FROM LINE TO LOOP

A circular 3D printing initiative for upcycling commercial fishing plastics

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By Matthew O'Hagan
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ABSTRACT

The current linear use of plastic products follows a take, make and waste process. Commonly used by large scale industries, including the commercial fishing industry, this process results in approximately 8 million tonnes of plastic entering the ocean every year. While the fishing industry supplies livelihoods, a valuable food source and financial capital to millions of people worldwide, it's also a significant contributor to the ocean plastics crisis. Without effective recycling schemes, an estimated 640,000 tonnes of plastic fishing gear is abandoned, lost or discarded within the ocean every year. New Zealand is no exception to this problem, as China's waste import ban, as well as a lack of local recycling infrastructures, has resulted in the country's commercial fishing gear polluting local coastlines as well as islands in the pacific. With the only other option for the plastic fishing gear being landfill, there is a critical need for circular initiatives that upcycle used plastic fishing gear locally into eco-innovative designs.

This research examines the issue by investigating how used buoys, aquaculture ropes and fishing nets from New Zealand's fishing company 'Sanford' may

be upcycled into eco-innovative designs through distributed manufacturing technologies. It introduces the idea of the circular economy, where plastic fishing gear can be reused within a technical cycle and explores how 3D printing could be part of the solution as it provides local initiatives, low material and energy usage and customisation. Overall, the research follows the research through design based on design criteria approach. Where materials, designs and systems are created under the refined research criteria, to ensure the plastic fishing gear samples are upcycled effectively into eco-innovative designs through 3D printing.

The tangible outputs of this research demonstrate how a circular upcycling system that uses distributed manufacturing technologies can create eco-innovative designs and provide a responsible disposal scheme for plastic fishing gear. It provides a new and more sustainable waste management scheme that could be applied to a range of plastic waste streams and diverts materials from entering the environment by continuously reusing them within the economy.

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Figure 1. Makara beach, ocean plastics

INTRODUCTION

There are not many materials like plastic. It's rapid adoption over the past century into almost every aspect of our lives, has made it difficult to comprehend a world without it. Plastics glorified attributes, including affordability and manipulability, makes it a revolutionary material within countless industries, and an obvious choice for a variety of different applications. However, the global demand for plastic has exceeded production rates as it is a finite source and the lack of sustainable disposal options has left us with a tremendous plastic waste problem that is negatively affecting our marine environment (Figure 1).

Amongst the millions of ocean plastics found within the marine environment, lies abandoned, lost or discarded plastic fishing gear. Plastic fishing gear is known to be one of the most dangerous forms of plastic pollution in the ocean today, as it can lacerate, drown and suffocate a variety of marine species (LI, Tse and Fok, 2016) With a lack of sustainable recycling options for existing synthetic gear and low chances in the commercial fishing industry adopting biodegradable gear (Kim, Lim, An and Suuronen, 2016), this problem will undoubtedly continue. Therefore there is a crucial need for more sustainable disposal options that reuse plastic fishing gear within a circular system.

Within New Zealand's own substantial fishing culture also lies this severe plastic problem. With China's recent waste importing ban as well as a lack of localised recycling infrastructure, New Zealand's commercial fishing industry has no other option than disposing of their plastic fishing gear

in landfills. Therefore the need for new distributed recycling or more accurately, upcycling initiatives are of the utmost importance to solve this problem locally. Distributed manufacturing technologies such as 3D printing combined with all in one shredding and extruding technologies have proven to recycle plastic waste into new designs successfully. However, little research has investigated how distributed manufacturing technologies can upcycle a range of plastic fishing gear into eco-innovative designs. With advancements in 3D printing and all in one shredding and extruding technologies, upcycling plastic fishing gear locally is becoming more feasible and the adoption of a circular system that continuously reuses waste materials in a closed-loop cycle is becoming more realistic. The potential of distributed upcycling initiatives could question our current recycling practices, reduce energy and material consumption and mitigate plastic waste from entering the marine environment.

This research investigates and demonstrates how distributed manufacturing technologies can provide a sustainable upcycling scheme for plastic fishing gear and create a vast range of different designs. It aims to promote the use of distributed manufacturing technologies to locally mitigate plastic waste from entering the environment, develop eco-innovative designs and keep materials within use through circular upcycling systems.

This influences the research question 'How can plastic fishing gear be upcycled through distributed manufacturing technologies to mitigate commercial fishing waste and create eco-innovative designs?'

Chapter 1:
METHODOLOGY

RESEARCH OVERVIEW

Aims & Objectives

	AIMS	OBJECTIVES
STAGE 1	01 - To identify and examine how distributed manufacturing technologies can upcycle plastic fishing gear to create eco-innovative designs and a circular waste scheme for the commercial fishing industry.	<ul style="list-style-type: none">- Identify how distributed manufacturing technologies can enforce circular systems, sustainable designs and reduce plastic waste.- Distinguish existing approaches and initiatives that successfully upcycle plastic fishing gear into new designs.- Investigate the largest plastic waste streams and current waste management options within New Zealand’s commercial fishing industry.
STAGE 2	02 - To explore, analyse and exemplify how distributed manufacturing technologies can be used to upcycle a range of plastic fishing gear through a selection of material and eco-innovative design outputs.	<ul style="list-style-type: none">- Process, formulate and experiment with a variety of plastic fishing gear through distributed manufacturing technologies to identify eco-innovative design directions.- Develop and prototype conceptual eco-innovative designs through distributed manufacturing technologies to exemplify circular upcycling initiatives for plastic fishing gear.

