FOSSILS FROM THE FUTURE

Exposing procedural efficiency in the context of 3D printing

A ninety point research portfolio submitted to Victoria University of Wellington in fulfillment of the requirements for the degree of Master of Design Innovation in Industrial Design.

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SCREEN-BASED RENDERED VISUALISATION

← Frame 50

Frame 300 →

Exported at frame 200

SELECTIVE AND
DEFINED 3D PRINT

Figure 1. Descriptive visualisation.

ABSTRACT

The future surrounding our world is unknown and difficult to foresee. There is a desire to communicate the innumerable amount of data produced from advanced scientific research about our present and predicted world into mediums that are comprehensible to the general audience.

This research explores the opportunity for data to be translated into an easily interpretable visual and physical medium. By using a procedural system, this allows for an undetermined number of outcomes to be explored efficiently, including those which are initially unknown or cannot be perceived. This is in contrast to traditional 3D modelling software, where the designer must fully control and manipulate the finer details of a model.

In this research portfolio, a Research Through Design methodology is utilised to enable practical experimentation based on a design criterion, incrementally developed alongside the progression of the

experiments. Through screen-based visualisations, the possible products of a procedural system are presented as a morphological timeline¹. The designer's implementation and influence of this procedural system guide the direction of this timeline through parameter manipulation, without having a precise vision for the output.

Through extracting models at desired points along the morphological timeline and applying a voxel-based 3D printing approach on the Stratasys J 750 to encapsulate them in resin (VeroClear), the models are introduced into the tangible dimension. This translates the screen-based model into a physical fossil to communicate information through a tangible medium. These fossils intend to elicit discussion around production of artefacts that are not yet known or cannot be perceived. Acting as a viewpoint, the procedural system may visually anticipate these products before privileging the physical. Hence the 3D printed object is provided as a new spatial understanding to communicate information.

¹ *Morphological Timeline: A frame based timeline within the software Houdini that visually simulates the possible variations in form*

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CONTENTS

Abstract.....	5	Chapter Two Methodology.....	19	Chapter Three Grounding The Research.....	31
Acknowledgements.....	7				
Table of Contents.....	8	Research Question.....	20	Literature Review	
		Research Approach.....	21	- Previous Examples of 3D Modelling Shells.....	32
Chapter One Formulation.....	11	Aims and Objectives.....	23	- Environmental Variables.....	33
		Aim 1 Methods.....	24	- Voxel-based 3D printing.....	36
Introduction.....	12	Aim 2 Methods.....	25	- Procedural Systems in Creative industries.....	39
Terminology.....	14	Software Process.....	26	- Conclusions.....	41
Research Layout.....	16			Design Precedents.....	42
Research Context.....	17				

Chapter Four Design Experiments.....	45
--------------------------------------	----

Format of experiments.....	46
----------------------------	----

Overall aim of Research Portfolio.....	47
--	----

Workflow Diagram.....	48
-----------------------	----

Preliminary research.....	50
---------------------------	----

Criteria Phase One.....	57
-------------------------	----

Criteria Phase Two.....	61
-------------------------	----

Criteria Phase Three.....	77
---------------------------	----

Chapter Five Designed Output.....	109
-----------------------------------	-----

Resolved Criteria.....	110
------------------------	-----

Expert Opinion.....	138
---------------------	-----

Chapter Six Discussion and Conclusion.....	141
--	-----

Overview.....	142
---------------	-----

Limitations.....	144
------------------	-----

Opportunities.....	145
--------------------	-----

Application.....	146
------------------	-----

Future research.....	147
----------------------	-----

Conclusion.....	149
-----------------	-----

List of Figures.....	150
----------------------	-----

References.....	151
-----------------	-----

Pteropod shell
Impacted by Ocean Acidification
Dissolution
Frame 50
Influences On Form: Ocean Current & Gravity

FORMULATION

Left;

Figure 2. 3D printed Future Fossil.

INTRODUCTION

The world is dynamic and changing, and the future is unknown. Across an innumerable amount of studies, data is produced in large quantities through advanced scientific research and desired to be communicated. However, often it is difficult to translate this information into mediums that are comprehensible to the general public, and a full understanding is typically reserved for those with specialised academic backgrounds. Ocean acidification due to climate change is one example of a significant and dynamic issue that is presently affecting our planet adversely and will inevitably continue to do so into the future with drastic impacts possible to occur within the next 80 years (Orr et al., 2005). In order to mitigate issues of this nature, it is crucial that an understanding is held by not only those with expertise in the field in order to reach a wider audience and encourage potential for change. The ability to communicate to the general public can be achieved through the narrative that a visual or physical object provides (Olson, 2015). For example, fossils encapsulated in rock avoided disintegration, preserving understandable and engaging information from a historical time through a tangible object.

This research explores the opportunity for information to be translated into an easily interpretable visual and physical medium. Through importing 3D models into a designed procedural system, a change in the object can be generated. This allows for an undetermined number of outcomes to be explored efficiently, including those which are initially unknown or cannot be perceived, however how might the context of time and environment be modelled efficiently in order to communicate a narrative through 3D printing? Through partnering screen-based visualisations displayed as renders, the possible products of this procedural system are presented as a morphological timeline¹. The designer's implementation and influence of this procedural system

guide the direction of this timeline through parameter manipulation, without having a precise vision for the result. Through scrolling along this timeline from one end to another, exploring the unknown and unthinkable, the designer selects a point of interest to extract and 3D print through a voxel-based approach. This printing approach allows the models to be encapsulated in resin (VeroClear), introducing them to the tangible dimension through high-resolution and colour vibrancy, otherwise unattainable through traditional 3D printing methods.

This research portfolio utilised a Research Through Design methodology to enable practical experimentation based on a design criterion, incrementally developed alongside the progression of the experiments. Due to the nature of procedural generation permitting an infinitely large number of possible products, this research utilises an appropriate and efficient method to control and produce a selection of these many possible forms. The proposed method involves utilisation of the software Grasshopper and Houdini. A combined usage of these software platforms allows for the generation and manipulation of a morphological timeline¹, which visually simulates how a change in external influences can generate and communicate a change in form. This is in contrast to traditional 3D modelling software where the designer must have full control and manipulation of the finer details of a model.

The intention of this research is communicated through how the possible unknown products from a procedural system can act as a viewpoint to anticipate the physical, therefore using the tangible 3D print as a tool to assist people in assimilating, comprehending,

engaging with, and communicating scientific information (Bader et al., 2018).

During a crucial stage of this research, Covid-19 significantly impacted progress and development. Specialist hardware was unavailable while specialist software was restricted to the availability of remote access or entirely unavailable. During March and April, a substantial amount of experimentation was planned to be conducted and as a result, delayed.

TERMINOLOGY

3D Printing Terminology

VeroClear	A rigid polyjet material available in white, black, vivid yellow, vivid cyan and vivid magenta
Agilus30Clr	A flexible polyjet material available in clear
Stratasys J750	Polyjet 3D printer
Voxel-based 3D printing	3D printing process in which a digital pixel represents a voxel, being assigned material and colour properties. Layers of PNG images then combine to create a 3D voxel matrix
Mono-material	An object consisting of one material
Multi-material	An object consisting of several materials
Voxel PNG image stack	A collation of PNG images in which one image is one layer of the 3D model. The amount of images depends on the height of the 3D model
STL	A typical file output for 3D model
OBJ	A typical file output for a 3D model
CAD	Computer Aided Design

Procedural Modelling Terminology

Procedural modelling	An umbrella term referring to the characteristics of 3D models automatically generated based on a set of rules or algorithms
Houdini	Procedural node modelling software primarily used for special effects
Grasshopper	Parametric node plug in for Rhinoceros 3D

Seashell terminology

Aperture	The opening of the shell
Apex	The smallest few whorls of the shell
Whorl	Each one of the complete rotations of the shell spiral
Periostracum	A thin layer of organic skin which forms the outer layer of the shell of many species
Sculpture	Ornamentation on the outer surface of the shell
Suture	The junction between whorls of most gastropods
Pteropods	A type of sea butterfly

Project Context Terminology

Ocean acidification	An increase in ocean CO ₂ and a reduction in ocean pH altering the oceans chemical balance as a result of increasing atmospheric CO ₂
Durophagous Predation	The consumption of prey with a hard shell through crushing and drilling
Dissolution	The process of dissolving or breaking apart. A process that is occurring to the delicate shells of pteropods due to an increase in ocean acidification

ABBREVIATIONS

3D	Three Dimensional
CAD	Computer Aided Design

RESEARCH LAYOUT

To narrate the iterative intent of this thesis, the content is structured so that it reflects the sequential order in which work was completed.

Chapter One Formulation

The first chapter features an introduction to the research and the research context. This chapter also establishes the research question, aims, and objectives so that the reader is aware of what this research intends to achieve.

Chapter Two Methodology

The second chapter sets a clear direction for the research, justifying the approach to using a research through design methodology. This is accompanied by descriptions of the methods employed through this methodology.

Chapter Three Grounding The Research

This chapter examines and discusses four topics:

- Previous examples of 3D modelling of shells through defined parameters
- External influences that impact marine organisms
- Research within the field of Voxel-Based 3D printing
- The use of procedural modelling within creative industries.

The research of these topics contextualises and validates the research question, to establish an area in which the research has value and potential. This chapter also examines precedents available within this research area to discuss how they have been approached through

design, how they are relevant to this research and how they can be expanded on.

Chapter Four Design Experiments

The design experiment chapter focuses on exploring the capabilities of procedural systems to develop a timeline of possible variations, producing outcomes that are representative of an abstract future state through the case study of shells. It also showcases how screen-based visualisations can act as pre-print visions before extracting and 3D printing using full-colour multi-material printing. This section is arranged in the iterative order experiments were completed with developing criterion that matches the development of the research.

Chapter Five Designed Outputs

This chapter focuses on the final designed outputs. Two morphological timelines representing an abstract future state were created and from each timeline models were extracted at the 50th and 100th frame, to show a comparison between how the models will progress through time.

Chapter Six Discussion and Conclusion

The final discussion and conclusion chapter provides reflection towards the designed output and research process, as well as whether the research met the overall research criterion. Additionally, it discusses the limitations, opportunities, applications, and future research.

RESEARCH CONTEXT

Communication between scientists and the general public has proven at times to be difficult, considering scientific material is data-heavy and challenging to convey (Olson, 2015). In an information-heavy world, communication requires an element of relatability and engagement to motivate the public to take an interest (Olson, 2015).

Olson (2015) has previously identified that an endless swarm of facts unaccompanied by visual counterparts or narrative are unable to resonate with those in the general public. Without a linear timeline or story to accompany an issue, such as environmental changes, the information is neither relatable nor engaging (Olson, 2015). Thus, providing a physical or visual object as a narrative may motivate the public towards an interest in scientific or environmental issues.

Previously, examples of scientific physical models engaging and fascinating the public were explored in the 1800s by the Blashcka

brothers (Callaghan, Doyle, & Reynaud, 2014). Their glass models were both scientific and works of art. The accurate portrayal of texture, colouration and translucency helped make them so successful as well as the emergence of the evolutionary theory (Brill & Huber, 2016).

Through design, physical objects can be created that are relatable and engaging to the audience, providing a unique form of scientific communication with a visual medium (Olson, 2018). An advanced method to produce high-quality objects that represent even the most complicated species could be accomplished through 3D printing (Armstrong, 2016). The Blashcka brothers have shown it is possible to emulate complex animals for scientific communication and there is the opportunity now, with the latest innovations in 3D printing technology to advance this complexity.

METHODOLOGY

Left;

Figure 3. Encapsulated 3D print.

RESEARCH QUESTION

How might the context of time and environment be modelled efficiently in order to communicate a narrative through 3D printing?

RESEARCH APPROACH

Introduction

To answer the research question, an understanding towards the most appropriate approach is required. Therefore, this chapter discusses the methodology suitable for this research. Additionally, the aims and objectives are outlined alongside the methods used to approach each aim described. The methodology was intentionally placed before the background research and design experiments, to establish expectations of the content produced in the following chapters.

Research Approach

Design research is an evolving concept, identified as having been broadly described as systematic and inquisitive for the goal of attaining knowledge and the presentation of findings communicated through an understandable manner. Additionally, it is defined as an explorative and iterative practice for the intention of investigating and discovering knowledge (Baskinger, 2010; Frankel & Racine, 2010; Milton, 2013).

Research Through Design is a methodology differentiated from research for or about design as it is considered legitimate through its practice of applying an action-reflection method (Frankel & Racine, 2010) or a criteria-based approach (Rodríguez Ramírez, 2017).

Furthermore, a concept that distinguishes this methodology is how it is guided by a specific question (Schneider, 2007). Through qualitative methods such as observation, diary annotations and various experimental prototyping, the design phase is given validation. These qualitative methods create an iterative design process, developing and improving after critical reflection towards each experiment with the intention to produce a designed artefact as a visual means to answer the research question (Schneider, 2007).

Therefore, as this research intends to use a practical, iterative and explorative approach to answer the research question, a research through design methodology is employed as a legitimate method of enquiry (Zimmerman et al., 2010).

This research also applied the *Research for Design* methodology to critically analyse the relevant past and present research contributions, grounding the current research and offering a solid foundation for the initial experiment criterion (Frankel & Racine, 2010).

