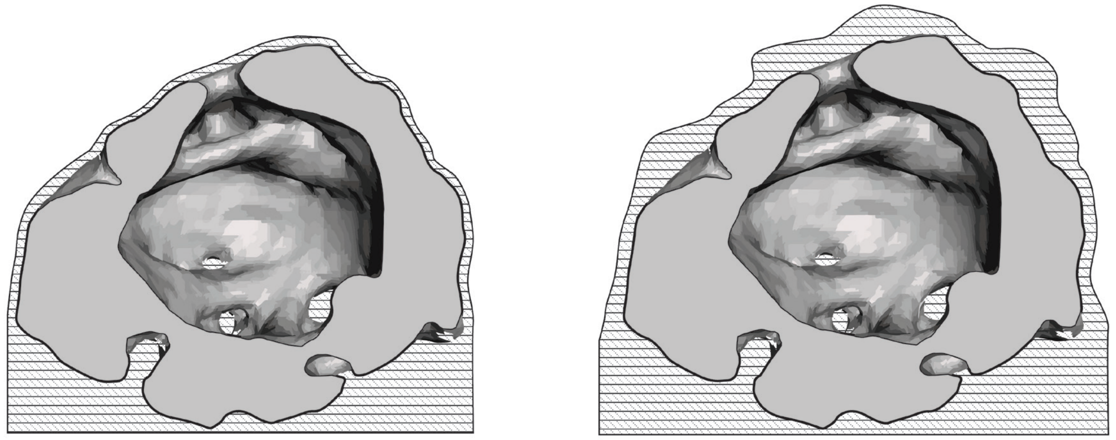

*Figure 1.22: Gen3 sectioned with encasement generation comparison based on thickness*

# 3

# PHYSICAL EXPERIMENTATION

While a 'desk study' can help understand viable candidates for collaboration and tooling, the methodology outlined for this research requires an approach that involves physical experimentation with not only the materials, but the entities that will contribute to the end result. As such, this chapter documents the application of action research to build tacit knowledge of the materials being used, in addition to the biological entities that are being worked with. The temporal solutions (Kwinter & Davidson, 2008) as a result of this process are used to develop ideas in a way that is not restricted by a regimented scientific process, allowing for exploration into new territories of experimentation where necessary.

For the purposes of this documentation the research has been grouped into distinct sections based on the species and materials being tested. Simulations of encasement excavation are carried out to engage with the target species and material at a small scale, before moving to larger scale prototypes. Material compositions and species viability as 'tools' are evaluated against the same factors outlined in the previous desk study, and used as a reflection point for further iteration and exploration.

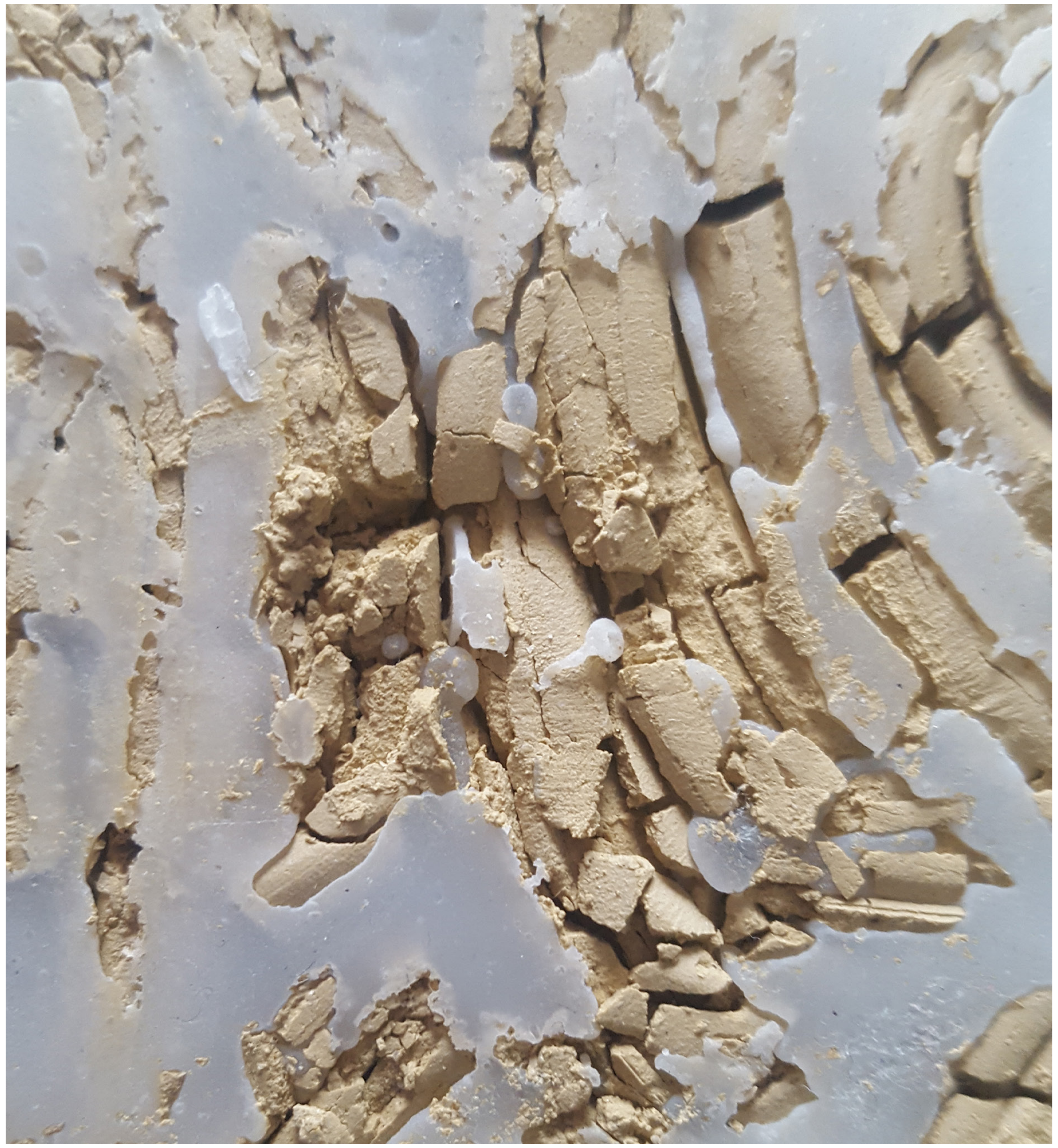

*Figure 2.01: Clay injection into wax*

Figure 2.02: Initial encasement curing tests

# Clay

As clay is the primary material being used, a base level of understanding is needed beyond what literature and precedent research can provide. Tacit knowledge of the curing process, how clay reacts to other materials, and the ability of clay to create form, all come together to form a foundation for further experimentation. These documented experiments are quite rudimentary, but follow a semi-structured scientific process, where new findings are explored and reflected on to develop new and alternative solutions.