Figure 2. Aims & Objectives

Methodology

Aim 1: To identify and examine how distributed manufacturing technologies can upcycle plastic fishing gear to create eco-innovative designs and a circular waste scheme for the commercial fishing industry.

To successfully fulfil the first aim of this project, this research begins by obtaining qualitative information through a ‘research for design’ method. Research for design situates this project within its respected field by gathering relevant literature, objects and data that can be applied where necessary for the design project to succeed (Downton, 2003). Primarily, the preliminary research consists of reviewing suitable literature on the plastic fishing gear waste crisis, upcycling, eco-innovation and distributed manufacturing. Additionally, existing approaches to recycling plastic fishing gear are analysed and discussed through literature and photographs. The initial research undertaken within this stage of the project is integrated within the background research through a contextual evaluation, literature review and precedent analysis to create a cohesive and robust structure for

the remaining research to build upon. To understand the severity of the commercial fishing industry’s plastic waste stream, field research is undertaken at Sanford’s aquaculture facilities in Havelock and fishing operations in Timaru. Observational studies and photographs are the primary sources of documenting the information on-site and are used to distinguish the types of plastic waste used within this research. Furthermore, initial design ideas informed through field research on upcycling plastic fishing gear into eco-innovative designs are recorded and used as the preliminary design ideas for this project. Overall the initial information acquired throughout the first stage of this research contributes to finding successful and feasible design outcomes (Frankel & Racine, 2010).

Aim 2: To explore, analyse and exemplify how distributed manufacturing technologies can be used to upcycle a range of plastic fishing gear through a selection of material and eco-innovative design outputs.

The second aim of this research project is mainly situated around formulating and producing 3D printing filament out of plastic fishing gear and upcycling it into eco-innovative designs. The primary research method used in this stage of the project is ‘research through design’ as it represents the entirety of the design process. Hanington and Martin (2012) propose that research through design consists of the designer reframing a problem to find a solution that is created through an extensive design process of sketching, modelling, prototyping and documenting. Within this research, the designing process is recorded and communicated through procedures, experiments, drawings, computer-aided design models, renders and prototypes. To ensure the research follows a coherent structure and objective throughout this broad stage of the project, ‘a postgraduate thesis model for research through design based on design criteria’ suggested by Rodríguez Ramírez (2017)

will be the fundamental research method used in this stage. As opposed to ‘research through design’, this method is based on sets of criteria that evolve throughout the research according to relevant findings (Rodríguez Ramírez, 2017). After the qualitative research within the first stage, an initial research criterion is established as a series of starting points for processing and experimenting with materials as well as developing the initial design ideas (Rodríguez Ramírez, 2017). The set of criteria are revisited and revised throughout the design process into a cohesive series of resolved points that are used to assess final material formulations, designs and scenarios. Overall, the action and reflection approach taken throughout this stage of the research creates new design knowledge that can assist future design projects. (Frankel & Racine, 2010).

Due to novel material formulations and 3D printing characteristics, this research will implement an artifact analysis proposed by Janlert and Stolterman (2010) that focuses on the properties and qualities of objects. Fundamentally used within the 3D printing testing phase and the design experimentation phase of this research, the artifact analysis aids in justifying what material formulations are developed and how well each material 3D

prints within a series of different abstract forms and conceptual designs. Janlert and Stolterman (2010) suggest that a focus on artifacts establishes an understanding of its properties, qualities and capabilities. Therefore, a coherent understanding of the overall 3D-printability of the materials is developed, and refined designs can be created.

Chapter 2:
BACKGROUND RESEARCH

CONTEXTUAL EVALUATION

Plastic

Among the many materials used within the production of goods today, few are recognised to be as successful as plastic. Developed in the early 20th century, plastics have grown to be used in our everyday lives through simple, complicated and sophisticated products (Chalmin, 2019). This rapid adoption of plastics is due to the synthetic organic polymers that plastics are made of, that allow it to be manipulated into cheap, lightweight, robust, durable and corrosion-resistant designs that suit a variety of applications (Li, Tse and Fok, 2016). Unfortunately, over the last century, our reliance on plastics has increased (Elvin, 2015), resulting in intense forms of consumption and a lack of responsible disposal options, leading to a severe waste problem that is now affecting our oceans (Cózar et al., 2014).

Today there is an estimated 150 million metric tonnes of plastic in our oceans (Fitterling, 2019), with an additional 6 to 12 million being added every year (Vince and Hardesty, 2017). Li, Tse and Fok (2016) propose that these plastics do break down through ultraviolet radiation or strong ocean swells and can slowly degrade within the environment, however, due to plastics high durability, this degrading process can take hundreds or even thousands of

years (Cózar et al., 2014). This long deteriorating process suggests that every piece of plastic that has entered the ocean since the beginning of the plastic age remains there to this day (Andrady, 2015).

The plastic debris commonly found within the marine environment are large objects, defined as macro plastics and tiny invisible particles often interpreted as microplastics (Andrady, 2015). Macro plastics are commonly larger than 5mm in size and originate from post-use consumer plastics on land and fishing activities at sea (Monteiro, Ivar do Sul and Costa, 2018). Whereas, microplastics are smaller than 5mm and regularly originate from the fragmentation of macro plastics within the environment, as well as cosmetic scrubbers and abrasives (Lee et al., 2013). Both macro and microplastics within the ocean pose a threat to marine fauna, the environment, human health and commercial operations (Harse, 2011). Therefore, this is a significant crisis that must be addressed, as plastic pollution is classified today as the most widespread problem affecting the marine environment (International Union for Conservation of Nature, 2018).