AIMS AND OBJECTIVES

AIMS	OBJECTIVES	METHODOLOGIES	CHAPTER
1. Ground the research. Investigate opportunities for modelling within procedural systems and voxel-based 3D printing to communicate science-based information through the context of shells.	1a. Conduct background research to investigate and analyse 3D modelling informed by parametric or procedural systems, environmental influences on morphology and current voxel-based printing approaches.	1a. Literature and precedent review (Hannington and Martin, 2012).	Chapter 3
	1b. Experiment with the design approach through parametric and procedural systems and refine 3D printing approach through the voxel method.	1b. Research Through Design for practical experiments and prototyping to establish the preliminary workflow.	Chapter 4
2. Showcase the capacity of creative procedural systems to produce unknown or undetermined products, producing a 3D printed output.	2a. Create a screen-based morphological timeline through a procedural system to visualise possible products, resulting from external influences.	2a. Research Through Design using a criteria-based design approach, incrementally developed to show the progression of the research (Rodríguez Ramírez, 2017).	Chapter 5
	2b. Extract models from pivotal points along a morphological timeline and translate the object to the tangible dimension through 3D printing with a voxel-based approach.	2b. Research Through Design using a criteria-based design approach, incrementally developed to show the progression of the research (Rodríguez Ramírez, 2017).	Chapter 5
	2c. Analyse the ability of the physical 3D print to communicate scientific information and successfully portray the objects narrative.	2c. Presentation of the designed artefact through photography to an expert in biological sciences. Evaluating the final results against the overall aim.	Chapter 5 and 6

Figure 4 Aims and objectives.

AIM 1 METHODS

Figure 4 shows the aims and objectives that were created as a means to approach the research question. While aim one focuses on contextualising and grounding the research, aim two focuses on the ability to showcase how iteration and development will lead to the final designed artefact.

Aim 1

Ground the research. Investigate opportunities for modelling within procedural systems and voxel-based 3D printing to communicate science-based information through the context of shells

Aim 1 methods

Given that design has a forward-thinking perspective, a literature review was used to develop an understanding of the relevant past and present research (Hannington & Martin, 2012). New technologies

are examined including the developments in procedural modelling capabilities, 3D printing technology and computational capacity towards generating models based on nature.

An analysis of design precedents is also conducted to investigate and analyse how others have explored new 3D printing technologies, procedural modelling and how information has previously been communicated in a tangible form. The precedents analysed are:

- The Blashcka glass models
- The style machine
- Lissom
- Hydrophytes

AIM 2 METHODS

Aim 2

Showcase the capacity of creative procedural systems to produce unknown or undetermined products, producing a 3D printed output.

Aim 2 methods

Procedural software exploration

This research will explore different uses and combinations of the software *Houdini* and *Grasshopper* as a means to generate a procedural system to explore the computational capacity to create unknown or determined forms. This allows a means to establish an efficient workflow for exploration and concept visualisation.

3d printing with a Voxel method

This printing method is sympathetic to nature based models where cellular material is desired to be replicated. The full-colour properties of this printing offer high levels of colour vibrancy and resolution to generate 3D printed models.

In comparison to traditional S.T.L. printing, voxel printing creates smooth blends of material and colour, offering the ability to develop complex external and internal geometry, moving past mono-material 3D part printing (Doubrovski et al, 2015, & Bader et al, 2016, & Bader et al 2018, & Stute et al, 2018).

Documentation

Consistent documentation is a powerful research tool and is integral to the design process as a method to measure and analyse (Hanington & Martin, 2012). It allows an assembly of the knowledge and awareness gained from the iterative design process to be combined into a designed output (Milton, 2013).

2D renders, photographs and annotation was used as a method of visual documentation. The decision to photograph the objects on a white background was to allow for the light to reflect and bounce through the model, offering a more dynamic range of colour.

Observation and annotation in an online diary

Behance was used as an online diary to document and annotate observations and critical reflections conducted for each iterative experiment. Through this diary, challenges, limitations, and surprising discoveries are identified on a platform that allowed for feedback from supervisors. The use of observation and annotation through Behance allowed for a smoother transition to the research portfolio.

Physical manipulation

Screen-based renders of an object and a tangible model offer different perspectives towards an understanding of the object. Manipulation through touch and viewing an object at different angles and lighting can reveal new and interesting physical characteristics that cannot be seen through screen-based visualisations.

Criteria Based Approach

The criteria-based approach is used as a systematic guide for the iterative process (Rodríguez Ramírez, 2017), incrementally developing throughout the phases of the design experiments.

Critical Reflection

Throughout the experimentation process, experiments will be both successful and unsuccessful (Milton, 2013). The unsuccessful experiments lead to the discovery of physical limitations on the 3D printed models and the procedural system being created. It encourages reflection and ensures there is a determination of success put into practice, an analysis of the experiment to its identified criterion determines success as well as how to develop the research, incrementally making adjustments to the criteria until a resolved criteria is reached (Baskinger, 2010; Rodríguez Ramírez, 2017; Zimmerman et al., 2010).

Cleaning of support material

When 3D models are voxel printed, there is no Vero White latticed among the support material. This allows for easier removal of the

support material. As many of the experiments within this research are delicate, there is a lot of support material to remove which takes time and care. Unfortunately, fragile parts of the prints are not strong enough to withstand cleaning and can break off during the process. Support material is removed with a toothpick, toothbrush (for stronger areas of the print) and an inter-dental brush (for extra fine areas). After manual support material removal, 3D prints can be put into a DT3 chemical bath to remove any residual support. A soak in water is required to then remove any chemicals left from the bath. Support material can expand if left in water for too long and can rip the prints. This is true for both tap water and salt water, except salt water has a more immediate effect.

Preparing the models for polishing

Preparing the encapsulated models to be printed involves a process of sanding on wet and dry sandpaper with dishwashing liquid to allow a smoother glide. After sanding, the prints are then polished with Autosol metal polish.

Figure 5 Method process.

Figure 6. Prints on printer bed.

Figure 7. Cleaning process.

SOFTWARE PROCESS

Grasshopper

Grasshopper is a plugin for Rhinoceros 3D that enables parametric design through visual coding. The components of the models created within Rhino are connected and linked through parametric sliders. Geometry edited upstream will have an effect downstream offering a live preview as parameters are altered. A limitation to this software is it does not have the capability to manipulate large files. Grasshopper was used to create the shell shapes using Raup's technique of changing the W, D and T parameters.

Houdini

Houdini is a Side F.X. software that is fully procedural with a flexible node-based workflow. Each node is wired into the network, allowing the ability to alter parameters upstream to affect downstream, offering sophisticated particle and dynamic simulations which provides more creative opportunities (*Houdini SideFX*, n.d.).

Houdini is the dominant software used throughout the design process to generate and manipulate large amounts of data, offering a means of rapid rendering and output of models in an iterative process. Providing the ability to create forms that coincide with the natural synergy of the J750. Ben Jack at Victoria University of Wellington created the V.D.B. to J750 node within Houdini to allow for quick exportation of 3D models in the PNG format. This node was then further developed by Zach Chailles and Dan Scudder to improve its capability and ease of use. This node is used within every design experiment.

GrabCAD Print

GrabCAD Print is a software released by Stratasys to easily allow their users to load and prepare their models for printing on their specific printer models. The Voxel Print Utility is used to format the PNG image stack into a .gcvf file for 3D printing.

Figure 8. Grasshopper screenshot.

Figure 9. Houdini screenshot.

Figure 10. GrabCAD Print Screenshot.

GROUNDING THE RESEARCH

Left:

Fig 11. Encapsulated 3D print.

PREVIOUS EXAMPLES OF 3D MODELLING SHELLS

Figure 12. Hypothetical snail forms drawn from cross sections made by the computer method. From “Computer as aid in describing form in gastropod shells”, by D. Raup, 1962, *American Association for the Advancement of Science*, 138, p.151.

David M Raup

A study conducted by David M Raup in 1962 identified through digital modelling that a difference in morphological form can be altered through changing four geometric parameters. He achieved this through the altering of parameters on a coiled or spiral form such as a Gastropod shell (Raup, 1962, & 1966). Raup identified that computers could aid in visually constructing geometry through the four parameters. Raup’s (1966) discovery of this parameter manipulation is what constituted the emergence of digital shell morphology. The parameters are D = Distance from Axis, W = Expansion Rate, T = Translation and S = Initial Generating Curve. Although these parameters are capable of producing shapes that are geometrically simple yet diverse in form, it lacked other crucial elements that contribute to the full shell morphology such as surface ornamentation, growth rings, internal structure, and shell thickness (Raup, 1966). Raup applied these parameters to present a model that can digitally visualise the total spectrum of hypothetical forms through a computer-based technique. Figure 12 shows this range of hypothetically possible forms that Raup’s parameters computationally produced (Raup, 1966).

Relevance

Raup identified a way to model hypothetically possible shell geometry through a computer modelling technique, but he lacked the computational capacity that is now available to create advanced forms. Raup mentioned and acknowledged this in his 1966 paper. Had Raup had access to modern 3D printing technology, he may have been able to advance his work and turn his digital models into physical realisation. Currently, 3D models are no longer limited to traditional CAD methods but can be produced procedurally, offering a more organic appearance. This is relevant when dealing with objects from nature as although they may be modelled by mathematical parameters, they are still inherently organic objects and therefore exhibit a level of variability.

ENVIRONMENTAL VARIABLES

There are several variables that demonstrate different influences on molluscs, resulting in morphological changes. To understand the influence that environmental variables have towards morphology, predation, colour, and ocean acidification are discussed.

Predation

Predation is a core environmental variable that takes precedence over other environmental influences. Predation associates morphological change with other fauna, displaying an arms race between predator and prey (Schweitzer & Feldmann, 2010).

Bourdeau (2009) identified morphological defences that are a result of exposure to single and multi-predator environments. Discrimination and prioritisation towards predation risk was also exposed.

Schweitzer & Feldmann's (2010) investigation focused on the morphological traits of durophagous predators, identified that an arms race between predator and prey had occurred. Stafford et al (2015) expanded on durophagous predation gastropods through discussing the range of shell crushing techniques including: complete fragmentation, spire damage, columella damage, holes in body whorl, aperture damage and aperture peeling.

Colour

Colour has been identified as a morphological aspect used as

camouflage against an environment. Unfortunately, there is a lack of research towards the colouration patterns of shells as a result of the fact that pigmentation decays and disappears after death (Caze et al., 2015). However, U.V. light has revealed the true colours of shells, revealing beautifully fluorescent colours and patterns that demonstrate colour and sculpture can have a positive or negative relationship, either parallel or perpendicular to the growing edge (Caze et al., 2011).

Other environmental variables have been shown to have an impact on a Gastropod shell's colour. In 2013 it was discovered that pigmentation patterns are a response to a fluctuating environment with dark pigmentation being a response to an increase in predation (Ahlgren et al., 2013). Furthermore drastic environmental changes such as ocean acidification has altered shell colour, causing a brown or milky translucency in pteropods (Harvey et al., 2018).

Ocean Acidification

Ocean acidification is one of the most pervasive variables towards change in the ocean's environment (Harvey et al., 2018). For 36 years, the discussion of the impact of increased acidification in the ocean has occurred. Whitfield (1984) initiated the discussion by identifying pteropod shell material to be composed of aragonite, the most soluble calcium carbonate in acidic waters. This led to the discovery that ocean acidification is a result of an increase in atmospheric CO₂ and causes shell dissolution. Both Doney et al (2009) and Caldeira & Wicket (2003) further enforce this argument nearly two decades later. Caldeira & Wicket (2003) observed the atmospheric pressure from

This content is unavailable. Please consult the figure list for further details.

Figure 13. The rise in atmospheric carbon dioxide dissolves shelled sea animals. From National Geographic image collection, by D. Liittschwager, n.d.

1975 to 2000 through geological and historical records, estimating emissions to occur from 2000-2100 to prove that ocean acidity is increasing.

In 2005 Orr et al (2005) expanded on this discussion, investigating the biological impacts for the pteropod *Clio Pyramidata* in acidic waters by subduing it in the levels of water saturation expected to occur in 2100. This experiment concluded that the increased CO₂ conditions resulting in acidic waters caused consequences of shell dissolution even while the animal was still alive, and with no sign of the ability to adapt quickly enough to survive. To accompany this written article, David Liittschwager's 2007 photograph visually simulated the consequences of this environmental variable as seen in figure 13. Liittschwager photographed the pteropod *Limacina Helicina* through different stages of shell dissolution in water saturation levels predicted to occur in 2100. Although both Orr et al (2005) and Liittschwager (2007) are communicating the same information, the photograph induces a more immediate response and understanding due to its visual nature.

Lischka et al (2011) further expanded this discussion and included imagery within their argument. Studying the morphological effects of the pteropod *Lumina Helicina* showed results of shell transparency both milky white and brownish, scarred structures, corrosion, and perforation. The study also identified that there was possibility for shell repair under these acidic conditions. This was further argued by Peck et al (2018) through the thickening of inner shell layers to counteract the negative effects of acidified oceans.