To begin with, a series of uniform 50 gram balls of clay were encased with different materials (above Fig 2.2), in an attempt to determine how this affects curing. At this stage the balls are fully covered with the chosen materials, these being; Salt, Gelatin, Sawdust, Clay slip (dry clay broken down into dust). To analyse the results, hardness through touch and colour are used to determine how well the clay has cured.

The results of this test showcased how different material properties can inhibit or encourage the release of moisture (water) from the platelets of clay. While salt delayed curing quite significantly, gelatin and sawdust operated at a similar rate, and the clay slip encouraged curing ever so slightly faster than having no encasement at all.

Upon discovering the delay in curing as a result of salt encasement, a cylindrical clay body was formed and encased with both salt and gelatin at either end. The aim was to determine whether the difference in curing rate would be visible across a larger volume of clay. This proved true via colour and hardness (Fig 2.05), bringing forward the proposition that multiple materials could be used selectively to control curing slower or faster in key areas.

Figure 2.03: Salt encasement after 3 days

Figure 2.04: Salt encasement after 7 days

Figure 2.05: Gradient in curing example

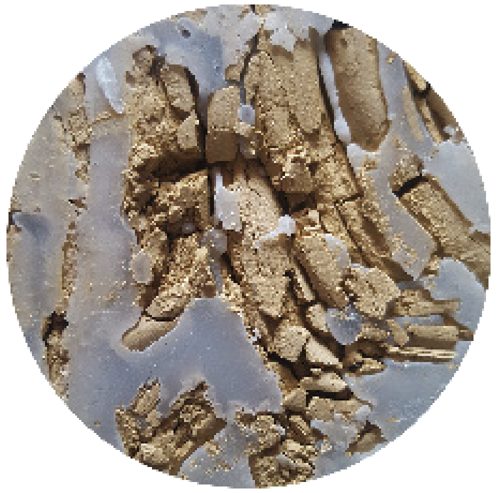

*Figure 2.06: Low pressure into wax*

*Figure 2.07: High pressure into wax*

Tests were also conducted to see how the injection of clay would react to an already existing volume or pool of encasement material, in this case wax and salt.

At a low velocity extrusion the clay splintered and cracked immediately after coming into contact with molten wax, the high temperature encouraging moisture to evaporate quickly. This also presented issues where the clay would not adhere to itself because it is immediately coated in another material (wax), which restricts the ability to progressively build a form layer by layer.

At a high velocity of extrusion the clay effectively exploded and spread across the surface of the vessel holding the molten wax, as well as creating sporadic extrusions throughout the rest of the area. In both of these cases the wax was left to set before being removed and left to cure for 2 hours before reassessing. After this time had passed the wax that had access to open air, due to being on the bottom surface during extrusion, cracked and splintered as it shrunk because of the difference in contact area.

Injections into a volume of salt provided an insight into how the printing process would function if an extruder head was embedded inside the encasement material. The pressure of the clay being extruded displaced the salt depending on the weight of the encasement, and in this case allowed for the clay to find its own form by moving the salt during extrusion. There were parts of the forms that protruded out from the encasement, with the majority remaining submerged underneath. After a period of two days inside this encasement, the areas that had surface contact with open air cured somewhat, but that which was submerged showed little to know signs of drying. These findings are similar to those of the injections into salt, showcasing the there is potentially a correlation between open surface area and rate of curing in encased clay bodies.

*Figure 2.08: Injecting/extruding into salt*

Figure 2.09: Varied encasement heights

Up until this point, all other experiments revolved around testing a hand-rolled or dipped layer of material with no thickness beyond a few millimeters. Moving forward it is important to determine how much of an effect this access to open air has on the curing of a clay body encased in a secondary material. To help understand this, a series of clay bodies identical in weight and shape were placed inside generic plastic cups, and filled with either iodised table salt, rock salt, or polystyrene balls. At the same time, a number of these cups were perforated to varying degrees to help increase air flow, as well as changing the height of the encasement relative to the height of the clay body.

The findings show that no matter what the encasement material used was, between fine and larger grains of salt there was no visible or tactile difference in curing time. The main finding from this series was the correlation between encasement height and curing time (Fig 2.10). Maximum height of encasement being at a lower level of the identical objects encouraged faster curing, due to the clay body having more surface access to open air. Those that were fully encased showed little to no evidence of curing after a lengthy period of seven days, still remaining in a plastic state. Additionally, there was no visible difference found in curing time based on the degree of perforations in the cup holding the encasement material in both of the iodised/rock salt samples as well as the polystyrene ball samples.

In summary, access to open air is paramount for the clay body to be able to cure, as this is where moisture can detach itself from the surface. Once the thickness of the encasement reaches a certain threshold - the clay body will not effectively cure and remain in its plastic state. This presents new problems when considering the intent to 3D print both the clay and the encasement material. The encasement can only work as a scaffold if it is self supporting in large quantities - something that inhibits the ability of the clay body to cure because of the full coverage required to support a high-filigree form.

Figure 2.10: Varying height of encasement results

Figure 2.11: Bubbling effect on exposed area

Figure 2.12: Moisture attempting to escape

*Figure 2.13: Handmade body submerged and baked*

*Figure 2.14: 3D print coated in slip and baked*

To mitigate this issue, environmental conditions are considered as added variables that can contribute to the efficacy of curing a clay body with this large amount of encasement. As the single most manipulatable variable, applying heat to the clay body while it is still inside its encasement forces the water between the platelets of clay to evaporate at a much faster rate.

For the first experiment a clay body was shaped by hand and submerged in salt before being 'baked' at 100 degrees Celsius for 4 hours. Salt is used because of its ability to draw out moisture and for not producing secondary emissions such as smoke or gas at higher temperatures. After this time had elapsed the clay body and its housing were left to cool before investigating further. The initial exploration revealed similar characteristics to earlier tests, with the clay body shrinking inside the salt and leaving a 'shell-like' structure around it. This gap between the encasement and the clay allowed the encasement to be progressively removed quickly, notably due to the shape of the clay body. The clay showed no signs of cracking, but had pieces detach from one another where there was a small contact area, due to shrinkage. The curing process was complete with the clay being bone-dry, though it does remain difficult to remove the encasement (salt) from the interior as it has solidified.

The next experiment involved using the same setup and parameters (time and heat), but instead with an extrusion of clay inside the salt encasement, built up in layers in a way that could simulate a 3D printing process. As clay was extruded, salt was added to create the support scaffold and allow for the clay to bridge areas that would otherwise not be possible. Various cavities and overhangs were created as a result of this process, albeit quite haphazardly. After baking for 4 hours at 100 degrees celsius and being left to cool, excavation proved somewhat difficult. The variable form created similar pockets of salt that could not be removed easily, but once selectively taken away the clay body revealed the fissures and cracking as a result of the curing process. This particular experiment shows that creating variable clay forms through a dual printing process can be done, although the curing of this clay body proves difficult, and necessitates the need for a more selective method of curing and excavation of the encasement material.