Fishing Gear

Synthetic

Synthetic fibres, namely plastics, represented a technological advancement within the fishing and aquaculture industry, throughout the 20th century (Lebreton et al., 2018). Due to population growth and a desire for seafood throughout society, commercial and artisanal fishers transitioned from organic fishing gear to more durable and long-lasting synthetic gear, to keep up with the increasing demand (Stelfox, Hudgins and Sweet, 2016). As a result, catching and farming marine species became more persistent (Lebreton et al., 2018), and the oceans were introduced to a global fleet of fishers using plastics (Andrady, 2015).

Although the transition to synthetic fishing gear benefited fisheries, it did not benefit the ocean. An estimated 640,000 tonnes of abandoned, lost or otherwise discarded fishing gear, (from here on out it will be referred to as ALDFG), enters the ocean every year (Li et al., 2016). ALDFG is considered to be responsible for 10% of the total plastic pollution within our oceans today (Stelfox et al., 2016), and can be found within the most remote marine environments around the world (Vince and Hardesty, 2017). An example of this can be seen in (Figure 3), where ALDFG was found on an isolated beach

in New Zealand. Another wider example is the Great Pacific Garbage Patch, located between Hawaii and California (Lebreton et al., 2018). Within the garbage patch is an estimated 79 thousand tonnes of plastic debris, and plastic fishing gear is accountable for 46% of this load (Lebreton et al., 2018), which highlights the magnitude of the ALDFG problem.

The increase in ALDFG within the marine environment creates a growing concern as opposed to other plastic debris because of its ability to continue catching fish even after they are no longer being controlled; this is characterised as ghost fishing (Link, Segal and Casarini, 2019). Most ALDFG are made from synthetic plastics, including polyethylene, polypropylene and nylon (Stelfox et al., 2016). These durable plastics are commonly used for their ability to withstand the marine environment (Lebreton et al., 2018); however, this also means they can drown, suffocate and lacerate marine species until they can no longer fend for themselves (Li et al., 2016). As a result, the capture of different marine fauna attracts other species, which, in turn, become entangled too and repeat the cycle (Link et al., 2019).

Figure 3. ALDFG found on New Zealand's coastline

Biodegradable

With many marine species suggested to be entangled by nets, ropes and monofilaments (Harse, 2011), some form of intervention is needed to develop a solution to this problem. Fortunately, advancements in biodegradable fishing gear may offer a solution. Bilkovic, Havens, Stanhope and Angstadt (2012) suggest that well designed biodegradable panels for crab pots can reduce ghost fishing and provide a productive habitat if lost or abandoned. However, Kim, Kim, Lim, An and Suuronen (2016) acknowledge that while biodegradable gear can contribute to the reduction in ghost fishing and plastic pollution, it is more expensive to produce than synthetic gear, it can degrade before use and is commonly weaker. Therefore, it will not

be adopted by fisheries unless another economic benefit is offered by the product. With low chances in the fishing industry adopting biodegradable gear until it performs as well or better than synthetic gear, the current ALDFG problem will continue. As a result the fishing industry may discover negative implications within their work as ALDFG can affect commercial operations through economic losses (Richardson, Gunn, Wilcox and Hardesty, 2018), as well as repair and replacement costs, as it is known to damage commercial fishing vessels (Harse, 2011). The commercial fishing industry will be discussed further in the next section.

Commercial Fishing Industry

Global Context

Globally, the fishing industry contributes immensely throughout societies by providing livelihoods, a plentiful food source and financial capital (Food and Agriculture Organisation of the United Nations, 2018). It plays a vital role in the economy. In 2018, 59.6 million people earned their income through the fishing and aquaculture industry (FAO, 2018), and an additional 200 million jobs are estimated to be connected to the fishing sector (Kituyi and Thomson, 2018). The fishing industry also supplies a critical food source to approximately 3 billion people around the world, who rely on fish as their primary source of protein (Petrossian, 2019). However, due to mismanagement in our fishing activities and the over-exploitation of the global fish stocks throughout the last century (Andrady, 2015), the prospect of providing this food source is depleting. The synthetic and technologically advanced fishing gear used in fishing operations today is a leading cause of overfishing. It is estimated

that over 70% of the global fish stocks have been exploited by the use of this advanced gear (Petrossian, 2019). The increase in using synthetic fishing gear has resulted in an increase in ALDFG that negatively impacts fisheries through the depletion of economic and ecological resources (Good, June, Ethnier and Broadhurst, 2010). Suppose the reduction in fisheries resources continues along with its current status. In that case, it is estimated that by 2050 global fish stocks will collapse and the fishing industry will no longer have anything to catch (Petrossian, 2019). Therefore, a shift in sustainable fishing operations, as well as a responsible recycling scheme for plastic fishing gear, must be adopted globally to reverse the damage that has been done. Without these changes, in the next 30 years, there may be more plastic in the ocean than fish (Wearden, 2016).