Further research concluded that ocean acidification does not just affect pteropods (Chatzinikolaou et al., 2016; Coleman et al., 2014; Harvey et al., 2018). Coleman et al (2014) identified a lacking aspect of their ocean acidification studies, not considering how the individuals in acidic conditions are also dealing with other variables such as predation. The defence system of shell repair was examined in this study through diagrams, identifying the negative effects of ocean acidification on shell repair, an aspect that was previously not considered until this study in 2014.

Chatzinikolaou et al (2016) and Harvey et al (2018) identified visually through Micro-CT imaging with both 3D and extracted cross sections that shell dissolution results in a decrease in shell thickness and density, smoothed shell whorls, rounded apex, smooth suture lines and a disappearance of natural ornamentation pattern and a deterioration of periostracum.

Relevance/Summary

These variables demonstrate the external influence that environmental and external impacts have towards morphological change and adaption, though there is no visual way to see these changes have an effect in real time. An interesting aspect of the experimentations towards ocean acidification on marine animals is the use of Micro CT cross sections, offering a visual cross section of the object, similar to a PNG image representing a singular layer of a voxel-based 3D print. This offers insight towards viewing the object internally, revealing hidden structures and details.

VOXEL-BASED 3D PRINTING

Technology

Voxel-based printing is the latest innovation and approach to 3D printing, enabling the simultaneous use of seven different ultraviolet curable resins, offering full colour and transparency and flexibility within 3D printed objects.

Process

Voxel-based printing requires layers of PNG images in which each pixel represents a voxel. This voxel is a droplet of liquid polymer, combining to create a 3D voxel matrix (Bader et al., 2018, & Bader, Kolb, Weaver, & Oxman, 2016). Each PNG image acts as a layer, upon printing each layer, adjacent materials are mixed and gently compressed with a metal roller, afterwards, curing each layer with ultraviolet light. (Stute, Mici, Chamberlain, & Lipson, 2018). Required support material is automatically generated by the printer (Stute et al., 2018) or assigned during the creation of the voxel-based print file.

Limitations of traditional 3D printing

Traditional top-down 3D printing workflows consist of the standard file format of S.T.L. and have remained virtually unchanged for 30 years (Bader et al., 2018). S.T.L. file formats are defined as simple, representing only external geometry. Stute et al. (2018) further explains that in combination with S.T.L.'s simplicity, there is a lack of design tools and printing workflows that encourage the exploitation of heterogeneous material opportunities through voxel-printing. Bader et al. (2016), Bader et al. (2018) and Doubrovski et al. (2015) further argue that traditional 3D printing focuses on mono-materials parts, making the file generation for voxel-based design labour intensive, requiring manipulation through several different software.

Voxel-based 3D printing approaches

Currently, there are three approaches to voxel-based 3D printing; scientific, colour management algorithms and creative artistic control (Bader et al., 2018; Brunton, Arikan, Tanksale, et al., 2018; Robinson & Furneaux, 2019).

M.I.T. Mediated Matter Group

M.I.T.'s Mediated Matter Group (M.M.G) is the most recognisable work so far. Their scientific-based approach enables the physical visualisation of data sets associated with scientific imaging. The purpose behind 3D printing these data sets is to prove that digital visualisations can be converted into physical objects with heterogeneous material compositions, attempting to bridge the gap between digital information and physical representation. M.M.G argue that physical manifestations of data enable spatial depth awareness of an object through physical touch and manipulation (Bader et al., 2018). Bader et al. (2018) argue that the recent advancements in 3D printing technology are resurrecting the appreciation of physical representations of digital objects or data, a quality that augmented reality cannot produce.

Cuttlefish

Cuttlefish's colour management algorithms approach enhances the realism in their 3D prints, focusing on translucency and how materials reflect light (Brunton, Arikan, Tanksale, et al., 2018, pg. 1). Their approach intended for aesthetics, visualisation and education. Cuttlefish identified the potential of voxel printing to reveal complex internal structures, developing a pipeline and algorithm to control colour and perceived transparency, forming a library of realistic materials. Cuttlefish's pipeline and algorithm allowed material assignments computed at the voxel level, overcoming the limitations

Figure 14. Robinson, T & Furneaux, W. (2019). A selection of 3D printed prosthetic eyes at varying scales and colours. In *Voxel Printing using Procedural Art-Directable Technologies. Proceedings of the ACM Siggraph 2019 international Poster conference on computer graphics and interactive techniques*. ACM DL. Copyright 2020 by Weta Workshop.

of requiring high computational power, storing material assignments for a selection of voxels at a time (Brunton, Arikan, Tanksale, et al., 2018).

Weta Workshop

Robinson & Furneaux's (2019) creative control approach to voxel-based 3D printing was for film and display work, applying their method to prosthetic eyeballs, as seen in figure 14. The identified limitations of traditional model-making techniques were a result of materials and an extensive modelling, multi-stage casting and painting pipeline. While capable, it still had a high failure rate. Therefore, the implementation of the voxel-based 3D printing method was adopted. This method was not constrained by the limitations of traditional model making, offering more opportunity to control features of the eye artistically. Robinson & Furneaux (2019) identified that voxel printing could increase achievable complexity and quality in high-fidelity models. Robinson & Furneaux's (2019) approach to voxel-based 3D printing is distinguishable. Although not through colour management algorithms or representing scientific data but rather achieving artistic realism through procedural systems within the software Houdini.

Relevance

All three groups are aware of the high computational power that voxel-based 3D printing requires, and all three have approached this limitation in a way that uniquely suits the work that they are conducting.

M.M.G's approach to printing science-based visualisations is a unique way to communicate science. As they argued, when presented a

physical item, new perspectives and appreciations are developed through physical touch, demonstrating how scientific data can translate into tangible forms. Currently, their models remain encased, but there is an opportunity to explore the capabilities of all available materials, including Agilus for science-based visualisations as physical forms.

Cuttlefish's approach, through colour algorithms, offered a level of control towards the colour and transparency of an object, engineering the object's surface to optimise colour with internal white material to ensure the surface colour was realistically permeable to light, achieving engineered complexity.

Robinson & Furneaux's (2019) artistic approach to voxel printing is the most recent addition of work to the research within this field. Robinson & Furneaux (2019) took advantage of Houdini's software capability to compute large amounts of data, the ability to manipulate that data and the application of a downstream approach through a procedural system to continuously update the final node.

PROCEDURAL SYSTEMS IN CREATIVE INDUSTRIES

Figure 15. Robinson, T & Furneaux, W. (2019). a) The digital model is sampled by a slicing grid. b) Slice 650 of 992 images generated for a 2:1 eyeball. c) Visualisation of the voxels in a small section of the iris. In *Voxel Printing using Procedural Art-Directable Technologies. Proceedings of the ACM Siggraph 2019 international Poster conference on computer graphics and interactive techniques*. ACM DL. Copyright 2020 by Weta Workshop.

Procedural modelling is an umbrella term in which characteristics of 3D models are automatically generated based on a set of rules or algorithms. Through a downstream or upstream approach, able to be repeated and altered, producing variations of 3D models and textures from the same procedural system (Ebert, 2003, pg 1). Under this term is a secondary term, parametric modelling. Parametric modelling automatically generates a digital model based on a set of rules or algorithms, known as the model's parameters (Designing Buildings Limited, 2019).

The use of procedural modelling or systems within two separate industries are analysed, the first is within the entertainment industry, and the second is within the 3D printing industry. The projects analysed are Voxel Printing using Procedural Art-Directable Technologies by Weta Workshop, Grove and Totara by Weta Digital and Cillia by M.I.T. Tangible Media Group.

Voxel Printing using procedural art-directable technologies

Robinson & Furneaux (2019) created a procedural art-directable workflow, customised for the six available materials required for voxel-printing. Robinson & Furneaux (2019) offer digital and physical benefits from using a procedural system to create a 3D model. Digitally using Houdini's procedural node network, data can be processed and manipulated easily, altering the output downstream, ensuring it aligned within the required art direction. Within the case study of prosthetic eyeballs, the use of a procedural art-directable workflow offered the ability to modify multiple conditions that influence appearance include the iris and sclera colour, limbus transparency and vein weight. Physically, this ensured that the outputted model aligns with the specific art-direction and not require an unnecessarily long process to create alterations or variations. As seen in figure 15, the final model is previewed and then sliced within the final stages of this procedural system to prepare it for printing.

Grove

Weta Digital, New Zealand's leading digital film effects company has employed procedural modelling within their animation system, Grove. Weta Digital was able to implement parameters within Grove, such as the ability to define branch length, branch angles and leaves per branch to produce a variance within their generated models. Weta Digital applied these parameters to different species within the Grove system (Aitken & Preston, 2003).

Totara

Following on from Grove, Weta Digital created a more advanced version of their procedural tree growing software Lumberjack for the 2017 film 'War for the Planet of the Apes'. Named Totara, this procedural system was able to generate the forest and surrounding ecosystem

with physical accuracy. It was achieved through developing naturalistic growth and ageing through incorporating the surrounding environment and climate within Totara (Computer Graphics World, 2017), ensuring realistic competition for sunlight and nutrients during the tree's growth (Robertson, 2018). Totara digitally grew the trees for 100 years before freezing the growth at the ideal moment (Computer Graphics World, 2017). Totara Shows how much of an impact an external factor can have towards growth and development in a procedural system.

Cilllia

Cilllia, a 3D printed hair structure developed by the Tangible Media Group at M.I.T, was created using a procedural design method. The authors address the discussion towards the limitations that static CAD offers through a top-down pipeline and attempts to resolve this through developing a bottom-up pipeline. Allowing Cilllia to automatically generate the strands of hair defined through the parameters of height, thickness and density (Ou et al., 2016).

Relevance

Through three different approaches, different benefits of procedural modelling are discussed, whether overcoming limitations, exploring new opportunities or creating something that appears more organic.

Weta Digital's procedural system's Grove and Totara showed how an organic object such as a tree could be not just created digitally, but grown. Totara displays that external influences have a direct impact on the growth and survival rate of a digitally grown tree and can completely change the final output organically. Including external forces to create organic growth has the opportunity to change how 3D models are created, moving past traditional C.A.D methods and allowing the procedural system to have more of an influence.

Both Ou et al. 's (2016) and Robinson and Furneaux's (2019) approach to a procedural system was for physical outputs. For the Cilllia project, the intention behind the use of procedural modelling was because of the limitations of static C.A.D modelling not being able to have adjustable parameters. However, for Robinson and Furneaux (2019) it was the opportunity that a procedural system offered when working with a technology that required manipulation of the features of an object while still matching the substantial computational and detailed requirements of voxel printing. Through this workflow, a recyclable system generates an output with 3D models created in other software easily converted and implemented into this system. This system adapts to an environment that requires alterations and adjustments under time constraints and a change in art direction.

CONCLUSIONS

This preliminary literature and published projects grounds this research; it identifies that there is a unique avenue for investigation in exploring procedural generation, geometric parameters for forms to adhere to, soft material (Agilus), encapsulation and the voxel-based printing method.

Constant changes in art direction require recyclable systems to produce variance in order to update models efficiently. Robinson & Furneaux (2019) expanded on this and addressed their use towards the potential and opportunity that these systems have for creating hyperrealism and the opportunities the voxel-based printing method present in contrast to traditional means of making.

This literature also addressed the potential and opportunity in areas such as scientific communication and education. An area of research that was particularly interesting to do with our changing world was ocean acidification. Although there is a large quantity of studies present and ongoing, the visual photographs from David Littschwager that accompany Orr et al's 2005 paper are the most engaging. However, it should be noted that Orr et al's paper was rather complex and difficult to understand at first glance but Littschwager's photograph

was not. This realisation in combination with Olson's (2015) statement discussing the importance of narrative, addresses the need for a visual or physical object to accompany the communication of information. Bader et al's (2018) argument reinforced this statement. Displaying scientific visualisations through the use of a tangible form to better present the data that is on screen. Through design, physical objects can be created that are relevant and understandable to the audience to accompany important information. Physical representations of data enable a more in-depth spatial awareness of an object through physical touch and manipulation.

The findings of this literature reinforced the capabilities of procedural modelling and the efficiency that it possesses to be used as a recyclable system or to generate form influenced by external influences. It also reinforced the high-resolution capabilities and the benefits that printing information through a tangible form has, for example the above mentioned in-depth spatial understanding.

DESIGN PRECEDENTS

Figure 16. Hodges, G. (2016). *Polybranchia prasinus*. [Photograph]. Cornell Collection of Blaschka Invertebrate Models: United States. Copyright 2020 Gary Hodges.

Figure 17. Hone, N. (2018). *Haven Flower*. Retrieved from Nicole Hone, by Nicole Hone, 2018, Retrieved 2020, July 2, from www.nicolehone.com/hydrophytes. Copyright Nicole Hone 2020.

Figure 18 Stevens, R., & Guy, B. (2015). *Lissom*. [Multi-material 3D print]. Retrieved from <https://made.ac.nz/project/computer-generated-objects-lissom/>. Copyright Bernard Guy and Ross Stevens 2020.

Figure 19. Jack, B. D., & Guy, B. (2017). *The Style Machine: Digital Tactility Through Generative Collaboration*. [Screenshot] In 20th Generative Art Conference GA2017, 12. Copyright 2020 Bernard Guy.