*Figure 2.15: Cracking in 'printed' clay body as a result of encasement*

Figure 2.16: Coconut-Feeder, 2020

# Birds

New Zealand (Aotearoa) is inextricably identified by its variety of native bird species, and this presents an opportunity to create a place-based solution to the propositions presented by this research. By targetting certain food groups that appeal to these birds, such as berries, some insects and leaves - it would be possible to attract and encourage species such as Tui and Kereru to eat, and in doing so, excavate an encased object. These species are rather rare to come by in number, and by nature birds only eat as much as necessary to maintain a 'goldilocks zone' of weight - as any more can effect their ability to fly.

With this in mind it is important to acknowledge that this excavation could be slow and periodic given the availability of these collaborators in a given location. Unlike insects/larvae where a population can be cultivated, the excavation of this object is dependent on the local environment.

This became evident during initial tests, with some simple clay bodies encased in a standard suet mix taking just under a week to be eaten by sparrows and blackbirds. From here it was difficult to determine how the curing actually happened - from exposure to air and sunlight after excavation, or due to sunlight heating the entire object beforehand. Based on tests in the previous section, it's understandable to make the assumption that it was due to light and heat from the sun.

Figure 2.17: Bird suet mixing

Figure 2.18: Clay ball preparation

Figure 2.19: Bird suet encased clay - cured

Figure 2.20: Pigeon excavation - live test

This constraint can be overcome by targeting larger populations of introduced bird species. Pigeons that inhabit large city centres are eager to consume anything that is deemed viable, as well as attracting others to do the same by sheer competition and mob mentality. For this reason, experiments were conducted to determine the viability of using Rock pigeons as tools for excavation of an encasement material surrounding clay. A clay body in the form of a double curved plane was packed inside a warm suet mix and then left to cool/set overnight before deploying. While observing the excavation happening in real time, it became apparent immediately that the rapid rate of excavation has presented two key problems. The first being that the clay had no chance of curing due to being in a solid encasement with no opportunity to release moisture. Additionally, because of the clay still being in a plastic state, the act of pigeons pecking away at the food source impacted the final result significantly.

This could be seen as a 'mark of the maker' in a way, the tool (in this case the pigeons) leaves behind a signature that showcases how the product was created, and even by whom. This observation is an example of how a partnership or co-authoring arrangement can yield results that are a bi-product of that collaboration. These results can potentially be accounted for by creating additional sacrificial thickness in the clay body, and maybe even encouraged in key areas by positioning the clay body in a specific orientation within the encasement material. Because the pigeons need a footing to be able to peck at the encasement, areas of the object that have a larger flat surface area will be excavated first, while the taller vertical elements may be left behind for a much longer period of time.

Figure 2.21: Graphic representation of pigeon excavation over time

Figure 2.22: Clay body after excavation showing results of pecking

Figure 2.23: Clay body cured

# Mealworms

Mealworms are the larval form of the darkling beetle. This stage of life lasts approximately 10 weeks before the transition into pupa and undergoing metamorphosis into an egg-laying beetle. During this larval stage mealworms predominantly feed on a diet of grains such as wheat bran, rolled oats, cornmeal or other grain mixtures. Mealworms were chosen as collaborators due to being easily accessed (purchasable online) and maintained in a controlled environment. The purpose of these experiments is to gain an understanding of the 'tool' through a trial and error approach to encasement materials. By trialling a series of different encasement options, the viability of mealworms as a tool for excavation is assessed by observing how a controlled number (25) react to new food sources.

Upon discovering that mealworms have shown an ability to process polystyrene as a food source when given no other alternative (Yang et al., 2015), the first number of experiments used polystyrene to not only gauge how long this process may take with a controlled number of mealworms, but also help understand the movements and behaviour of the 'tool'. Immediately the mealworms were observed eating, tunnelling, and navigating the volume of polystyrene. Notably, the mealworms elected to hide underneath the polystyrene or move as far as they could to the perimeter of the container serving as their confines. This suggests a drive for the mealworms to both explore to the extent of their environment, while also showing a desire to hide away from sunlight (Balfour & Carmichael, 1927).

*Figure 2.24: Mealworms eating expanded polystyrene*

*Figure 2.24: Baked bird suet mix + mealworms*

Although this observation proves valuable for the purposes of this research, polystyrene (or styrofoam as it's commonly referred to) needs to be expanded and compressed with hot air or steam to create the porous and light structure that it is commonly associated with. Because of this, the volume that the material takes up is large in comparison to the weight and density of the plastic, with the composition of the end result being at least 95% air. This process does not fit the constraints for 3D printing, as the required compression and additional water/steam would be difficult to combine with an additive deposition method.

*Figure 2.25: Solidified (unbaked) bird suet mix + mealworms*

The next stage of experiments involved discovering alternative food sources for mealworms that also have the capability to be extruded as part of an additive manufacturing process. Multiple combinations of materials were attempted, with the viability of each assessed based on daily observations of the mealworms behaviour, notably how and if they were attempting to eat and create a habitat out of the material. Polyurethane foam was tested as an alternative to expanded polystyrene. Unfortunately, in just over a week the larvae had either died or transitioned to pupae and started undergoing metamorphosis, with some even resorting to cannibalism.

Birdseed is a common favourite for mealworms, though a binding agent is needed to adhere the variety of grains together to create an extrudable paste. Different mixes of a birdseed suet were trialled with the same controlled number of mealworms (25). The ingredients included different ratios of flour to water to begin with, in an attempt to create a loose binding agent that still held the material together for extruding and subsequent drying. This continued with additional additives that are commonly found in a birdseed mix such as peanut butter, cornmeal, lard, and oats.

Observations showed that mealworms fed on the more solid mixes discussed hastened their transition into pupa much faster than those fed on loose grains, suggesting a stress response to a lack of food source. These experiments show that mealworms treat their food source as their habitat by burrowing in and underneath loose material, particularly for reducing exposure to light. As such, the excavation material would have to be porous and light enough to be easily broken apart and maneuvered through - something that does not correlate with the material composition required to support clay as a free-standing, scaffolding material.