Figure 4. Henderson Island Beach Clean-up (McGregor, 2019)

New Zealand Context

New Zealand is the largest oceanic based country within the Pacific Ocean, with a sea area 15 times larger than its land area (Gordon, Beaumont, MacDiarmid, Robertson and Ahyong, 2010). Its large marine environment is home to a wide variety of species as well as a substantial fishing culture (Walrond, 2005). Due to the nation's large exclusive economic zone of 4.2 million km² (Gordon et al., 2010), aquaculture and fishing have become rapidly commercial industries that are known to contribute significantly to the country's economy (Walrond, 2006). It is estimated that New Zealand's fishing industry employs over 13,000 people (Seafood New Zealand, 2019), and generates approximately \$1.8 billion in exported goods (Seafood New Zealand, 2020). Which exemplifies how significant the ocean and the fishing industry is to the country's community as well as its economy.

Unfortunately, while New Zealand's marine environment supports New Zealanders immensely and is a unique habitat for a diverse range of species (Ministry for the Environment, 2019), it is no stranger to plastic pollution. Reports going as far back as 1977, showed a considerable amount of plastic pellets washed up on New Zealand's city beaches (Gregory, 2010). This report represents the fact that New Zealand has had a plastic problem for decades

and it is not getting any better, as the Ministry for the Environment (2019), claims that more than 60% of beach litter found on New Zealand's coastlines is plastic. Furthermore, plastic fishing gear originating from New Zealand's own fishing companies has been found to pollute New Zealand's coastlines as well as remote islands within the Pacific Ocean. On a recent exhibition to a remote island in the Pacific, known as Henderson Island, 6 tonnes of plastic waste was collected and organised into piles of different plastic waste (Vance, 2019). It is estimated that 60% of the waste originated from commercial fishing operations and amongst the piles of discarded buoys, ropes and nets, as seen in figure 4, were plastic fishing bins and crates belonging to New Zealand's own fishing companies, as seen in figure 5 (Vance, 2019). Similarly, a recent clean-up collected a total of 16.6 metric tonnes of rubbish from Stewart Island (Fisheries Inshore New Zealand, 2019), the bulk of which was plastic fishing gear originating from New Zealand's own major fishing companies (Sanford, 2018). With New Zealand's marine environment being substantially significant for the country's economy and biodiversity, a sustainable recycling scheme for the commercial fishing industry must be implemented to maintain ecological and economic resources, and mitigate ALDFG from entering the marine environment.

Figure 5. Stolen From Talley's (McGregor, 2019)

Recycling

Global Context

Recycling is a significant waste management method of reusing materials to offer economic benefits, conserve the use of virgin resources and to reduce the amount of waste that is destined for landfill or incineration (Richman, 2014). Despite the benefits, global recycling rates are relatively minimal. Countries including Germany, Austria, South Korea and Wales have some of the best recycling rates in the world and are known to recycle between 52% to 56% of their municipal plastic waste (Gray, 2017). However, the potential for plastic recycling is significantly unexploited globally. Milios, Davani and Yu (2018) report that within the European Union, 70% of plastic waste goes to landfill and incineration for energy, while only 30% gets recycled. Although seen as an unbalanced percentage, the European Union should not be discredited for their efforts as O'Neill (2017) proclaims that China recycles approximately 22% of their plastic waste, while the United States recycles around 9%. While the statistics on recycling rates globally may not be precise, as there's a lot of inconsistency across reports (O'Neill,

2017), it would be inaccurate to claim that the global recycling scheme for plastics is sustainable, especially in terms of plastic fishing gear. The recycling schemes for plastic fishing gear are still in their early stages, as only a few companies are known to have the infrastructure in place, to recycle them at a large scale (Fritts, 2017). One Italian yarn company who does have the technology and resources to recycle plastic fishing gear is Aquafil. They successfully recycle nylon fishing nets into a product they call Econyl that is used in manufacturing to produce sportswear, swimwear and carpets (U.N. Environment, 2018). While this is a tremendous step forward for recycling plastic fishing gear, it is only one company that does not recycle any other plastic fishing gear other than nylon. Without smaller scaled and localised options for recycling different types of plastic fishing gear, we may see an increase in ALDFG within the marine environment. Or as suggested by World Animal Protection Canada (2015), fishing companies will have to pay for their gear to be buried in landfills or stored in costly warehouses.

New Zealand Context

New Zealand's low recycling rates have spoiled their clean and green image, leaving the country with a severe plastic problem. The low recycling rates New Zealand has for plastics could be attributed to low landfill levies (Recycle, n.d.), which allow individuals to dispose of waste at a small price. Additionally, the 2018 national sword policy that stopped New Zealand from sending approximately 15 million kilograms worth of mixed plastics annually to China (Sage, 2018), is another significant cause. Due to the lack of recycling infrastructure and technology throughout the country, over eight councils throughout New Zealand have decided to no longer collect types 3 to 7 plastics (Woolf, 2019), (categories of plastic types can be seen in figure 6). More towns and city districts around New Zealand will undoubtedly follow in their footsteps as the global plastic market change has left councils with no other option than to dispose of plastics labelled 3 to 7 in landfills (Porirua City, 2019). With stockpiles of plastics growing throughout the country, Peace (2018) suggests that New Zealand has now been given an opportunity

to reflect on its recycling schemes and look more into onshore recycling methods. Fortunately, the New Zealand government is currently investing in new localised strategies that help recycle materials through circular systems, with funds raised from more substantial landfill levies that are being implemented throughout the country (Ministry for the Environment, 2019b). One onshore recycling scheme that was recently granted 3 million dollars by the New Zealand government is a new recycling facility by Pact Group (NZ) Ltd, that recycles type 1 plastics into new food packaging (Sage, 2019). Although seen as an achievement, it is only one facility that recycles only one kind of plastic. Therefore, New Zealand must continue investing in more onshore recycling initiatives to manage its broader plastic waste streams (Sage, 2018). In regards to plastic fishing gear, some may be recycled within New Zealand's regulations, including polyethylene buoys (Fisheries Inshore New Zealand, 2019); however, other gear falls into the 3 to 7 plastic categories and will be destined for landfill.