While some of the design precedents are previously listed above, it is essential to further analyse and explore the relevance that these projects have concerning this research. The precedents discussed are Blashcka, Lissom, Hydrophytes and The Style Machine.

Blashcka

Due to the scientific communication of this research portfolio, an influential precedent for this research that is both artistic and scientific is the Blashcka Glass models. As discussed in the research context section of this research portfolio, Blashcka is significant in terms of showing the possibility of the impact of scientific communication through a physical medium and the possibilities of emulation of complex creatures through a traditional manufacturing technique. There is room to expand on this precedent through procedural modelling and voxel printing to create models that may emulate real animals or take a creative approach to an animal's form.

Lissom

Lissom was a project undergone during a summer scholarship to explore the opportunities and possibilities for multi-material printing. Victoria University has always been interested in the exploration of multi-material printing. Through Lissom, the intention was to blend the qualities of the digital and physical world while showing the interactivity and lifelikeness of the 3D print. There was no narrative behind this work as this model shows that an object does not need a narrative if it offers a spectacle and the spectacle and the physical characteristics of the model create its own story (Guy & Stevens, 2015).

Hydrophytes

For Nicole Hone's Master of Design Innovation degree Hone explored the boundaries by refining 4D aspects like movement and

expression of emotion. For her research, Hone created a collection of aquatic plants called Hydrophytes. These plants responded to their environment through choreographed movements to perform specific tasks in the environment. Hydrophyte's relevance to this research is the creation of each Hydrophyte through altering parametric values while being influenced by the environmental factor of climate change. Hone also applied a scientific aspect to her work, discussing the impacts of climate change and allowing this to influence her designs (Hone et al., 2018).

Style machine

In collaboration with Ben Jack, Bernard Guy developed the Style Machine, developing a generative system that has four components: the designer, generative artist, software, and 3D printer. Within this project, a generative system could offer a new way to think about design as well as how to approach design. Through designing automated systems, designs can arise naturally, and the designer influences the parametric characteristics of the design but does not know what the design will be upon beginning the process, removing the top-down influence of the designer (Jack & Guy, 2017). The Style Machine is one of the few examples available within the industrial design area that applied a modelling approach through sliders and a simple downstream workflow influenced by the parametric system rather than the designer.

Relevance

This research portfolio looks at showcasing the possibilities of procedural systems to create morphology that can be voxel printed for scientific communication. Exposing procedural efficiency and value in the context of 3D printing by exposing generated forms and rendered pre-print visions in an un-designed timeline.

DESIGN EXPERIMENTS

Left:

Figure 20. Encapsulated 3D model.

FORMAT OF EXPERIMENTS

The following experiments include an initial parametric process in Grasshopper and a procedural process in Houdini to render the form's morphology. The physical models are manufactured through voxel-based 3D printing. There is an overall design criterion for the aim of the whole research portfolio and separate design criteria for batches of experiments. As the research developed and new knowledge of software was gained, new opportunities and therefore, new criteria were able to be completed. Each design features an experiment number, name and is presented through a visual and written approach as outlined below:

Render of the morphological timeline

Where applicable, the timeline of the model screen-based visualisation will be presented through a render at frame 50, 100, 150, 200, 250 and 300. This visually demonstrates the available range at which to extract the 3D print from.

Selected Image from the voxel PNG image stack

To represent how much detail is in each layer of the 3D model, a chosen PNG image from the image stack will be presented alongside the model. However, this is only displayed for experiments under the initial criteria until criteria phase three as it is only during these stages that it offers more insight into the detail of the model.

Photograph of the physical model

A close-up photo of the model is included to visually present the details within the print. Where applicable, the scale of the model is presented through contextually placed hands.

Analysis

A written analysis is included for each experiment. This involves outlining the aim and a reflective paragraph summarizing the results of the experiment.

OVERALL RESEARCH PORTFOLIO CRITERIA

- Showcase the creative opportunities for full colour multi-material printing through the voxel method.
- Demonstrate through a procedural work flow that through external forces influencing a system can create forms that are not known or perceived, extracting models at a pivotal point for the context of 3D printing.
- Explore the dialogue between translating an object from a screen-based visualisation to a 3D printed tangible object through extracting models from a pivotal point along the morphological timeline and encapsulating them in resin (VeroClear), to maintain data.
- Be contextualised towards communicating a significant and dynamic issue in scientific information, using a visual and tangible object as a narrative with accompanying scientific information.

WORK FLOW DIAGRAM

STAGE ONE

GRASSHOPPER

Creating the Parametric Shell Model

Adjust constant
geometric variables
W= Whorl Expansion
T=Translation
D=Distance from axis

Add patterning
variables, eg. ribs
on outside

Add width to
object so it isn't
paper thin

Export Model as
.obj

STAGE TWO

HOUDINI

Procedural dynamic growth

Created by Ben Jack. Developed by
Dan Scudder and Zach Chailles

Import Model

Identify variables to impact the
model Ocean Acidification, Gravity,
Temperature etc

Apply dynamics to the
model eg. DOP network
and Vellum network

Turn those dynamics back into
geometry eg. polywire, convert to
polygons

Figure 21. Work flow diagram.

STAGE THREE

HOUDINI

Exporting model to J750 in encapsulated form

STAGE FOUR

3D PRINTING

EARLY RESEARCH - DEFINING THE TOPIC

The research began looking at how a slider-based system could be created so that muscles, ligaments etc could be adjusted and redefined as displayed through early shown in Figure 22, 23 and 24. Frogs were used as an example, describing how the morphology/form of a creature could be altered. It was during this stage that environmental forces were considered, initially examining the influence of adjusting the weather, observing changes that could occur during hotter and colder climatic conditions. The below experiments are not marked against the criteria as they are used to refine the research topic.

Figure 22. Parametric design plan.

Figure 23. Design plan.

Figure 24. Visual representation of external force on designed creature.

Figure 25a-c. Images of small Agilus ligament flexing.

Figure 26a-d. Images of small Agilus ligament flexing.

These experiments explored how Vero and Agilus worked together in union to explore changing a creatures morphology through their limbs. The experiments explored different lengths and widths of Agilus and Vero as well as the overall scale of the object.

Procedural Shell Variation: Shapediver

Figure 27a. Shapediver Screenshot.

Figure 27b. Shapediver Screenshot.

Figure 27c. Shapediver Screenshot.

Figure 27d. Shapediver Screenshot.

Shapediver is online software that works in union with Grasshopper scripts to present the script in the format of a clean user interface while creating variation. This is the earliest iteration behind what would become the morphological timeline.

ESTABLISHING PRELIMINARY PROCESS

These experiments are not marked against the criteria as they establish the process and workflow for the experiments for creating models in both Grasshopper and Houdini for 3D printing. Use Houdini to explore colouring options expressed through different dithering techniques.

Exploring ordered and stochastic dithering techniques

Figure 28. Yellow Ordered dithering.

Figure 29. Yellow Stochastic dithering.

Figure 30. Cyan Ordered dithering through mapping colour on a UV plane.

Creating flexible colour through ordered dithering

Figure 31. Green ordered dithering through Point Attribute Transfer.

Figure 32. Magenta ordered dithering through Point Attribute Transfer.

Figure 33. Cyan ordered dithering through Point Attribute Transfer.

Creating flexible opaque colour through ordered dithering

Figure 34. Opaque Cyan Dithering.

Testing the floyd steinberg dithering technique

Figure 35. Yellow Floyd Steinberg dithering.

Testing applying noise patterns to achieve a flexible vibrant print

Figure 36. Stochastic dithering with colour applied through noise.

Testing the application of noise patterns to achieve a flexible vibrant print

Figure 37. Stochastic dithering with colour applied through noise to achieve a snake like skin.

Reflection/Discovery

Figures 28 to 37 identified that floyd Steinberg was the best dithering technique available for mixing colour; however it was an unreliable and unstable dithering technique causing Houdini to crash on multiple occasions. Therefore stochastic dithering was the chosen dithering technique for following experiments. Through ordered dithering it was revealed that flexible colour could be achieved by increasing the amount of Agilus material composition every second layer. Although this works for flat rectangular models, it is much harder to achieve in other forms and the thicker a form is, the more unsuccessful it will be at being flexible.

It also revealed that applying noise patterns and the combination of Vivid Vero materials can make quite vibrant prints as seen in Figure 37 but can also be unsuccessful if too many materials are mixed together as seen in Figure 36.

While establishing this preliminary process, software issues with GrabCAD print were created. As seen in figure 43-45, although the model was exported properly, somehow data was lost during the printing process. Thankfully this issue was resolved after these experiments.

Printing Shells

Figure 38a. 3D printed shell one.

Figure 39a. 3D printed shell two.

Figure 40a. 3D printed shell three.

Figure 41a. 3D printed shell four.

Figure 38b. 3D printed shell one PNG image.

Figure 39b. 3D printed shell two PNG image.

Figure 40b. 3D printed shell three PNG image.

Figure 41b. 3D printed shell four PNG image.

Figure 42a. 3D printed shell five.

Figure 42b. 3D printed shell five PNG image.

Reflection/Discovery

The first attempt at printing shells revealed the complexity of modelling a realistic shell shape through Grasshopper. It also revealed that due to the fineness of the prints, GrabCAD print would not preview fragile meshes, causing confusion and leading to increasing the VDB count of the models within Houdini. This did however produce

an external grey layer around the models as the VDB count at the time was too big. Another challenge through this first print set of shells was the inclusion of several geometries to apply colour and material properties that could be exported together. This was overcome through VDB combine.

Refining VDB amount

Figure 43a. Refining VDB amount one.

Figure 44a. Refining VDB amount two.

Figure 45a. Refining VDB amount three.

Figure 43b. Refining VDB amount one PNG image.

Figure 44b. Refining VDB amount two PNG image.

Figure 45b. Refining VDB amount three PNG image.

Reflection/Discovery

Due to the issues surrounding VDB and the fragmented mesh preview in GrabCAD Print, this experiment successfully lowered the VDB count, for example as low as 0.05, testing that an object with a fragmented mesh may still 3D print as desired.

Additionally, this experiment identified that fragile areas on a model were best printed in Agilus as the Vero material broke extremely easily.

The VDB combine technique was also refined, identifying the most successful way to combine several parts with different colours. The VDB Combine settings were 'Combine A/B Pairs' and 'Replace A with Active B'.

CRITERIA PHASE ONE

Showcase the creative opportunities for full colour multi-material printing through the voxel method.

Explore the dialogue between translating an object from a screen-based visualisation to a 3D printed tangible object (exploring procedural techniques to apply colour).

Be informed by David M Raup's geometric parameters for shell architecture.

Be contextualised towards a scientific narrative through the case study of shells.

Morphological Form Development

#1

Aim: To parametrically create a set of shells that are visually noted to have developed in form.

Figure 46a. Experiment 1 3D printed model one.

Figure 47a. Experiment 1 3D printed model two.

Figure 48a. Experiment 1 3D printed model three.

Figure 46b. Experiment 1 model one PNG image.

Figure 47b. Experiment 1 model two PNG image.

Figure 48b. Experiment 1 model three PNG image.

Discovery/Reflection

Through parametric modelling in Grasshopper, the tip of the whorl of the shell was extended by increasing the height translation slider, to demonstrate a development in form in an attempt to show an evolution of form.

Colour was applied in Houdini through applying a gradient to the model. The gradient was slightly changed for each model in an attempt to differentiate the model through colour as well as form. Unfortunately there is an external layer of

grey, a result of exporting the model for printing and this is an issue that needs to be resolved.

The colours were successfully generated through procedural modelling; however there is a layer of grey being exported around the outside of the model that results in a layer of agilus. This will need to be resolved as it impacts the quality and intended output of the design.

Morphological Form Development

#2

Aim: To attempt to emulate a possible evolutionary connection between a shell form similar to Monoplacophora generating into a shell form similar to Perunelomorpha, Loxonematoidea and then Caenogastropoda.

Figure 49a. Experiment 2 3D printed model one.

Figure 50a. Experiment 2 3D printed model two.

Figure 51a. Experiment 2 3D printed model three.

Figure 52a. Experiment 2 3D printed model four.

Figure 53a. Experiment 2 3D printed model five.

Figure 49b. Experiment 2 model one PNG image.

Figure 50b. Experiment 2 model two PNG image.

Figure 51b. Experiment 2 model three PNG image.

Figure 52b. Experiment 2 model four PNG image.

Figure 53b. Experiment 2 model five PNG image.

Discovery/Reflection

These models successfully demonstrate a change and development in the form through extending the height translation and whorl expansion of the form through parametrically generated models. Attempting to achieve an evolutionary development in form was unsuccessful as there is no direct line-age and everything is only speculation. It also successfully demonstrates voxel-based printing.

The colours are based on the fluorescent yellow of ancient shells (Caze et al., 2015) and were successfully generated through procedural modelling by applying noise to the object to generate the colour. The layer of grey seems to have been resolved through these models. However, the VDB count is still too high producing very thick shells. An aspect of these models that needs to be improved is applying the colour noise to match the growth lines of the shell.

CRITERIA PHASE TWO

Criteria Phase One

Showcase the creative opportunities for full colour multi-material printing through the voxel method.

Explore the dialogue between translating an object from a screen-based visualisation to a 3D printed tangible object (exploring procedural techniques to apply colour).