*Figure 2.26: Flour+water+Birdseed mix*

*Figure 2.27: Flour+water+Birdseed mix*

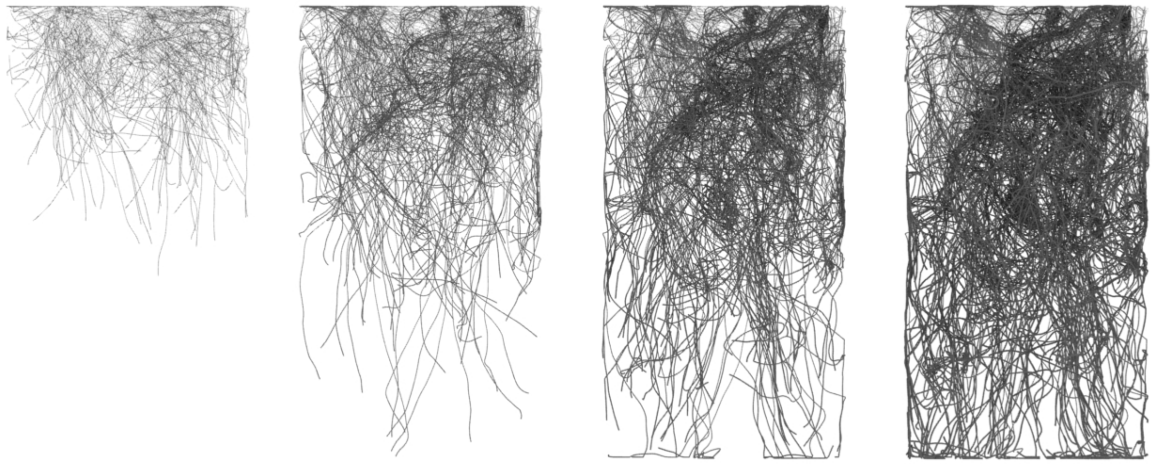

Figure 2.28: Mealworm tool pathing simulation - no light source

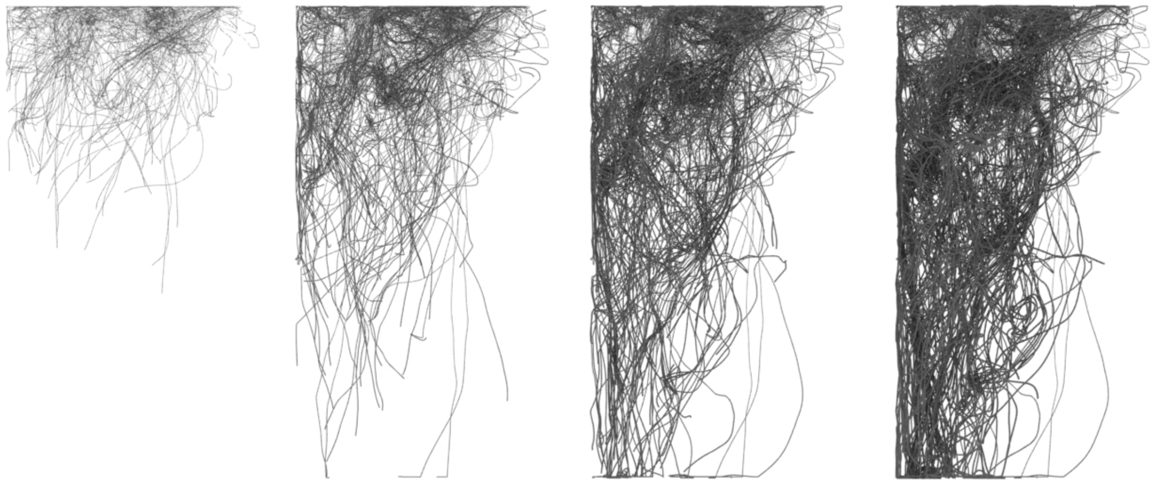

Figure 2.29: Mealworm tool pathing simulation - right-hand light source

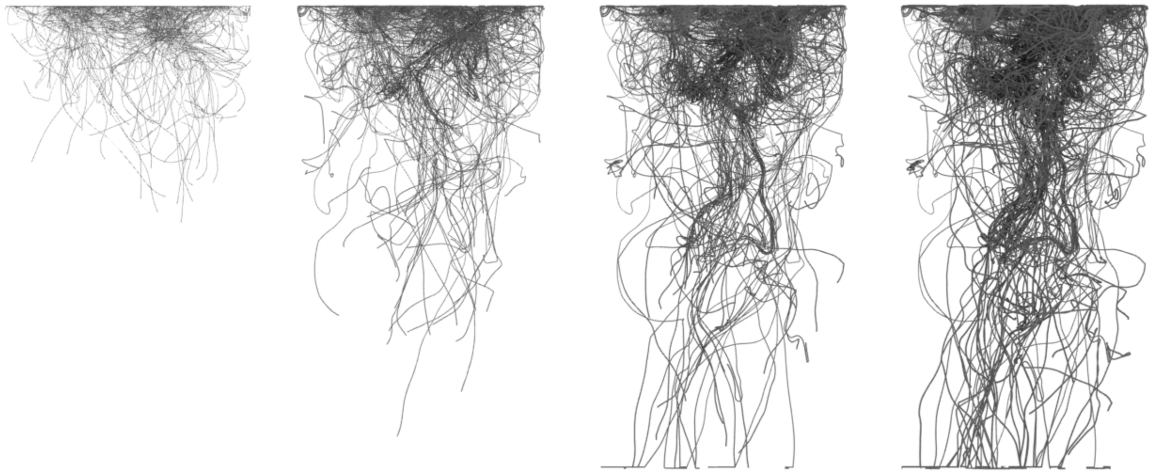

Figure 2.30: Mealworm tool pathing simulation - right/left light sources

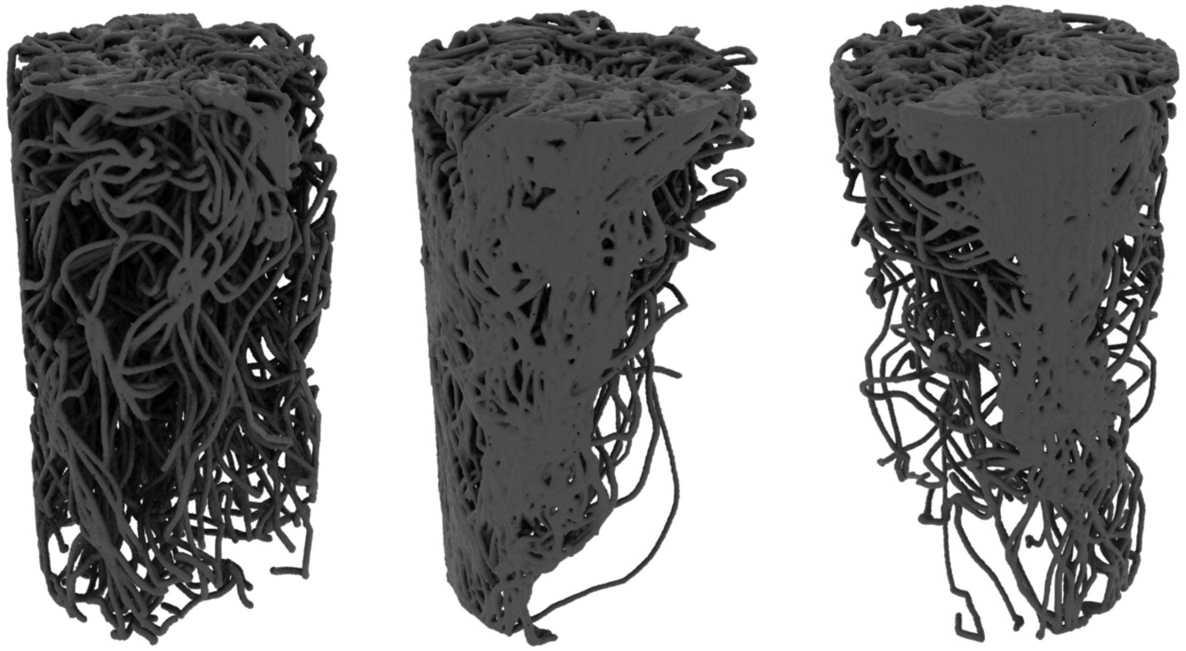

Figure 2.31: Mealworm tool pathing under light conditions

Digital simulations of the mealworms movements have been created (Fig #) to communicate the behaviour of larvae under different conditions. These simulations have been carried out inside a cylindrical container, with the changing variables in the form of forces (fields) that serve as substitutes for light and heat. The agents (particles) are driven by these forces based on real-time observation of the effects of light on mealworms during the previous experiments, with loose encasements like oat bran providing a valuable insight into how the larvae can be orchestrated and guided in certain directions.