Figure 6. Types of plastic

UPCYCLING

The Linear Economy

The current linear pattern for the production and use of plastics has adverse effects on the natural world and is therefore unsustainable. Most plastics are currently operating within a linear economy, where they are extracted, manufactured, used and disposed of within the environment (Gupta, Thakur and Matharu, 2018). The global extraction rate of materials has tripled between 1970 and 2010, from 22 billion tonnes to 70 billion tonnes (Schandl et al., 2016), and the disposal of plastic waste increased dramatically between 1950 and 2015, from 2 million tonnes to 381 million tonnes (Ritchie, 2018). Unless the current linear life cycle of materials is interrupted, there shall be an increase in both extraction and disposal statistics, and nonrenewable resources will exponentially start to deplete as they are finite sources (Andrady, 2015). While recycling appeared to be the solution for the plastic waste problem, only 9% of all plastic waste produced between 1950 to 2015

has been recycled (Ritchie, 2018). Therefore, McDonough and Braungart (2002) propose that recycling is hardly a finalised solution to the overall problem. In their book 'Cradle to Cradle' McDonough and Braungart (2002) suggest that a large quantity of recycling done today is downcycling, as material qualities are reduced because they are mixed with other types of materials and moulded into a low-quality product. When a low-quality item is produced, the valuable materials that are combined cannot be separated or used again. This procedure then results in the inability to recycle the new product and the continuation of the linear life cycle for the materials, as the fateful trip to landfill has only been delayed (Braungart, McDonough and Bollinger, 2007). It is within this context that a paradigm shift in reusing materials is needed and the concept of upcycling is introduced.

Upcycling and the Circular Economy

Upcycling is a neologism and a form of true recycling, where waste materials or discarded products are converted into new quality designs (Sung, 2015). The concept of upcycling can be defined into two distinctive categories. The first category focuses on recovering materials through developed recycling and remanufacturing technologies to keep their merit (Sung, 2015). While, the second category consists of creating products with high value or quality out of waste material (Sung, 2015). McDonough and Braungart (2002) propose that synthetic materials can be upcycled if they are designed to return to the technical cycle, this would require separating materials to maintain their purity or continuously using hybrid materials within a closed-loop system. The overall goal behind introducing upcycling is to encourage more sustainable forms of recycling that shift away from the current linear economy, to something more circular. The circular economy focuses on eliminating the idea of traditional linear processes of ‘take, make and waste’,

by introducing a circular system that continuously reuses materials within a closed-loop (Ellen Macarthur Foundation, 2017). McDonough and Braungart (2002) define this idea as ‘cradle to cradle’, where materials are thought of as nutrients for one of two cycles, the biological or the technical (as seen in figure 7). The biological cycle focuses on natural or compostable materials that are disposed of at the end of their life cycle within the planet to enrich the biosphere, whereas, the technical cycle encompasses industrial materials that can be disassembled, returned and remanufactured into a new design (McDonough and Braungart, 2002). If a circular economy is adopted, then more products can follow biological and technical cycles that can help in nourishing ecosystems and reduce the amount of waste that is buried, burnt or dumped within the environment as they are continuously reused within a circular system.

Figure 7. Biological and Technical cycles, adapted from Ringmajandus Circular Economy

Upcycling Precedents

Over the last decade, the increase in ALDFG within the marine environment has prompted several companies to adopt and upcycle the discarded materials into new high-quality products. The noho move™ chair, designed by New Zealand based design company 'Formway', tackles the plastic pollution crisis by upcycling discarded fishing nets into an elegant piece of furniture (Figure 8). The chair offers comfort, versatility, style and a better method for furniture design as it focuses on both people and planet (noho, 2020). Likewise, 'Net Effect' is a series of carpet tiles designed by David Oakey Designs out of fibres collected from discarded fishing nets (Figure 9). The carpets are designed to mimic the beauty of the oceans from a topographical view and to raise awareness on pressing environmental issues surrounding

the oceans today. Similarly, the famous shoe brand Adidas collaborated with Parley for the Oceans to produce a prototype shoe made from yarn and filament from plastic fishing nets (Mills, 2015). The design was created to raise awareness of plastic pollution and to encourage others to introduce ocean plastic materials within the production of high-value products (Mills, 2015). All three of these precedents successfully share how ALDFG can be upcycled into new high-quality products. They also all unconventionally move beyond upcycling as they share how innovative paradigms such as alternative productions and collaborations can be introduced to create more sustainable outputs.

Figure 8. noho move™ chair (noho, 2020)

Figure 9. Net Effect Carpet Tile (David Oakey Designs, 2013)

ECO-INNOVATION

Sustainable Design Intervention

"People are becoming more concerned about the repercussions of their everyday behaviour. As materials and resources on our planet become scarcer and the impact of their use becomes more evident. Designers have an obligation to themselves and future generations to introduce sustainability within every aspect of their work (McDermott, 2017)."