Be informed by David M Raup's geometric parameters for shell architecture.

Be contextualised towards a scientific narrative through the case study of shells.

Criteria Phase Two

Showcase the creative opportunities for full colour multi-material printing through the voxel method.

Demonstrate through a procedural work flow that applying external forces can have an impact on the form that is organically produced (exploring procedural techniques to apply colour).

Be informed by David M Raup's geometric parameters for shell architecture.

Be contextualised towards a scientific narrative through the case study of shells.

Explore the relationship between an object's digital rendered appearance and physical 3D printed appearance after removing the support material.

Ocean Acidification

#3

Aim: To recreate the pteropod shells that were impacted by changing pH levels as a result of climate change from David Liittschwager's 2007 photograph 'Ocean acidification on pteropod shells.' as seen in figure 13. Intending to generate deformation in both colour and thickness.

Figure 54a. Experiment 3 3D printed model four.

Figure 55a. Experiment 3 3D printed model four.

Figure 56a. Experiment 3 3D printed model four.

Figure 57a. Experiment 3 3D printed model four.

Figure 54b. Experiment 3 model four PNG image.

Figure 55b. Experiment 3 model four PNG image.

Figure 56b. Experiment 3 model four PNG image.

Figure 57b. Experiment 3 model four PNG image.

Discovery/Reflection

To generate the change in form was a manual process through squishing the model with meta balls in *Houdini*. This meant that the procedural process was manual and controlled, rather than unknown. The result of this experiment meant that only on the forms of shells three and four were changed. There is some resemblance to the photo it is based on but the shell's thickness is too high.

These models don't exploit the capabilities of printing through the voxel method, as there are only two materials present - VeroPureWhite and Agilus30Clr. It was however discovered how prominent and overpowering a small amount of Vero materials is.

Red and Yellow noise

#4

Aim: To refine the colouring of shells through Volume VOPS and noise parameters.

Figure 58a. Experiment 4 3D printed model.

Figure 58b. Experiment 4 PNG image.

Discovery/Reflection

This colour generated in this model was done through volume VOPs and adding noise to the model in order to mix the colours. There was no attempt through this experiment to change the form.

This generated noise pattern was pixelated and blocky, an undesirable effect.

This may have been a result of the VDB level in *Houdini* but the problem was not able to be resolved.

Shining a light through this model revealed hidden details and exposed the material characteristic that Vero materials are somewhat transparent.

Yellow and Brown

#5

Aim: To alter and deform the morphology of the shell model through procedural DOP networks.

Figure 59a. Experiment 5 3D printed model.

Figure 59b. Experiment 5 PNG image.

Discovery/Reflection

This experiment explored applying a procedural DOP network to change the model's form. The surface is no longer smooth but has bumps in the vertical direction. However, a downside to this alteration is that it deforms the full morphology, including the protoconch causing unwanted disfigurement.

The change in this model's form was abstract and not influenced by external factors.

Through noise-based colouring, a successful mix of colours was achieved in line with the growth lines of the shell, creating visually pleasing results.

Green Shell

#6

Aim: To alter and deform the morphology of the shell model through procedural DOP networks.

Figure 60a. Experiment 6 3D printed model.

Figure 60b. Experiment 6 PNG image.

Discovery/Reflection

The same procedural DOP network that was applied in experiment 5 was applied in this experiment. However, the system was changed and the bumps along the surface were both vertical and horizontal.

The mix of colours in the 3D printed model was unexpected to be as green as what was produced, but it is visually stunning. Seeing the droplets of colour expressed how many different materials were mixing together in the object. It also demonstrated that the rendered preview in Houdini before printing isn't completely reliable for predicting colour mixing.

Volume Density

#7

Aim: To create a shell with different density and thickness throughout to achieve degradation and dissolution in the morphology of the form.

Figure 61a. Experiment 7 3D printed model.

Figure 61b. Experiment 7 PNG image.

Discovery/Reflection

This experiment attempted to use volume VOPs and VDBs in Houdini to procedurally alter the model's density and thickness in certain areas to make it appear as if a disintegration process was occurring. This was unsuccessful and only produced a model consisting of two colours: VeroCyanV and VeroMagentaV.

The form is too thick, creating a 'manufactured' look along the apertural lip.

The procedural colour was an accident and therefore unsuccessful. Although the colours are interesting, they look obviously fake.

External Growths/Aging

#8

Aim: To experiment with a change in time represented through growing morphology on the external areas of the shell. For example barnacles growing on the outside to represent aging and degradation. Colour was also stripped to represent this degradation.

Figure 62a. Experiment 8 3D printed model one.

Figure 63a. Experiment 8 3D printed model two.

Figure 64a. Experiment 8 3D printed model three.

Figure 62b. Experiment 8 model one PNG image.

Figure 63b. Experiment 8 model two PNG image.

Figure 64b. Experiment 8 model three PNG image.

Discovery/Reflection

This model's procedural generation of growths on the shell is successful as it increases along a time-line/frame rate, procedurally adding to the form.

To procedurally generate this form, this model was influenced by the possible external influence of algae growing on a shell and degradation of the shell.

The model successfully demonstrates a form generated through David M Raup's parameter guidelines within the separate Grasshopper file.

This model was successful at voxel printing as it is used to define material compositions and blend colour throughout the model. The model's colour was generated through procedural noise techniques and the level of cyan within the models was reduced to further show degradation in the models.

A Strummeri Shell

#9

Aim: To attempt to recreate the shell 'A Strummeri' found in hydrothermal vents (Johnson et al., 2015). Exploring how a procedural system may grow hairs on the shell model and printing them with Agilus to prevent breakage.

Figure 65a. Experiment 9 3D printed model.

Figure 65b. Experiment 9 PNG image.

Discovery/Reflection

This model's procedural generation of the external hairs is completely procedural and generates further as the timeline/frame rate increases. The hairs print both externally and internally but are successful in procedurally adding to the form. This model is successful at demonstrating voxel printing as the hairs go straight through the shell, altering the material composition, increasing the amount of agilus and create colour and squishiness.

The model successfully demonstrates a form generated through David M Raup's parameter guidelines within the separate Grasshopper file.

During the cleaning process some hairs broke during cleaning showing a loss of data. It would be interesting to see how this model would look encapsulated. This model emulated the 'A Strummeri' snail shell, found in hydrothermal vents, demonstrating that the vent's environment could possibly influence the hair growth.

Ocean Acidification Thinner and Predation

#10

Aim: To expand on experiment #3 'Ocean Acidification'. Achieving a thinner model and changing the colour applied from Vero Pure White to a more noticeable Vero Vivid Cyan. Also introducing the external influence of predators onto a weakened shell.

Figure 66a. Experiment 10 3D printed model.

Figure 66b. Experiment 11 PNG image.

Discovery/Reflection

This model successfully demonstrates the use of voxel printing to have a difference in material. However, the PNG was not exported with the right colours and the white had to be selected as Cyan in GrabCAD print.

The model successfully demonstrates a form generated through David M Raup's parameter guidelines within the separate Grasshopper file. Houdini was used to incorporate the holes to generate a change, although partly procedural and part manual so somewhat successful.

When removing the support material, the shell model was very fragile, causing concern that the model would rip during the cleaning process. Through adding procedural noise, the cyan colour was achieved which was more noticeable than white.

Adding the external influence of predator attacks causing holes in the body whorl was successful, adding a further level of degradation to the shell to accompany its overall weakened state and vulnerability in a changing environment.

Predation

#11

Aim: To explore the effects of Durophagus predation from crushing predators like crustaceans through procedural modelling. Emulating predation causing damage to the shell such as holes in the body whorl and apertural lip chipping. As predation is the main driver towards morphological change, it associates morphological change with other fauna.

Figure 67a. Experiment 11 3D printed model.

Figure 67b. Experiment 12 PNG image.

Discovery/Reflection

The model successfully demonstrates voxel-based printing. The colour and patterning applied to this model is very successful and is what was anticipated. It was the result of having extra yellow on the internal side of the shell as well as having a higher VDB of 1.5.

The model successfully demonstrates a form generated through David M Raup's parameter guidelines within the separate Grasshopper file.

The procedural model was not successfully procedural but rather more manual with one slider that could alter where the holes were located on the body of the shell. Through Houdini a change in form was successful through creating holes from predators in the body whorl and chipping on the aperture lip.

Predation Repairs

#12

Aim: To expand on experiment #11 'Predation', and attempt to emulate shell repair as if the creature had survived.

Figure 68a. Experiment 12 3D printed model.

Figure 68b. Experiment 12 PNG image.

Discovery/Reflection

This model successfully demonstrates voxel-printing. Successful in the use of Agilus for the repaired sections but unsuccessful due to the unpredicted colour mixing and the thickness of the repaired sections.

The model successfully demonstrates a form generated through David M Raup's parameter guidelines within the separate Grasshopper file. This model successfully demonstrated a change in appearance, but it was procedural but rather manual. The form was influenced by how shells repair themselves after an attack from an external predator.

Procedural modelling was successful in applying colour to the model. Through VDB from particles and noise applied to the model the colour pattern was achieved. The repaired sections achieved a similar colour pattern so that it somewhat blended into the rest of the model but there was still a level of differentiation.

Dissolving Pteropod Shells

#13

Aim: To explore how a shell might dissolve and float in the ocean due to ocean acidification and in doing so, attempting to achieve a ‘washed away’ appearance and texture to see how it may react when being submerged in water.

Figure 69a. Experiment 13 3D printed model One.

Figure 69b. Experiment 13 PNG image.

Figure 70a. Experiment 13 3D printed model Two.

Figure 70b. Experiment 13 PNG image.

Discovery/Reflection

The Cyan 3D printed model was more successful at being voxel printed as the white material was not distinguishable from the Agilus material. The models successfully demonstrate a form generated through David M Raup's parameter guidelines within the separate Grasshopper file.

The intended procedural system for this model was to change the Pteropod shell's appearance model to achieve a washed away texture and appearance through volumes as though it was suffering from the external influence of ocean

acidification and the shell was so dissolved that it was washing away. It was unfortunately unsuccessful because through the process of turning it into VDBs to prepare it for exportation, it lost its weightlessness/floating appearance that it rendered with, making the areas composed of Agilus stiff and not delicate. However, in terms of colour the Cyan model appears as though dissolution has affected the shell's colour, slowly making it wash away.

There is opportunity to print an encapsulated version of this model to see if it maintains its weightlessness/floating appearance.

Dissolving Pteropod Shell Expanded

#14

Aim: To expand on experiment #13 'Dissolving Pteropod Shell' and attempt to achieve a look and texture of dissolution in a Pteropod shell.

Figure 71a. Experiment 14 3D printed model.

Figure 71b. Experiment 14 PNG image.

Discovery/Reflection

The intended procedural system for this model was to expand on experiment #13 'Dissolving Pteropod Shells' to attempt to achieve the washed away texture and appearance through volumes by making the volume wash away in a more relaxed appearance. It was unfortunately once again unsuccessful because through the process of turning it into VDBs to prepare it for exportation, it again lost its weightlessness/floating appearance that it rendered with. However, in terms of colour the colours fading away gave it a different washed away appearance after being printed.

3D Printed Glitch

#15

Due to the boundary of the 3D models not always being visible in Grabcad print as a result of the model's fineness and fragmented previews. It resulted in the two models below merging into one.

Figure 73a. Experiment 15 3D printed glitch.

Figure 73b. Experiment 15 3D printed glitch, png image from first model.

Figure 73c. Experiment 15 3D printed glitch, png image from second model.

Discovery/Reflection

This experiemnt demonstrates how voxel printing can glitch and produce undesirable/interesting results. This glitch created very interesting results and it wasn't until all of the support material was removed that the two models were revealed to be printed together. There were also areas in the model that weren't even printed because there was a lot of data lost when the two models merged.

CRITERIA PHASE THREE

Criteria Phase One

Showcase the creative opportunities for full colour multi-material printing through the voxel method.

Explore the dialogue between translating an object from a screen-based visualisation to a 3D printed tangible object (exploring procedural techniques to apply colour).

Be informed by David M Raup's geometric parameters for shell architecture.

Be contextualised towards a scientific narrative through the case study of shells.

Criteria Phase Two

Showcase the creative opportunities for full colour multi-material printing through the voxel method.

Demonstrate through a procedural work flow that applying external forces can have an impact on the form that is organically produced (exploring procedural techniques to apply colour).

Be informed by David M Raup's geometric parameters for shell architecture.

Be contextualised towards a scientific narrative through the case study of shells.

Explore the relationship between an object's digital rendered appearance and physical 3D printed appearance after removing the support material.

Criteria Phase Three

Showcase the creative opportunities for full colour multi-material printing through the voxel method.

Demonstrate through a procedural work flow how an unknown form can be generated and explored through scrolling along a timeline, extracting a model at a certain point.

Be informed by David M Raup's geometric parameters for shell architecture.

Be contextualised towards a scientific narrative.

Explore encapsulation as a printing method to ensure that no data is lost as a result of removing support material.

MORPHOLOGICAL TIMELINE PROGRESSION AND ENCAPSULATION

During this stage of the research, with a more in depth understanding of Houdini, the morphological timeline began to take shape through the procedural system. Rather than achieving results manually, models were extracted at certain points along a timeline at the desired location.