Moving forward, this information could be used to develop workflows around excavation and pre-determined tooling. Potentially this could also be used to develop a lighting system that is customised per object, encouraging systematic excavation via a toggling of the external stimuli.

# Maggots

Maggot is the non-technical term given to the larval stage of flies in the Diptera family (Merriam-Webster.com, 2020), who are notorious for very fast gestation periods and speed of infestation in decaying matter. Eggs are laid quickly as soon as a viable food source is found, and the speed of which they can consume biomatter is astounding, with the ability to process two times their body weight every four hours. To gauge the viability of this method of excavation was relatively simple in theory, though quickly brought forward new contingencies that needed to be managed.

A small clay ball (100g) was packed inside a volume of meat and left to decay outdoors over a period of three days. Within the first 6 hours, blowflys were observed laying eggs, as well as a large chunk of the meat being eaten by another unknown species. After being left overnight the majority of the encasement had disappeared, as well as any sign of maggots, leaving only the clay ball with a small amount of meat left attached. The clay had cured to a bone-dry state, most likely because of its placement in the sun and well ventilated area.

What is noteworthy from this experiment, is the observation that all of the flies eggs were lain downwind, assumingly to stop the eggs being blown away from the primary food source. This is an important factor to consider when aiming to use this method in an open environment subject to the elements, as the starting point of excavation could be targeted towards a key area where curing needs to occur faster.

*Figure 2.32: Beef-encased clay ball*

*Figure 2.33: Fly landing to lay eggs*

Figure 2.34: Eggs after 24 hours lain downwind

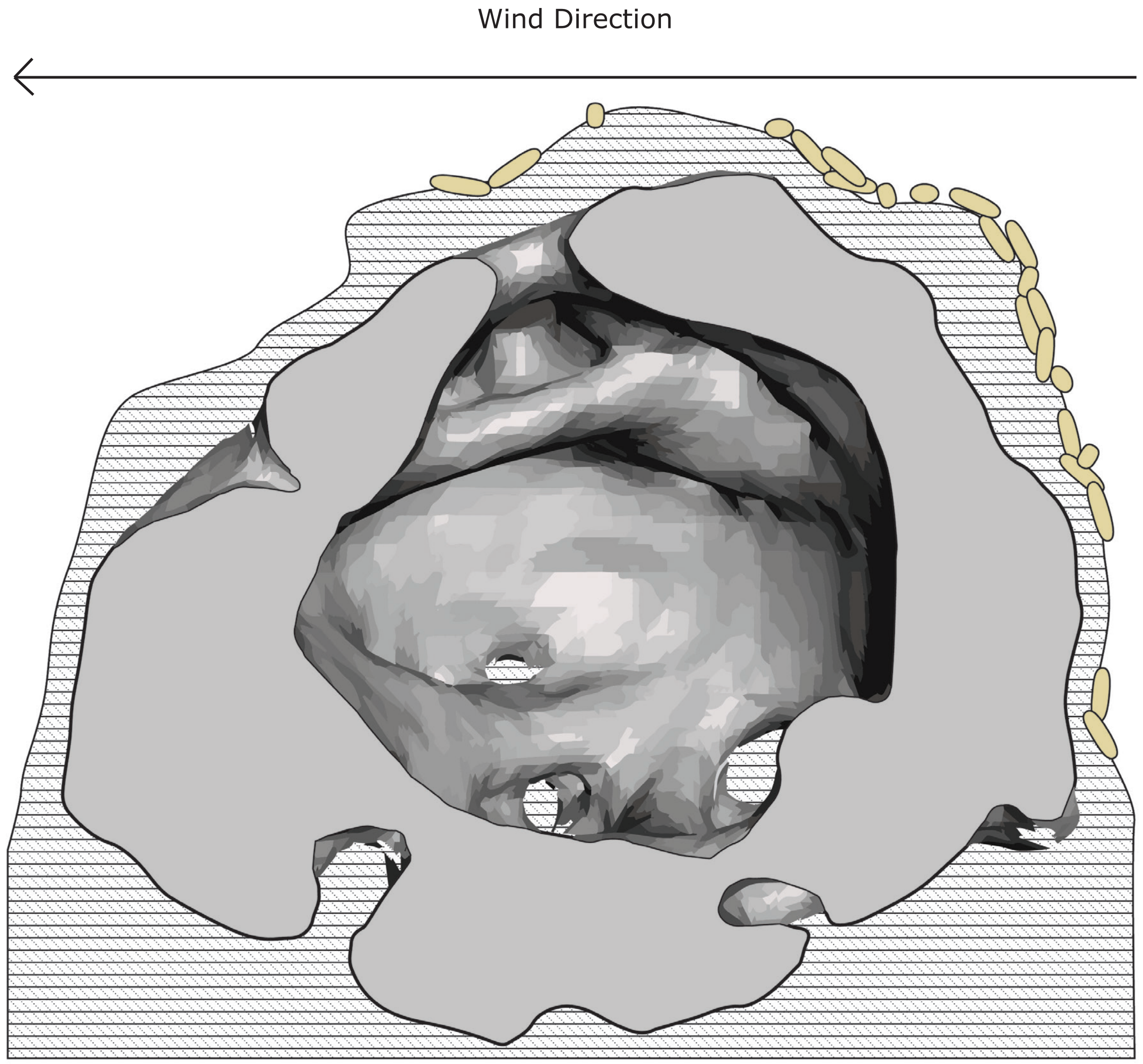

Figure 2.35: Graphic representation of egg-laying

# Conclusion/Findings

As core components of this research, both the material and biological factors have been explored to gain an understanding of how the original proposition can move forward into scenario development. This understanding comes as a result of numerous experiments that can now be used to outline a criteria for the efficacy of this proposition.

The main variables that are difficult to overcome without a controlled environment include:

**Pest control**
By using an organic encasement as a scaffold, the material used can be targeted towards a certain species for attraction, unfortunately this has the potential to attract other unintended species as a consequence. In doing so, this can encourage pests such as rodents or other predatory species to eat the same encasement, spreading disease or endangering other native wildlife.

**Rainfall**
With the intent of using outdoor wildlife as partners and tools, this requires the lengthy process of excavation to be carried out in a natural setting. Using birds as an example, this research finds that when dealing with a small population density of wildlife (that doesn't include feral pigeons), the time it takes for these species to consume the encasement material stretches days and into weeks, depending on the size of the object. During this time rainfall can have an immediate and lasting effect on the product, as the clay has been given an opportunity to soak up moisture and eventually slump and fall apart.