Sustainable design is more than just designing with recycled materials or renewable energy. It is a complex topic that has many variables and can mean so many different things, making it difficult to define (Sherin, 2013). The generalised definition is 'design that considers the environmental, economic and social impacts of a product, service or system' (Andrady, 2015). While this is a significant definition as it focuses broadly on the three most important areas of sustainability, it is challenged by many designers and scholars today. Allan (n.d.) suggests that there is no universal definition for sustainable design and that designers should have their own unique perspective, as it provides a diverse range of ideas that respond to complex problems. Moreover, Sherin (2013) indicates that the broad subject of sustainability challenges designers to be more innovative and visionary within their practice, necessarily suggesting they become more adaptable. Similarly, Thorpe (2007) specifies that to design with sustainable intentions, change must be adopted as it can challenge the notion of design and systems.

As the previous paragraph suggests, there is no overall definition or one way to design sustainably as it is a multifaceted subject. Therefore, when attempting to create sustainable products, services or systems, designers need to consider all attributes associated with sustainability by maintaining a holistic perspective. This method is proposed further by Sherin (2017) in 'The Routledge Handbook of Sustainable Design', as a wide range of sustainable attributes that designers should consider. These attributes include consumption, innovation, technology, materials, production, problem-solving, recycling, efficiency, new markets, storytelling, fair trade, strategy, collaboration and entrepreneurship (Sherin, 2017). While not every sustainable attribute listed above will apply to every design project, they are significant starting points and functional areas to focus on if one is to produce sustainable product designs.

Innovation

Innovation through design is a useful tool in creating new ideas, products or services. It commonly follows a solution based methodology that uses everything from imagination, logic and intuition, to develop or explore the best outcomes for complex problems (McKinney, 2017). Used within companies such as Patagonia, innovation can offer thousands of ideas within a short time frame, as it builds on top of existing product ideas or designs to find areas of development and potential (Chouinard, 2016). While the use of innovation throughout companies is often dependent on its ability to increase economic performance, a shift in utilising its capabilities for the environment is growing (Bossle, Dutra, Vieira and Sauvée, 2016). In the early 20th century, innovation was characterised as nothing more than a

proposition for economic expansion (Pacheco, ten Caten, Jung, Ribeiro, Navas and Cruz-Machado, 2017). Today, innovation is used for similar purposes; however, Bossle, Dutra, Vieira and Sauvée (2016) suggest there is a developing shift in innovative thinking. In recent years consumers have started to become more environmentally conscious, and society, as well as governments, are pressuring companies to focus on environmental and social issues linked to the new products they are manufacturing (Bossle et al., 2016). It is within this context that de Jesus and Mendonca (2018) propose a new form of innovation may help us transition to alternative sustainable productions.

Eco-Innovation

Eco-Innovation is a new conceptual idea that includes the conjunction of sustainability and innovation (Bossle et al., 2016). It is typically defined as creating new products, processes, marketing methods or services that reduce environmental impacts (OECD, 2009); however, like sustainable design, eco-innovation definitions vary throughout literature. Reid and Miedzinski (2008) propose it offers novel and competitive products, systems and services that satisfy humans while minimising the use of natural resources and energy. On the other hand, de Jesus and Mendonca (2018) interpret eco-innovation as finding solutions that preserve natural resources, mitigate environmental damage and recover existing materials within the economy for reuse. While these definitions differ in some ways, recurring ideas on combining innovation with ecological considerations can be observed, and are beginning to be implemented within companies today.

With rising numbers of environmentally conscious consumers, Pacheco et al., (2017) propose that companies should look into adopting more eco-innovative practices if they want to survive. One company who is implementing eco-innovative ideas is the young Chilean company Bureo, who started a collection and recycling system they call 'Net Positiva' in 2015 (Ritchies, 2016). 'Net Positiva' works with local fishermen to reduce the increase of ALDFG by providing innovative solutions for their used nets (Ritchie, 2016). The fishing nets are processed through technical recycling systems to create a 100% recyclable material that has end of life solutions

(Bureo, n.d.). The recycled material can then be implemented within production lines by environmentally conscious brands and used to create products such as skateboards and sunglasses (as seen in figure 10) that help in generating positive solutions for ocean plastics (Bureo, n.d.). By combining innovative thinking with environmental considerations, Bureo successfully became an environmentally conscious company that makes a profit through the use of a technical closed-loop system.

The proposal of using technical closed-loop cycles to create eco-innovative products comes from the idea of adjusting industrial systems to mimic ecosystems, as it provides the highest opportunities for sustainability (Carrillo-Hermosilla, Del Río and Könnölä, 2009). Industrial adjustments come down to technical modifications as eco-innovative products usually rely on the development of technologies used within manufacturing (OECD, 2009). This idea is challenged by Reid and Miedzinski (2008) who suggests that rather than developing existing technology to become more sustainable, new technologies that minimise the amount of material used within production should be implemented within industrial systems to provide environmental growth. While new technology is not the only asset that can be changed to create more eco-innovative products (Pacheco et al., 2017), it is an excellent place to start. The use of new technology can influence the adoption of technical closed-loop cycles, which contributes immensely to the overall goal of mitigating environmental problems while continuing to produce innovative products.

Figure 10. Bureo Skateboard and Sunglasses (Bureo, 2014)

DISTRIBUTED MANUFACTURING

"Distributed manufacturing can be defined as the ability to personalise product manufacturing at multiple scales and locations, be it at the point of consumption, sale or within production sites that exploit local resources, exemplified by enhanced user participation across product design, fabrication and supply, and typically enabled by digitalisation and new production technologies (Srai et al., 2016)."