The method of encapsulation was also included in the second revised criteria as there was potential for this to be an effective way to ensure data was not lost as a direct result from the support cleaning process.

Tendrils Hole Repair

#16

Aim: To explore procedural particle growth influenced by forces from an area of the shell where a predation attack had occurred. Using the holes in the body whorl and apertural lip as the constraints for the particles growth system.

Figure 73. Experiment 16 morphological timeline.

Figure 74. Experiment 16 loose 3D print.

Figure 75. Experiment 16 encapsulated 3D print.

Discovery/Reflection

This experiment is presented in the form of a loose model and an encapsulated model.

The use of materials in the loose model achieve a distinction between the shell shape and the tendrils. In the encapsulated model, due to similar colours that are applied to both the shell and tendrils, they blend into the same shape pattern. The thinness of the encapsulated model and the material composition consisting of Vivid Vero materials produces the ghostly appearance.

Using a Vellum and DOP node network in Houdini, with the forces of gravity and wind influencing the direction of growth, a change in morphology is generated.

The procedural system responded in an interesting manner when the holes left from a predator attack were the form constraints for the particle growth. Rather than spreading out, the tendrils remained constrained to that area of the shell.

In the loose model there is evidence of the tendrils fusing together during the printing process due to their small scale and fragility. This produced minimal breakage but also visually and physically communicated a loss in data through 3D printing due to consequences of physical constraints imposed during the cleaning process. In contrast, the encapsulated model suffered no loss of data as the VeroClear which encapsulated the shell and tendrils preserved all of the data.

Tendrils Growth Middle Form

#17

Aim: To explore how procedural particle growth that are influenced by forces such as wind and gravity may become tendrils and how they might occur from a clipped area of the shell. Comparing the advantages and disadvantages of having the shell loose with tendrils that encourage physical interaction or an encapsulated model that can print without loss of data or compromise towards the thickness of the model.

Figure 76. Experiment 17 morphological timeline.

Figure 77. Experiment 17 loose 3D print.

Figure 78. Experiment 17 encapsulated 3D print.

Discovery/Reflection

The loose model produced a form with both rigid and flexible aspects. The particles previously present in the rendered visualisation became fused together, while the most fragile ones did not survive the cleaning process.

In contrast, the encapsulated model produced an entirely rigid model with highly fragile tendrils encased inside. Some of the details within the encased model were not seen in the rendered preview before printing. Therefore, this approach to printing revealed hidden details through introducing the object to the tangible dimension. Not only was data retained, but after the threshold from digital to physical was crossed, more data was visible.

The particle growth system was generated through a Vellum and DOP network influenced by gravity and wind. The particles began at the back of the shell, growing towards the edge before spraying outwards in opposite directions. The forms this system generated are interesting in comparison to experiment #16 when viewing how an imposed boundary can alter the generated form.

The encapsulation of this model was an attempt to view how fine the model can be printed, observing that there was no loss in data. Rather, more data was now visible.

ENCAPSULATION PROGRESSION

At this point, an opportunity was discovered and defined as a pivotable stage in the research. Through encapsulating the 3D prints and sectioning them to reveal the complexity of the internal structures, 'future fossils' were created. Furthermore, the morphological timeline began to take shape through the procedural system. Through screen-based visualisations, the possible products of this system that were unknown or determined were now visible. The generation of this morphological timeline now allowed for models to be extracted at certain points to be translated into the tangible dimension through 3D printing.

Tendril Growth Middle Form Sectioned

#18

Aim: To expand on experiment # 17 'Internal Tendril growth Middle Form', exploring how much extra hidden detail is exposed in an encased model through sectioning the model.

Figure 79. Experiment 18 encapsulated 3D model Section One.

Figure 80. Experiment 18 encapsulated 3D model Section Two.

Discovery/Reflection

Through sectioning the encapsulated model, hidden internal details were exposed. Within 'Section One' a paper-thin line from the beginning of the next whorl adds an extra element of detail to let you know the full scale of this print. Section One appears more delicate than Section Two. Sectioning the prints exposes a depth of colour and thinness and fragility of the model that was not previously visible.

Tendrils First Form

#19

Aim: To expand on the success of the experiment # 17 '*Tendril Growth Middle Form*' and experiment with a smaller form with less whorls, to showcase how the procedural model generates morphology differently when given different smaller form constraints.

Figure 81. Experiment 19 morphological timeline.

Figure 82. Experiment 19 loose 3D model.

Figure 83. Experiment 19 encapsulated 3D model.

Figure 84. Close up of experiment 19 encapsulated 3D model.

Discovery/Reflection

The particle system from experiment #17 was recycled for this experiment. The difference in the system was the form that the particles are being generated from. When a boundary from a smaller shell with less whorls is imposed on the system the particles react in a different way, swirling around in a circular motion curling in on itself before branching outwards.

Within both the loose model and the encapsulated model the tendrils form and motion are visible. Applying a colour similar to the base of the shell and white to the tips made the tendrils appear more that they were changing colour while growing outwards.

The tendrils in the loose model are not as engaging or vibrant as the tendrils in the encapsulated model. There was no benefit gained from printing the model loose and it felt dull. However, printing the model encapsulated made the tendrils appear more dynamic and vibrant. This model was not sectioned because of the lack of whorls, it did not seem beneficial as there would not be much hidden detail encased inside the whorls.

Tendrils Last Form

#20

Aim: To explore how the recyclable procedural system generated in experiment #17 'Tendril Growth Middle Form' responds to a shell form that is larger, offering less constraints and more cavities in the form.

Figure 85. Experiment 20 morphological timeline.

Figure 86. Experiment 20 loose 3D print.

Figure 87. Close up of experiment 20 encapsulated 3D prints.

Figure 88. Close up of experiment 20 encapsulated 3D print Section One.

Figure 89. Close up of experiment 20 encapsulated 3D print Section Two.

Figure 90. Close up of experiment 20 encapsulated 3D print Section Three.

Figure 91. Holding experiment 20 encapsulated 3D print Section One.

Figure 92. Holding experiment 20 encapsulated 3D print Section Two.

Figure 93. Holding experiment 20 encapsulated 3D print Section Three.

Discovery/Reflection

Once again, the particle system from experiment #17 was recycled for this experiment. However, due to the larger form with more whorls and ultimately more cavities for the tendrils to grow into, a much more visually stunning result was produced. The tendrils not only grew outwards beyond the shell but also twirled up through the whorl cavities.

A successful aspect of this experiment is the vibrant colouring. Through the technique of attribute transfer, a darker orange was created around the edge of the whorls and an unintentional white tip at the top and bottom added to its amazement.

The loose model demonstrates the curled nature of the tendrils expanding out from the shell but the tendrils fuse together after being printed. The encapsulated model shows fine and fragile tendrils individually to the point where particles mixing together can be identified. This would not have been possible without printing through the voxel method. The sectioning of this model into three separate parts was decided upon seeing how the particles were reacting to this larger form, generating upwards into the whorls and identifying the benefit of revealing those hidden details. This came with the disadvantage that Section One didn't contain as much visually interesting data as the other two sections. However, an advantage is seen in Section Two and Three with part of the printed model appearing to be floating inside the VeroClear encapsulating it.

Sectioned Prints Together

#21

Aim: To photograph the encased prints from experiment #17, #18, #19 And #20 to visually compare the same procedural system responding differently to three different forms.

Figure 94. Experiment 17 -20 3D printed encapsulated sections.

Discovery/Reflection

Photographing all of the forms together showed how differently the particle growth system reacted to three forms with different height translation and whorl expansion. It also showcases the colour vibrancy and high-resolution details on possible printing through the voxel method.

Island Bay Photographs

#22

Aim: To photograph the loose shell models in a natural seawater environment at Island Bay to observe how the objects look in a contextualized environment.

Figure 95a 3D print in rock pools at Island bay.

Figure 95b 3D print in rock pools at Island bay.

Figure 95c 3D print in rock pools at Island bay.

Discovery/Reflection

After placing the prints in the rock pools at Island Bay, it did significantly help towards the contextualisation of the models. A notable difference between the real shell and the 3D printed ones was the size and colour. The real shells were much duller and darker with faded colours in the protoconch. They were also a lot smaller.

A notable discovery from the experiment was the reaction that saltwater had with the support material. Almost instantly the support material trapped inside the whorls began to expand and split the prints open.

Internal Creature

#23

Aim: To create an internal creature within the shell through a procedural system.

Figure 96. Experiment 23 morphological timeline.

Figure 97. Experiment 23 loose 3D print.

Figure 98. Experiment 23 sectioned loose 3D print.

Discovery/Reflection

This experiment was only printed in a loose model as there was seen little benefit to be gained from printing an encapsulated model due to the experiment's unsuccessful nature and lack of visual vibrance.

This experiment applied a different vellum and dop network with changed forces from experiment #17. However, there was a much less influential impact on the particle system and as a result the tendrils lack visual interest. This may have been a result of clipping the shell from the top of the whorls rather than the back of the shell which would have a significant influence on the produced result.

In this experiment, sectioning was tried through a loose model to compare the difference. Unfortunately, the model was not sectioned at an ideal spot and since the model is not encapsulated in VeroClear, the other half was not attached together and fell away.

Sectioning a loose model did reveal some interesting qualities towards the Agilus30Clr material. The tendrils only became milky white after splitting into tendril forms. The unsuccessful result produced from sectioning the loose model is also what influenced the decision to not create an encapsulated model.

Internal Creature and Predation

#24

Aim: To further expand on experiment #23 'Internal Creature' and #16 'Tendrill Hole Repair', generating particles inside the shell, influencing them to grow towards and outside the holes in the shell from predation attacks.

Figure 99. Experiment 24 morphological timeline.

Figure 100. Experiment 24 loose 3D print.

Discovery/Reflection

When exporting the loose model, all six colours were applied to be mix together within the print. As a result the tendrils could not be applied one sole colour to be assigned as Agilus30Clr. Therefore, one colour had to be sacrificed to be Agilus, in this case white was chosen. This meant that some Vero droplets are able to be seen inside the tendrils.

Within this model the procedural particle system was influenced by holes left in the shell by an external predator. After nudging, the tendrils were directed towards the outside of the already established holes in the shell from a predator.

To achieve this colour patterning, VDB from particles and a noise influence were used. As a result, there was also the same patterning occurring in the tendrils. This is because when more than one part is being exported, VDB combine must be used so the VDBs have to be the same. The tendrils were also applied a VDB from particles and noise influence.

Due to the thickness of the Agilus, no tendrils ripped and data was lost only at a minimal. This print was also not printed encapsulated as it appeared as though no hidden details would be exposed from that process.

Timeline for Multiple Clipping Points

Aim: To expand on experiments #23 'Internal Creature' and #24 'Internal Creature with Predation', the procedural system was advanced to have several areas clipped where the particles may begin to generate from. Rather than trying to manually nudge it in the right direction, the procedural particle system has several starting points to grow from.

Figure 101. Experiment 25-27 morphological timeline.

The above renders apply to experiments 25-29

Large Multiple Clipping Points

#25

Figure 102. Experiment 25 loose 3D print.

Figure 103. Experiment 25 loose 3D print brushing tendrils.

Figure 104. Experiment 25 encapsulated 3D print section one.

Discovery/Reflection

The purple colour in these models are very similar to the blue used in experiment #17, achieving a similar depth of colour.

A decision was made to make the tendrils the same colour as the shell in experiment #17 to see how a different colour could produce similar or different results. The tendrils blended into the shell shape but due to the thickness of the tendrils in comparison to the thinness of the shell model, from the external side, you can see where the tendrils are as the shell colour appears darker in those areas.

Through applying multiple clipping points to generate the particles form, more details and interesting results were produced. The procedural model linked each location on the shell where the particles began. The particles seemed to be less

Figure 105. Experiment 25 encapsulated 3D print section two.

affected by wind or gravity as a result. However, due to the clipping points being inside the whorls, a lot of the detail is hidden as you cannot see much in the loose model. However, within the encapsulated model, it was not as interesting as previous experiments. It lacked a level of detail and intrigue but it also possessed a type of simplicity that other models did not have.

Applying different colours to the shell model and tendrils could allow for differentiation between them and show more details.

This model was also the first to add text to the bottom. It does offer more insight to what is trying to be accomplished in a scientific manner but using white font makes it difficult to read.

Small Multiple Clipping Points

#26

Aim: This experiment applies the same procedural system as experiment #25 but explored different use of colour and scale.

Figure 106. Experiment 26 loose 3D print with Agilus tendrils.

Figure 107. Experiment 26 loose 3D print with Vero tendrils.

Figure 108. Experiment 26 encapsulated 3D print section one.

Figure 109. Experiment 26 encapsulated 3D print section two.

Discovery/Reflection

The loose models explored two different colour techniques, the first involved a coloured shell with Agilus tendrils and the second explored an Agilus shell with coloured tendrils. Due to the small scale of these models, neither of the two were able to survive the constraints of cleaning. Both shells and tendrils ripped due to their thinness. Another downside of their scale is that it is difficult to understand

the qualities of the prints when a lot of data is lost during the cleaning process.

In comparison to these models, the encased model, although small, no data is lost and is easily comprehensible to the person viewing it. Emphasising the benefits to printing encased, that scale and physical limitations are no longer a factor.