**Time**
Folowing this, the sheer amount of time it takes to yield a product suitable for the building industry does raise questions about economic viability. With the excavation of a clay body spanning weeks and potentially even months in larger objects, this process could be more catered to one-off designs that are not intended to be recreated, and with alternative value as a result of this collaboration with natural systems. Although this economic consideration sits outside the focus of this particular research, it is still an important factor to consider.

**Mold/Bacteria**
When using a 'loose' organic encasement material like oats, bran, or other grains that allow larvae the freedom to move and even be guided (in the case of mealworms), the slow release of moisture from the clay will inevitably result in the growth of mold or other bacteria. Although this doesn't necessarily pose many problems to the larvae, as they could be prone to inhabiting damp/soggy environments, it does create a potential breeding ground for other fungus or bacteria that could be harmful to other species or the immediate environment.

**Conclusion**
With these constraints in mind, the original proposition - to use an organic encasement coupled with biological collaboration to control curing of a clay 3D print - becomes difficult to navigate while still ticking all of the criteria outlined earlier in this exegesis. The necessity of a scaffold has become its own hindrance in allowing the clay to breath and thus release moisture, prompting alternative approaches for both biological collaboration, and selective material deposition.

# 4

# DESIGN SYNTHESIS

In an effort to maintain a critical output and/or outputs as a result of this research, a turning point is needed that focuses on two key aspects of the inquiry:

Can high filigree clay forms be fabricated using a novel approach to encasement and/or scaffold support structures?

Can an effective collaboration between human, machine, and nature play a part in the design and creation of the built environment?

To answer the first question, further experiments are conducted to discover the potential for high filigree clay structures to be fabricated using alternative methods for encasement and curing. In doing so, these experiments should set a framework for how to design for and with a material that does not 'naturally' want to be used for high filigree structures.

To answer the second question, a number of design outputs are theorised and produced digitally, to communicate how sharing authorship with machines and nature would manifest under set conditions. These scenarios will manipulate these variable conditions based on the insights gathered in previous physical experimentation, engineering digital environments that facilitate a range of results. In doing so these visualisations will also showcase the parameters for the proposed biological collaboration at a human scale by producing quantifiable results.

## Part I - High filigree clay

*Figure 3.01: High filigree clay slip*

*Figure 3.02: High pressure extrusion into plaster*

*Figure 3.03: High pressure extrusion into sand*

These experiments were conducted to test the possibility of creating complex clay geometries, albeit uncontrollably, and examining how the curing is affected by a material that actively attracts moisture outward. Injecting into plaster at a high pressure creates clay bodies that are variable in shape, though settle into their form due to being densely compacted while still in a plastic state. The plaster creates an encasement that draws out moisture from the clay, speeding up the curing and allowing for water to travel out of the clay and solidify - unlike other alternatives thus far that simply stop the water from escaping.

After being left to cure for over a week in sunlight, the encased clay body was removed and the plaster chipped away to reveal significant cracking. This cracking has occurred, presumably and based on previous experiments, because of the variable shapes that create different thicknesses of material throughout the form. Similar experiments were carried out by exchanging the plaster of paris for sand, with comparable results. Although the sand cannot solidify and bond together with the release of moisture, it did result in some interesting geometries. These two examples, as seen in figure #, were extruded in a matter of seconds and left to cure for the same week as the plaster experiments. The clay bodies themselves were easier to remove and excavate, but still had areas where cracking and breakages occurred.

Although these experiments are simulations of the printing process and what could happen, it is safe to deduce that 3D printing via pultrusion inside a volume of powder/particles could not yield controllable results. In contrast to the likes of D-Shape printers that build in layers, the lack of control in these results creates inconsistencies in wall thickness and surface area, which encourages the differentiation in curing rates that leads to cracking.

# Part II - Design Application

The following design scenarios showcase the potential for a collaborative design process between human, machine and biological authors. By creating digital environments that drive the design of a range of furniture applications these design experiments are born from a ‘conversation’ (Caranza & Coates, 2000) with the agents that drive the form. Additionally, these design experiments go through a selection process by the human partner of this collaboration (the author), and are then used to construct digital simulations of the 3D printing process. This includes encasement generation and slicing.

These simulations act on the assumption that further material research has yielded a viable method for controlling the curing of a clay structure without imposing the same restrictions discussed earlier at the conclusion of physical experimentation. Within this digital environment, time, accessibility, and other real-world constraints do not apply, and allow for an exploration of possibilities that could potentially become feasible. For the purposes of this research, the slicing process has also been used to quantify the time it would take to produce an object, based on the previous inquiry into various species for co-collaboration and tooling.

*Figure 3.04: Agent-driven stools Gen1*

*Figure 3.05: Agent-driven stools Gen2*

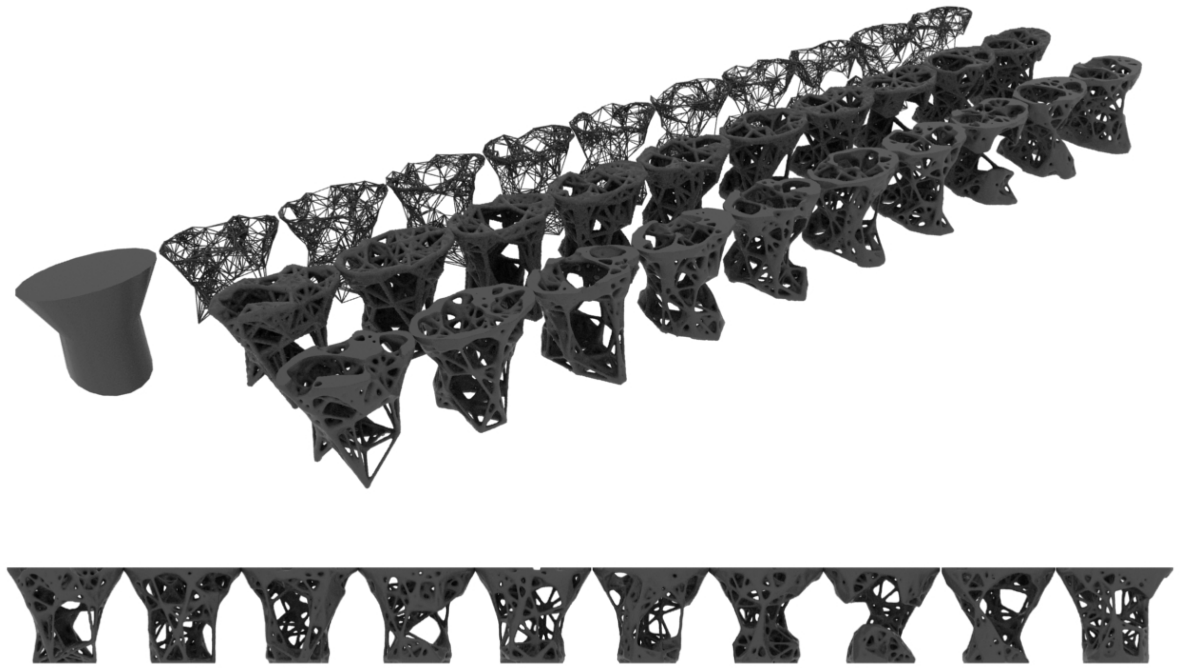

Figure 3.06: Agent-driven stools Gen3

The design workflow is a methodical process, firstly particles (the agents) are emitted with a high velocity into a turbulent environment. This environment also has pre-defined geometry that creates parameters for the digital agents to work within and navigate. As the agents navigate this space, additional paths are created that connect one particle to the next, progressively building a structure that can be used as a base for polygonal meshing. After emitting particles from this structure, converting these particles to polygons, and averaging the vertices of the resulting mesh, the end result is created.