Additive Manufacturing

3D printing is a continuously developing additive manufacturing (from here on out it will be referred to as AM) technology that is a crucial enabler for distributed manufacturing (from here on out it will be referred to as DM). 3D printing technology commonly follows an adding and solidifying approach, where physical artifacts are created layer by layer through the use of digital files (Park, 2017). The use of digitalisation within the manufacturing process offers new opportunities within the production of products that include personalised customisation and localised manufacturing (Despeisse and Ford, 2016). Both of these attributes are more challenging to achieve through traditional manufacturing (Fratila and Rotura, 2017) and are key attributes for DM (Srai et al., 2016).

The idea of customisation within manufacturing is interpreted by Wits, Garcia and Becket (2016) as a vital component for high-value designs, suggesting

that AM is no longer limited to the production of prototypes or low-quality models. This idea is exemplified through its recent adoption by large industries, including the automotive and aerospace industry (Srai et al., 2016), who use 3D printing because of its capability to customise geometries that cannot be achieved through other manufacturing methods (Despeisse and Ford, 2016). The freedom to construct modern geometries gives designers fewer limitations on the shapes they can build, which Fratila and Rotaru (2017) suggest, gives designers more opportunities to produce innovative designs. Improved 3D printing technology that promises more digitally customised, high quality and innovative designs, not only enables itself as a significant technology for DM but also contributes to the development of sustainable manufacturing. This proposition is made evident by Srai et al. (2016), who suggests that 3D printing can promise more sustainable forms of production and material utilisation.

Sustainable Benefits

While no technology is 100% environmentally friendly, areas within the manufacturing process can be addressed to ensure greener practice (Kurman and Lipson, 2013). AM is often considered only to produce rapid prototypes that serve short lifespans (Despeisse and Ford, 2016). However, in comparison to traditional manufacturing methods, AM can have less environmental impacts in terms of its consumption of energy and materials (Agrawal and Vindoh, 2019). The amount of energy that is consumed through AM depends upon multiple factors including the time dependency, geometry dependency and Z height dependency of a model (Agrawal and Vinodh, 2019). To reduce energy consumption within AM, Fratila and Rotaru (2017) suggest that designers be more strategic by optimising geometries to work

with the capabilities of the technology, whereas, Mognol, Lopicart and Perry (2006) propose that production time, as well as support material volume, should be reduced. In regards to material consumption, AM's layer by layer technique only applies the necessary amount of material that is needed, which results in minimal waste (Park, 2017). Additionally, AM can create honeycomb-like structures that result in models not having to be 100% solid, thus creating a model that can reduce the amount of material being used (Barnatt, 2013). Overall AM can offer cleaner and more sustainable forms of manufacturing if its unique capabilities are utilised within the production process to ensure greener practice (Kurman and Lipson, 2013).

Distributed Recycling

"Fused Deposition Modeling (from here on out it will be referred to as FDM) is a material extrusion based AM process in which a product is fabricated by melting polymer based filaments and depositing molten materials on a platform (Kumar and Czekanski, 2018)."

FDM is recognised to finding applications across a variety of disciplines as well as playing a pivotal role in the development towards sustainable manufacturing (Agrawal and Vinodh, 2019), as waste plastic can now be repurposed into new filament for FDM (Despeisse and Ford, 2016). Recent advancements in cheap technological hardware have brought open source waste filament extruding machines including the Recyclebot, the Lyman Filament Extruder and the Filabot more accessible. When these extruders are combined with open-source shredders, they can create an all in one recycling system that can shred, compress, melt, mix and extrude recycled plastic filament for 3D printing (Kreiger, Mulder, Glover and Pearce, 2014). The all in one system creates a distributed recycling scheme that can reduce energy consumption because transportation for recycling is no longer needed as local resources can be locally recycled (Zhong and Pearce, 2018).

One company who successfully recycles local materials into 3D printing filaments for FDM is Fishy Filaments. Located in Cornwall UK, Fishy Filaments repurpose Cornish nylon fishing nets into high quality, engineering-grade 3D printing filament (as seen in figure 11) (FishyFilaments, 2019). While the production of 3D printing filament made from recycled fishing nets is an excellent example of distributed recycling and a revolutionary step towards recycling ALDFG, Fishy Filaments only recover and produce filament made from nylon fishing gear. Other types of plastic fishing gear may be harder to recycle, as impurities within the plastic may alter its recyclability through AM (Despeisse and Ford, 2016). However, the opportunity to experiment in recycling different types of plastic fishing gear through AM locally is significant as the ALDFG crisis is not limited to one material and is a global waste stream that requires innovative recycling initiatives.

Figure 11. 3D printing filament made from recycled nylon fishing nets (Fishy Filaments, 2019)

3D Printed Upcycling

Distributed 3D printing systems can help in transitioning to a circular economy (Zhong and Pearce, 2018). With advancements in all in one shredding and extruding technology allowing the formulation of recycled plastic filament, comes an opportunity to upcycle plastic waste into high quality, eco-innovative products through closed-loop 3D printing systems. 3D printing filament made from waste can produce 3D printed products that can serve a significant purpose. All 3D printed products made can then re-enter the closed-loop 3D printing system at the end of their life by being shredded and extruded again into new recycled filament for future production (Woern, McCaslin, Pringle and Pearce, 2018).