Medium Multiple Clipping Points

#27

Aim: This experiment applies the same procedural system as experiment 25 but explored through encapsulation at a larger scale.

Figure 110. Experiment 27 encapsulated 3D print section one.

Figure 111. Experiment 27 encapsulated 3D print section two.

Discovery/Reflection

This experiment was a brief experiment to print the encased shell from experiment 26 in a larger scale so that the text may be readable. Although experiment 26 proved that encapsulating a print removes the limitations of the scale of an object, it did not remove the limitations of the scale of readable writing.

Tendrils Through Pteropod Shell

#28

Aim: To explore how procedurally generated particles occur in a pteropod form which has significantly different shell architecture to the previous explored forms.

Figure 112. Experiment 28 morphological timeline.

Figure 113. Experiment 28 loose 3D print.

Figure 114. Experiment 28 loose 3D print with light shining through.

Figure 115. Experiment 28 encapsulated 3D print section one.

Figure 116. Experiment 28 encapsulated 3D print section two.

Discovery/Reflection

The way the procedural model generated particles for this form was very different from the other experiments. Due to the architecture of the shell, the particles reflected and collided with the boundary of the shell shape before reaching the apertural opening and branching outwards. This was a feature that was not noticed until the encapsulated object was printed.

This is noticeable in the loose model as well, but only after shining a light through the shell, producing a veined appearance which was a different perspective in comparison to the encapsulated model. The finer tendrils seen in the encapsulated model are lost to the cleaning process in the loose model.

Full Body Scatter Tendrils

#29

Aim: To expand from experiment 17 - 20, exploring not only by how a procedural system generates particles inside a model but how the particles respond after being scattered across a shell's external surface.

Figure 117. Experiment 29 morphological timeline.

Figure 118. Experiment 29 large loose 3D print.

Figure 119. Experiment 29 medium loose 3D print.

Figure 120. Experiment 29 small loose 3D print.

Figure 121. Experiment 29 encapsulated 3D print section one.

Figure 122. Experiment 29 encapsulated 3D print section two.

Figure 123. Experiment 29 encapsulated 3D print section three

Discovery/Reflection

The procedural generation for this model was changed so that instead of generating tendrils internally, it was changed to generate externally from 200 scattered points along the external surface of the shell. Although the intention was to only generate particles externally, the system still generated them internally. This produced an aesthetic where the shell shape is visible but only because of the scattered particles along the surface.

The loose model was printed in three different sizes so to compare which size was more successful after the printing and cleaning process to maintain detail. It was shown that the smaller the print, the more the tendrils fused together and

lost detail. The large Agilus model was the most successful having the most individuality in the tendrils.

The loose model's tendrils felt very uncomfortable and surreal but the encapsulated models tendrils are beautifully dense and complex. The different colours are evident as well as the mixed depths in colour. However, it did still generate on the internal side of the shell as well. The tendril's fragility is so entrancingly exposed. So much more data is revealed after printing that isn't thought to be there during the procedural generation.

The design experiments also identified that photobleaching models makes them lighter, that salt water can split prints and that the printer can have malfunctions, causing streaks in the print.

Figure 124. Not photo bleached model (left) and photobleached model (right).

Figure 125. Lines through 3D printed model.

Figure 126a. 3D prints that had split as a result of being in salt water.

Figure 126b. 3D prints that had split as a result of being in salt water.

Figure 126c. 3D prints that had split as a result of being in salt water.

Figure 126d. 3D prints that had split as a result of being in salt water.

DESIGNED OUTPUT

Left:

Figure 127. Section two of final output one frame 100 encapsulated 3D print.

RESOLVED CRITERIA

This criterion is the result of the incrementally developed criteria throughout this research.

Showcase the creative opportunities for full colour multi-material printing through the voxel method.

Demonstrate through a procedural work flow that through external forces influencing a system can create forms that are not known or perceived, extracting models at a pivotal point for the context of 3D printing.

Explore the dialogue between translating an object from a screen-based visualisation to a 3D printed tangible object through extracting models from a pivotal point along the morphological timeline and encapsulating them in resin (VeroClear), to maintain data.

Be contextualised towards communicating a significant and dynamic issue in scientific information, using a visual and tangible object as a narrative with accompanying scientific information.

The final *future fossils* intend to explore the communication of one focused and significant issue, ocean acidification, in a form that is comprehensible to a general audience. The possible products of the procedural system are displayed through a rendered morphological timeline to anticipate the physical object. At two separate locations along the timeline (frame 50 and frame 100), the physical fossils provide a realisation towards how the form could progress and change.

The future fossils are presented in a physical form through close up photographs, revealing hidden and exposed high-resolution details and colour vibrancy. The models are sectioned for the intention of inquisitive engagement by those viewing the models as they are intended to be examined separately and as a whole. Additionally, contextual photographs are used to show the inquisitive examination from those viewing them as the models are displayed in an exhibition context. Examining the object, the text on the object and the written summary provided to gain a further understanding as to what narrative the object is trying to portray.

Final Output One

Aim: To explore a visualisation of a pteropod shell *limacina helicina* being impacted by ocean acidification and dissolution, the procedural system and resulting timeline produces an abstract representation of the washing away and dissolving of the shell. Applying the concept of dissolution in an abstract form looked at dissolution in a more abstract manner. This future fossil attempts to visually communicate the information surrounding the issue of ocean acidification presently discussed in several scientific studies for decades in a tangible and comprehensible way.

Final Output One Morphological Timeline

Figure 128. Final output one morphological timeline.

Final Output One 3D Printed Models

Figure 129a. Encapsulated 3D print section one of final output one frame 50.

Figure 129b. Encapsulated 3D print section one of final output one frame 50.

Figure 130a. Encapsulated 3D print section two of final output one frame 50.

Figure 130b. Encapsulated 3D print section two of final output one frame 50.

Figure 131a. Encapsulated 3D print section one of final output one frame 100.

Figure 132a. Encapsulated 3D print section two of final output one frame 100.

Figure 131b. Encapsulated 3D print section one of final output one frame 100.

Figure 132b. Encapsulated 3D print section two of final output one frame 100.

Figure 133a. Encapsulated 3D print section three of final output one frame 100.

Figure 133b. Encapsulated 3D print section three of final output one frame 100.

Figure 134. Encapsulated 3D print of final output one frame 50.

Figure 135. Encapsulated 3D print of final output one frame 100.

Final Output Two

Aim: Pteropod shells impacted by ocean acidification and dissolution. Through the procedural workflow and timeline, an abstract representation of the washing away and dissolving of a shell is being presented. This time not only is the shell washing away but it has been crumbled and deformed. Applying the concept of dissolution in an abstract form looked at dissolution in a more abstract manner. This future fossil attempts to visually communicate the information surrounding the issue of ocean acidification presently discussed in several scientific studies for decades in a tangible and comprehensible way.

Final Output Two Morphological Timeline

Figure 136. Final output two morphological timeline.

Final Output Two 3D Printed Models

Figure 1387a. Encapsulated print section one of final output two Frame 50.

Figure 1387b. Encapsulated print section one of final output two Frame 50.

Figure 138a. Encapsulated print section two of final output two Frame 50.

Figure 138b. Encapsulated print section two of final output two Frame 50.

Figure 139a. Encapsulated 3D print section one of final output two frame 100.

Figure 140a. Encapsulated 3D print section two of final output two frame 100.

Figure 139b. Encapsulated 3D print section one of final output two frame 100.

Figure 140b. Encapsulated 3D print section two of final output two frame 100.

Figure 141a. Encapsulated 3D print section three of final output two frame 100.

Figure 141b. Encapsulated 3D print section three of final output two frame 100.

Figure 142. Encapsulated 3D prints of final output two frame 50.

Figure 143. Encapsulated 3D prints of final output two frame 100.

Reflection on Designed Output Future Fossils

The final future fossils show incredibly fragile details perfectly preserved in VeroClear. Through inquisitive investigation, high-resolution details become more evident. These high-resolution details are only possible through the voxel printing workflow and can only be examined in their purest state through encapsulation. Sectioning the models is successful in encouraging those viewing them to physically interact with the models, examining them individually and with their counterparts. The procedural system used to generate the abstract representation of dissolution due to ocean acidification is represented through the approach of extracting two models from different points on the timeline, in this case frame 50 and frame 100. It allows you to see physically the changes that the context of time and environment have towards communicating the narrative of ocean acidification through 3D printing.

Although an available array of frames are presented through the rendered morphological timeline, the 3D print offers a perspective that cannot be seen digitally. It is not until the fossil is translated into the tangible dimension that its full potential is exposed in a medium that is vibrant, comprehensible and engaging, eliciting the discussion towards the narrative that informed the output.

Pteropod Shell
Impacted By Ocean Acidification Dissolution
Frame 100
Influences On Form: Ocean Current & Gravity

Final Output One Frame 100

As the pteropod shell based on limacina helicina is impacted by ocean acidification, the shells form suffers from dissolution. This is represented in an abstracted form through the shell breaking off into strands, appearing as if the shell is breaking off into strands, appearing as if the shell is breaking off into strands, appearing as if the shell is breaking off into strands.

Pteropod Shell Captured During Dissolution
Impacted By Ocean Acidification
Frame 50
Influences On Form: Ocean Current & Gravity

Final Output Two Frame 50

As the pteropod shell based on limacina helicina is impacted by ocean acidification, the shells form suffers from dissolution. This is represented in an abstracted form through the shell breaking off into strands, appearing as if the shell is breaking off into strands, appearing as if the shell is breaking off into strands.

Figure 144. Close up of contextual exhibition of experiments 16 – 30, final output one frame 50 and 100 and final output two frame 50 and 100.

Figure 146. Contextual exhibition with general audience examining experiments 16 – 30, final output one frame 50 and 100 and final output two frame 50 and 100.

Figure 147. Close up examination of final output two frame 50.

Figure 148. Close up of examination of final output one frame 50.

Figure 149. Inquisitive examination of final output one frame 50.

Figure 150. Second contextual exhibition photograph of experiments 16 – 30, final output one frame 50 and 100 and final output two frame 50 and 100.

Figure 151. Close up examination of experiment 28 3D prints.

EXPERT OPINION

The intention for gaining the opinion of an expert, is to discuss and examine the objects. Observing whether or not they have achieved the intended response and elicit engagement and discussion of the information that is attempted in being portrayed. For this expert opinion, the design experiment and designed output section of the research portfolio was presented to an expert within the area of biological sciences. This feedback is valuable in reinforcing the potential application for these objects and is further reflected on in the Chapter Six: Discussion and Conclusion.

“Having three-dimensional visual representations, specifically for shells, is quite valuable. People’s brains work in ways where understanding something can be helped by seeing it and turning it around. An object may have greater worth and value in what it is communicating than trying to describe this in words or a flat drawing which can be misrepresenting.

The same way it is hard for people to visualise and understand what scientific results mean in words can also be said about scientists. A visual representation could be a cool tool to help more deeply understand the information they are talking about if they can see it. Even when the information is understood, seeing how things work in three-dimensions is helpful. Even better if it has a tangible aspect

An interesting thing to do with this work would be to see how a random person off the street with no prior knowledge to this project would react to these models.”

NICOLE PHILLIPS

Senior Lecturer at Victoria University of Wellington, School of Biological Sciences

■ Pteropod Shell
■ Impacted By Ocean Acidification Dissolution
■ Frame 100
■ Influences On Form: Ocean Current & Gravity

DISCUSSION AND CONCLUSION

Left:

Figure 152. Encapsulated 3D printed model.

OVERVIEW

This research sought to answer the question: how might the context of time and environment be modelled efficiently in order to communicate a narrative through 3D printing?

This research experienced a pivotal turning point after experiment 18 when the decision to encapsulate objects in VeroClear was made. This brought to light several opportunities and possibilities including a level of precision and vibrancy that was visible in the models. Through celebrating these opportunities, it enhanced the model's appearance by exploiting the ability to print at an extremely refined level. This led to a deeper engagement of the models as they were visually stunning and intriguing.

This research aimed to complete four research criteria, as outlined, and discussed below.

1. Showcase the creative opportunities for full colour multi-material printing through the voxel method.

The voxel printing method was initially used to combine Vero and Agilus materials to print shell models during the early stages of this

research but it provided no physical material benefits. Through using the combination of these materials and printing in a loose format, the high-resolution capabilities were not exploited. This was a direct result of the transition from a screen-based render to a physical 3D print becoming impacted by physical limitations imposed on the model (such as gravity and durability) that ultimately resulted in broken and torn models.

However, after experiment 18 when the models were encapsulated in VeroClear, the high-resolution capabilities that only printing through a voxel-based method can provide were now seen. The methodological choice to encapsulate the models proved to be a reliable and appropriate area for progression and development of this research towards the final output. It offered the ability to print incredibly fine models, developing an aesthetic in which the depth of colour of the model and materials were exposed. Material mixing was also able to be seen within the droplets of digital materials, especially when the encapsulated models were sectioned into separate prints.

2. Demonstrate through a procedural workflow that applying external forces influence a system for the creation of forms that are not known or designed.

This research recognised the limited and analogue results of traditional solid and surface 3D modelling that can be conducted in software such as Solidworks.