These high filigree results are examples of an organic geometry that would be difficult to reproduce using conventional clay 3D printing. As such, the resulting mesh is used to create a negative cavity inside another mesh that will serve as the encasement, via a boolean function. To simulate the printing process, these two meshes can be imported into Simplify3D and concurrently sliced to visualise how this printing process will occur. In these visualisations the organic encasement (blue) and clay object (green) are printed using two different printing heads, concurrently controlled and alternated via G-code.

A cylinder has been used as the starting shape for the encasement model, with the assumption that this secondary material will likely be organic and subject to the same potential for slumping and subsequent breakage. To mitigate this, a cylinder is used to maintain an equal distribution of weight throughout the printing process.

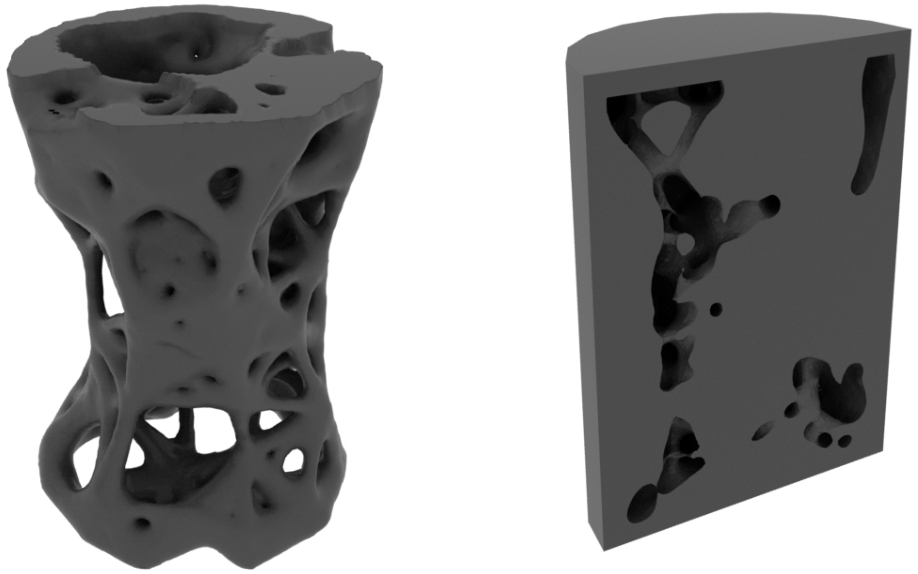

Figure 3.07: Gen2 stool selection with encasement section

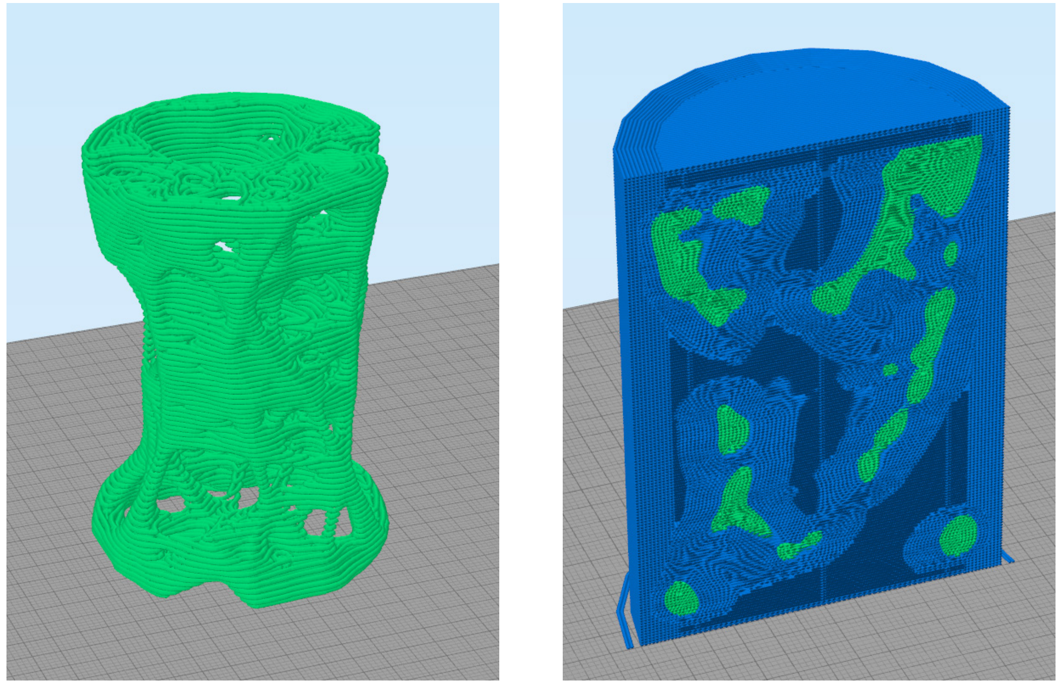

Figure 3.08: Stool selection sliced with cross section of encasement

With an object this size the stool has been estimated at using roughly 5kg of clay and 20kg of encasement material. The large amount of encasement material is due to the increased amount of perimeter shells (10) that are used to ensure a consistent support of the clay object. Referring to the previous research into potential co-collaborators, maggots are still the prime candidate given their ability to consume a large amount of material quickly. With the example shown above, an estimated 20kg of organic encasement material would take roughly 2.5 days to excavate with 1kg of larvae, scalable depending on how many pre-prepared larvae are introduced.