Entering this research, having limited knowledge towards Houdini and consequently, its generative possibilities were disconcerting. However, time was set aside to learn aspects of this program and the combination of the software Houdini and Grasshopper were utilised to create a procedural workflow and recyclable system. This offered flexible experimentation and levels of complexity unachievable through normal CAD software, which proved to be advantageous in the implementation of the procedural workflow. Within the digital environment of Houdini, dynamic properties were applied, including the implementation and application of forces acting on the model such as gravity and wind force as two examples. This resulted in practical and experimental methods to test theories and develop an understanding of how procedural workflows can generate forms along a

morphological timeline. Within Houdini, there was a vast range of exploration towards achieving complex results and the ability to manipulate outcomes efficiently. Exploring the complexity of these controls revealed a new type of workflow in which the designer no longer has full control over a precise final output, but rather is an influencer on a system, transforming Computer Aided Design to Computational Aided Design.

3. Explore the dialogue between translating an object from a screen-based visualisation to a 3D printed tangible object through extracting models from a pivotal point along the morphological timeline.

Connecting with physical objects is a natural instinct, and through touch and manipulation we can observe an object's material characteristics through different perspectives. The tactile characteristics of the final output allow a means of further interpretation by the audience beyond what is created and viewed on screen (Bader et al., 2018). The designed outputs have greater worth and value is greater for communication in contrast to words or a 2D image. Although the possible outputs of the morphological timeline are viewed on screen and establish an understanding, it is not until the object is

manifested into the tangible dimension that you can clearly see what is happening.

Through a selective and defined printing methodology as a result of the morphological timeline acting as a pre-print vision, the investment towards a physical 3D print is more valuable. Careful time and consideration was taken towards selecting which frame along the timeline to print. It can be considered an investment towards understanding where along the timeline there is a pivotal point and would encourage engagement with the tangible object was important.

4. Be contextualised towards communicating scientific information, using a visual and tangible object as a narrative.

The model output demonstrates that there is opportunity and possibility to communicate scientific information through a visual and tangible medium from a timeline of undetermined forms influenced by determined forces. This research offers an abstract form representation; however there is opportunity to create scientifically accurate manifestations of information through static preservation from the procedural timeline.

Through the tangible nature of the objects produced, there becomes an emotional desire to the object which does not exist when the object merely exists on screen. This emotional connection has the capability to make this information more impactful and encourage action.

The procedural timeline from the influences (for example ocean acidification and the journey of degradation) acting on the object also offers a narrative for the objects that is missing to go along with this information, reinforcing the story and emotional desire.

Through preservation of static instances in the timeline of the procedural workflow by 3D printing the models, the stages of degradation of the shell may be preserved in what could be considered as a fossil from a future state.

LIMITATIONS

Earthquake Strengthening at Te Aro Campus

This research suffered limitations that were out of control of the author. Earthquake strengthening at Victoria University's Te Aro campus was conducted from November until March, halting progress by making specialist hardware (J 750) unavailable.

Covid-19

During the course of this research, New Zealand alongside the rest of the world was impacted by the Covid-19 pandemic during March and April with New Zealand entering level 4 lockdown. For six weeks, a transition to working both digitally and remotely was necessary. As a result, specialist hardware (J 750) was once again unavailable, and specialist software (Houdini) was limited in its capability to achieve results through remote access. During this time, this research had to adapt to a completely digital workflow, a transition that was difficult to become accustomed to as the rest of the world followed the same steps, putting pressure on the capabilities of remote accessing software.

Adoption of new software

Initially, this research was limited by the process of adopting new software. At the

beginning of this research the knowledge towards Houdini was extremely limited. However, now, a substantial amount of knowledge has been acquired. Although only the surface has been scratched, there is a general understanding towards the types of nodes, the process to achieving a desired effect and understanding when and why there is a problem. Applying these acquired skills enabled me to nudge Houdini towards generation of form that reflected the optimal art direction. The capabilities of Houdini are unlimited, the main limitation is the user's knowledge and the capability of the node network that is built by the designer.

Grab CAD Print

Grab CAD Print was used as the software for final exportation of files in a .gcvf format. The low-resolution quality of this software resulted in complete fragmentation within object previews and unidentifiable boundaries of objects.

Material Assignment

When applying digital material assignments through colour, the colour assigned was grey for Vero Clear/Agilus30Clr. This caused limitations when trying to specifically assign Agilus30Clr within the model as black and

white pixels mixed together to produce grey pixels. This issue was however resolved by substituting a different colour to act as Agilus30Clr but also meant the amount of materials available went down to five. After the decision to encapsulate the models was made, this was no longer an issue as the models were surrounded by grey to represent Vero Clear.

Physical limitations and durability

There were physical limitations towards the 3D printed objects as a result of gravity, their susceptibility to degradation and material weakness that caused models to dry out, break and split. The methodological choice to encase the objects in resin (Vero Clear) was a response to these physical limitations and constraints as they were impacting the visual impact, effectiveness, and beauty of the tangible model.

OPPORTUNITIES

Houdini

Although the lack of knowledge within Houdini can be seen as a limitation, it can also be seen as an opportunity, to explore the procedural process without prior knowledge limiting the scope of the approach.

Precedents

Branching away from previous and similar works such as 'The Style Machine', this workflow approaches creating undetermined forms in a dynamic and unpredictable way. Rather than the designer finding their style through altering parameters, this workflow offers the generation of form in an unpredictable and unknown way, with the design merely influencing the system towards an optimal output, applying influences such as gravity into the environment. The opportunity to encapsulate and fossilise the objects allowed this work to be more durable than the Blashcka glass models. Although they are precise and beautiful, they do not offer durability and the

ability for the object to be passed around to people of all ages, nor did it maintain its original beauty and colour vibrancy.

Investing in the tangible dimension

Investing in the tangible dimension was a methodological choice that changed the perspective towards how the model was viewed. A procedural workflow offered an undetermined amount of outcomes to be explored efficiently, generating a variety of forms that are not known or cannot be perceived that could be rendered and viewed as pre-print visions before investing the tangible dimension. It is not until the model is printed that you get a full understanding of the size of the object or an understanding towards the details hidden inside the form. The 3D printed objects possess a much greater opportunity to be used as a tool to assist people in assimilating, comprehending and communicating visual scientific information.

Durability

Although the durability of the digital materials in early experiments proved to be limited, however, through reassessing the printing possibilities it was seen as an opportunity to approach the physical form encased within (Vero Clear) resin. Encasing the model in resin revealed details that meant manifestation from a screen-based image into a physical form retained all available data. It offered a higher level of detail, colour vibrancy and resolution. The thickness of the prints and depth of colour were much more obvious.

Support Material

Through the voxel printing method, the support material (SUP 706) did not have any Vero Clear latticed through it, making the support material removal process much easier and quicker as a result of its solubility.

APPLICATION

The methodologies proposed by this research provide great value within the area of scientific visual communication. Data is communicated and exhibited in a manner which is alternative to the many existing means of communicating scientific research. Rather than providing data and examples in the form of purposefully created concrete examples, a procedural workflow may instead be used to showcase information in a much larger variety of cases. This more efficiently demonstrates the effect that individual parameters have on resulting outcomes.

Olson (2015) stated that an endless swarm of facts unaccompanied by visual counterparts or narrative are unable to resonate with those in the general public. Without a linear timeline or story to accompany an issue, such as environmental changes, the information is neither relatable nor engaging. This research showcases that through the use of a procedural workflow and 3D printing there is opportunity to fulfil this crucial element of communication, achieving engagement as well as emotional connection.

For example, in the context of ocean acidification, the journey of the degradation of a shell may be portrayed through a procedural workflow, transforming what may once have been a vibrant and flourishing specimen, into what may become a dull and blemished sample. Through preservation of static instances in the timeline through voxel printing the extracted models, the model's snapshots of degradation may be preserved in what could be considered as a fossil from a future state.

The physical nature of the preservation of these models provides benefits in not only the general public, but also for those conducting scientific research, the models aim to enable them to gain a new perspective. Additionally, offering an understandable narrative for those with limited knowledge in an identified area of research.

The accompanying narrative encourages an emotional connection and perspective, elicited from the fact that these modelled objects are based on shells that are not commonly perceived nor do we have a common interaction with. The 3D printing of these models enables interaction with the typically untouchable, visually, and physically displaying the narrative of a future state that may be avoided.

FUTURE RESEARCH

Future studies have the opportunity to improve the efficiency and accuracy of this system. While the output will remain inherently abstract due to its form not yet having a concrete existence, the inclusion of real-world data and variables could be considered. The use of accurate data and variables within a procedural system could be applied to explore environmental changes to provide a platform for experimentation without consequences enforced by physical restraints. For example, in the context of ocean acidification variables such as ocean pH and temperature could be an influencing variable. Furthermore, geographical conditions could be taken into consideration as different climatic conditions would produce different variables to act as influences.

There is also an opportunity to improve the efficiency of the method for influencing a procedural system. Possible long-term applications could come from embracing artificial intelligence and machine learning to add complexity. The addition of accurate data informed by environmental variables in combination with these technologies could help to converge and optimise parameters for the procedural system. Ultimately, optimising the speed and efficiency that the system could generate alternate forms from influences.

How might the context of time and environment be modelled efficiently in order to communicate a narrative through 3D printing?

CONCLUSION

This research was guided by the question: how might the context of time and environment be modelled efficiently in order to communicate a narrative through 3D printing?

Through a procedural system that permits an infinitely large number of possible products, implementing and influencing the system to guide the direction of the system through parameter manipulation, without having a precise vision for the result, creates a generated change in form. The combination of the software Grasshopper and Houdini efficiently offers this parameter manipulation, in which the context of time and environment are the manipulated influences to create a morphological timeline visualised through screen-based renders. The use of the software Houdini allows for the most highly computational results and complexity in producing models with detailed amounts of fragility.

The extraction of models along this timeline offered more value towards the 3D printed object. It was a selective and defined decision to extract the model at that particular point along the timeline. Through the designed outputs, extracting the future fossils at two defined points along the morphological timeline offered the opportunity to physically see how changing the influences through the context of time and environment had towards communicating the narrative of ocean acidification through 3D printing in a manner that encourages engagement and inquisition from a general audience.

The use of the voxel-based printing method that translated the rendered visualisations into tangible dimension through high-resolution, colour vibrancy, and encapsulation explored the dialogue between digital and physical. Utilising the fragility of the real world is what encouraged the decision to encapsulate models, turning them into fossils so that all of their data may be preserved and viewed, and the object is durable for handling.

This research sought to answer the desire to communicate information surrounding the unknown future of our world. It did so through a tangible medium with a 3D printed object, representing fossils from a future that is unknown. The fossils offer people of all ages the chance to view information in a spatial way as a tool to assist people in assimilating, comprehending, and communicating scientific information. Through their colour vibrancy, engagement is achieved, and curiosity is piqued to enquire more towards the accompanying narrative.

To advance this research, future studies have the opportunity to improve the efficiency and accuracy of this system, moving away from an abstract perspective and towards a realistic perspective informed by inputted data and variables. The option to improve the efficiency of those influencing the procedural system could also be explored. Possible long-term applications could come from embracing artificial intelligence and machine learning ability to add complexity and real time data, optimising the system to engage with the physical world.

LIST OF FIGURES

All figures not cited here are produced by the author.

Figure 12. Hypothetical snail forms drawn from cross sections made by the computer method. From “Computer as aid in describing form in gastropod shells”, by D. Raup, 1962, *American Association for the Advancement of Science*, 138, p.151.

Figure 13. The rise in atmospheric carbon dioxide dissolves shelled sea animals. From *National Geographic image collection*, by D. Liittschwager, n.d.

Figure 14. Robinson, T & Furneaux, W. (2019). A selection of 3D printed prosthetic eyes at varying scales and colours. In *Voxel Printing using Procedural Art-Directable Technologies. Proceedings of the ACM Siggraph 2019 international Poster conference on computer graphics and interactive techniques. ACM DL*. Reprinted with permission

Figure 15. Robinson, T & Furneaux, W. (2019). a) The digital model is sampled by a slicing grid. b) Slice 650 of 992 images generated for a 2:1 eyeball. c) Visualisation of the voxels in a small section of the iris. [Photograph]. In *Voxel Printing using Procedural Art-Directable Technologies. Proceedings of the ACM Siggraph 2019 international Poster conference on computer graphics and interactive techniques. ACM DL*.

Figure 16. Hodges, G. (2016). *Polybranchia prasinus*. [Photograph]. Cornell Collection of Blaschka Invertebrate Models: United States. Retrieved from <https://digital.library.cornell.edu/catalog/ss:20108137>. Reprinted with permission.

Figure 17. Hone, N. (2018). *Haven Flower*. Retrieved from *Nicole Hone*, by Nicole Hone, 2018, Retrieved 2020, July 2, from www.nicolehone.com/hydrophytes. Reprinted with permission

Figure 18 Stevens, R., & Guy, B. (2015). *Lissom*. [Multi-material3D print]. Retrieved from <https://made.ac.nz/project/computer-generated-objects-lissom/>. Reprinted with permission.

Figure 19 Jack, B. D., & Guy, B. (2017). The Style Machine: Digital Tactility Through Generative Collaboration. [Screenshot] In *20th Generative Art Conference GA2017*, 12. Reprinted with permission.

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