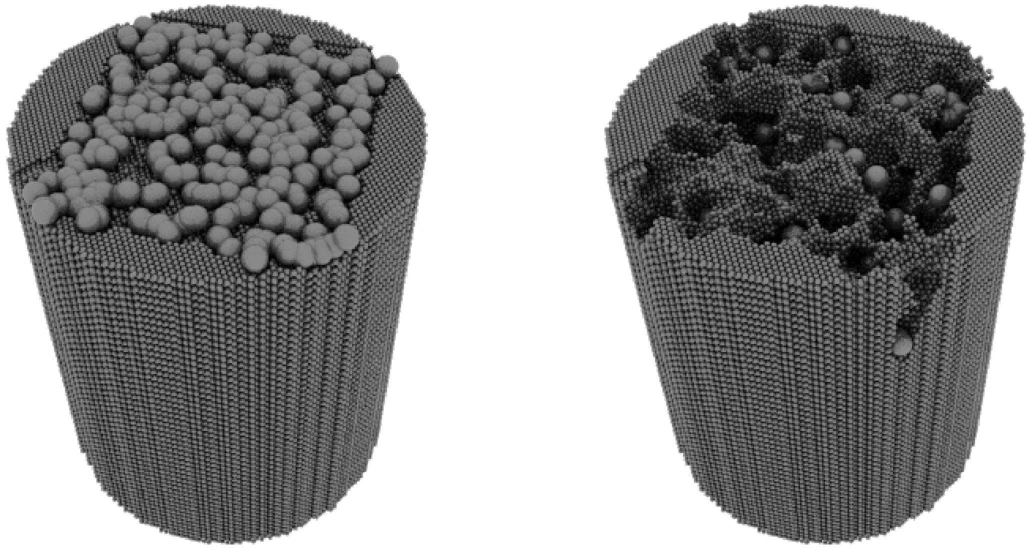

*Figure 3.09: Excavation simulation with digital agents*

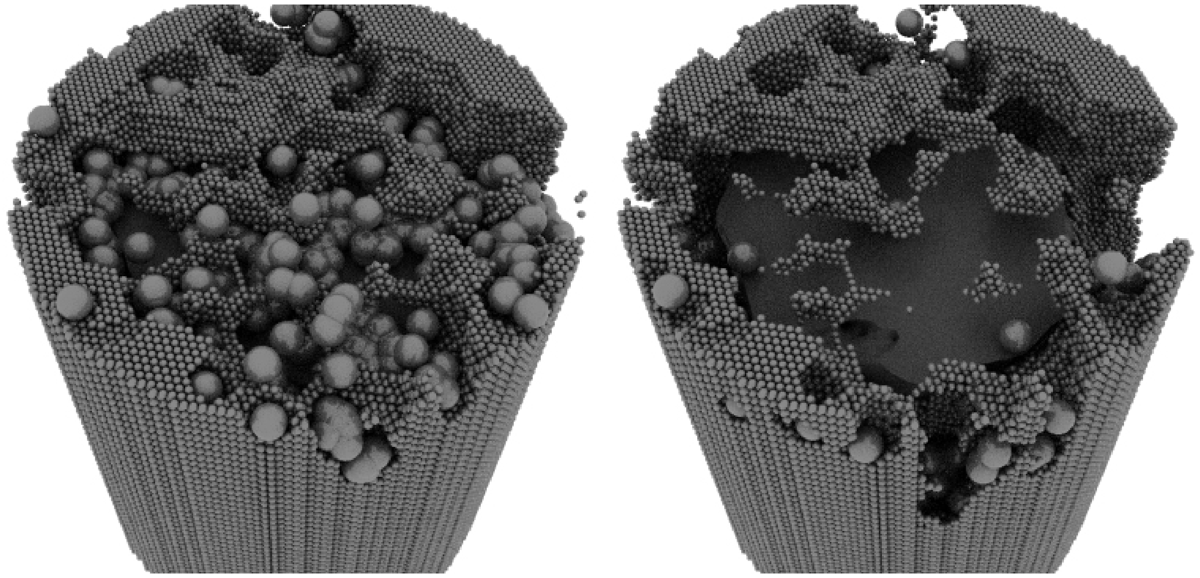

*Figure 3.10: Excavation simulation with digital agents - Gen2 form*

Small-scale simulations of this excavation were then conducted to visualise the potential 'tooling' of the biological co-collaborator, particle systems are used in place of the encasement material and selectively removed with collision events. Although these simulations are rudimentary, they showcase the potential to determine how fast this excavation will occur, and even how to control it. With additional forces placed in the digital environment in place of real-world variables, sunlight, wind, and breeding behaviour can be predicted and accounted for, creating a workflow that both emulates and works with nature's tendencies.

# CONCLUSION

This research has investigated a new approach to the 3D printing of clay, in an attempt to solve the issues surrounding creating high filigree structures using an age-old material, notably the encasement and subsequent controlled curing/shrinking of complex clay geometry. After examining existing collaborations with nature, machine and material, a framework and criteria were developed that focuses on co-authorship and co-collaboration between these parties. In a way, this treats each party as a contributor and client that has needs to be met, personifying them in an attempt to create agreeable parameters for solutions going forward. This investigation has served as a valuable context for understanding the negotiations with both material and machine that occur as part of this developing process.

Physical experimentation showed that biological collaboration requires the management of various additional factors, with this exegesis serving as a small example of the infrastructure required. The controlled excavation and subsequent curing of clay requires the management of additional variables when working with a biological organism as a partner. By analysing and testing this collaboration with a range of species and food sources, this research has identified a number of factors that must be navigated through and designed for. By introducing these additional co-collaborators as tools, new environmental conditions such as rain, wind and sunlight need to be catered for as this can drastically affect the ability for the clay to cure in a controlled manner. A bird population could be employed to excavate a clay body that has been simultaneously encased in a suet mix as part of the 3D printing process, though would need a housing system and shelter from harsh winds and rainfall, while still remaining an accessible food source. Mealworms could be guided by the use of light sources inside a loose encasement that is deposited alongside the clay body as it is being printed, though would not act as a viable method for curing the clay due to the moisture being trapped in the loose encasement and creating a buildup of mold. Maggots are a very efficient tool for consuming decaying bio-matter, but also encourage danger to the local environment by encouraging pests and the spreading of disease. In summary, a collaboration with nature as a tool for the task this research proposes, needs to have a heavily controlled environment before it can mimic the efficiency and precision that comes with other manufacturing methods.

Dual extruder 3D printing systems combined with organic materials are in a relative infancy, with most applications being restricted to single extruder configurations. By adding an additional material and extrusion system, there is a potential to create dual-material solutions for materials that are otherwise difficult to use reliably and consistently with 3D printing. Although this research has identified that this may not be viable for clay and a subsequent secondary encasement, the inquiry does highlight a potential avenue for new approaches to designing both with and for materials. As opposed to thermoset polymers which can be meticulously controlled with precision, clay requires a mediation of expectations with what the material can achieve, and a degree of care to 'guide' it towards the end result. This research serves as a case study for this relationship with the material, particularly the necessity to engage with and understand the material beyond simply applying a new or innovative approach to its use.

Additionally, the developing capacity for designers to engage in a process of co-authorship across software, hardware and nature has the potential to expand new possibilities for the built environment. Whether at a large scale or small, this research aims to start a dialogue whereby creatives shift away from consulting with only their colleagues, peers, and the paying client. By working towards a more symbiotic relationship with nature and the materials that we could potentially use to build our environments, consideration can be given to how the material would 'like' to be used, much like the 'conversation' between the human and computer that has served as a secondary driver in this research.

Designing 'with' the technology and encouraging agency within software presents a unique opportunity for the generation of high filigree structures. The decisions made by agents in this digital environment help create forms that could only be designed in this way, and are examples of the complex geometry that lends itself to 3D printing. This process of using digital agents in design has the potential to create functional products through a new form of collaboration, where software and the forces acting within the digital environment are partners and co-authors of the final result.

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