Various companies around the world are now implementing circular 3D printing systems to recover existing materials in the economy, create new eco-innovative products and to protect our environment. Blue Cycle is a new company who has implemented a circular 3D printing system in

Greece. With the use of a robotic 3D printing arm, designed by the New Raw, Blue Cycle has successfully upcycled plastic waste from the fishing and shipping industries into high quality, large scale furniture (as seen in figure 12) (BlueCycle n.d.). Similarly, the famous shoe brand Adidas partnered with Parley to 3D print the midsole of a conceptual shoe out of recycled polyester and fishing nets (Vincent, 2015). The prototype was 3D printed to incentivise the hopeful future for shoe production, where consumers can have customised shoes 3D printed from recycled materials (Vincent, 2015). These projects both show how 3D printed upcycling systems can be implemented for waste streams such as ALDFG and how a selection of different high-quality eco-innovative products can be created through this process. Furthermore, they propose the feasibility of using distributed 3D printing systems to mitigate environmental waste and create closed-loop upcycling schemes for a variety of plastic waste.

Figure 12. 3D printed furniture made from marine plastic waste (BlueCycle, 2020)

Chapter 3:
FIELD RESEARCH

INTRODUCTION TO SANFORD

Sanford is the largest integrated fishing and aquaculture business operating within New Zealand’s exclusive economic zone. With access to 23% of New Zealand’s fishing quota as well as 47 vessels and 210 aquaculture farms (Sanford, n.d.), Sanford has a significant role to play in ensuring New Zealand’s natural resources are respected, preserved and protected. Fortunately, the company has developed a sustainability agenda that focuses on six significant performance-based outcomes, as seen in figure 13. (Sanford, 2018). The approach towards sustainability has been in practice with the intention of differentiating the company from other businesses

within the commercial fishing industry and mitigating environmental risks. As part of the approach, initiatives have been introduced surrounding marine plastic since 2018. These include funding a coastline cleanup with Talley’s, adding a plastic reduction programme, reusing and recycling throughout their operations and aiming to reduce their plastic waste by 70%, by the year 2025 (Sanford, 2018). To continue expanding their marine plastic initiatives, Sanford is contributing to this research project by granting access to their facilities in Havelock and Timaru and supplying material samples for experimentation.

Figure 13. Sanford's six performance outcomes for sustainability (Sanford, 2018)

Figure 14. Sanford San Discovery vessel

SANFORD LIMITED. HAVELOCK

Located at the top of the South Island in New Zealand, as seen in figure 15, Havelock is famous for green mussels and is home to Sanford's aquaculture facilities. The conventional plastic fishing gear used within Havelock includes HDPE buoys as well as a wide selection of PP and monofilament ropes. Both buoys and ropes are used in conjunction with one and other to farm green mussels and are collected at their end of life within Sanford's recycling and production yards. While the buoys are classified as type 2 plastic and can technically be recycled within New Zealand's recycling regulations, a large quantity of them can be seen stockpiled together (figure 16). The reasons why so many of these buoys are not currently recycled may include a lack of

localised recycling infrastructure, contamination and an overwhelming amount of plastic not being recycled due to recent waste import bans. Similarly, the vast selection of ropes used are all classified as combinations of type 2 and 5 plastics and cannot be recycled within New Zealand's current recycling scheme. As a result, the ropes can be seen stockpiled in large bags in figure 17, to be reused if possible or transported to the only disposal option offered to the material, which is landfill. Therefore, there is a crucial need for a circular upcycling system that can locally process buoys and ropes into new materials and products, that can continuously be reused within a technical cycle and not have to be disposed of in a landfill.

Figure 15. Havelock location

Figure 16. Stockpile of used buoys

Figure 17. Stockpile of used aquaculture ropes

SANFORD LIMITED. TIMARU

Found on the east coast of the South Island in New Zealand, as seen in figure 18, Timaru is home to one of Sanford's most significant fish processing facilities and where many of their fleets make port. One of the most common forms of plastic fishing gear used within this section of Sanford's operations is large nylon, polypropylene, polyethylene and monofilament fishing nets. Similar to their aquaculture facilities that use a selection of ropes, Sanford's fishing operations have a range of different sized nets that are separated by colour. These nets are used for a variety of fishing methods that include purse seine fishing, longline fishing and trawling (Sanford, n.d.). When not in use, many of Sanford's fishing nets are collected and stockpiled in a large yard according to what fishing vessel they belong to, as seen in figure 19. Other nets that need to be repaired are sent to an Iceland-Based company located on the port called Hampidjan NZ limited. However, some

nets cannot be repaired or reused and are placed within large bins or labelled as rubbish, as seen in figure 20. These nets will then be disposed of in landfills, as they are classified as combinations of type 2, 5 or 7 plastics and cannot be recycled under New Zealand's current recycling schemes. Additionally, large quantities of plastic waste from vessel kitchens and living quarters are collected in nets after a long voyage and are disposed of within landfills alongside unusable nets, as seen in figure 21. Overall, while a considerable portion of the plastic fishing gear is reused within fishing operations, there is a large quantity that is not. Therefore, it is imperative that a localised upcycling system that repurposes fishing nets and potentially other plastic waste used on board vessels is implemented. In doing so, a technical cycle for the plastic waste stream can be introduced, and more waste can be diverted from entering landfills.

Figure 18. Timaru location

Figure 19. Stockpiled nets ready for use

Figure 20. Discarded fishing nets

Figure 21. Plastic waste from fishing vessels in landfill

INITIAL DESIGN IDEATION

The extensive observations undertaken at Sanford's facilities in Havelock and Timaru has helped in identifying the most relevant plastic waste streams as well as Sanford's sustainability agenda. Sanford has recognised in order to become the most sustainable fishing company in the world, innovative solutions to their vast range of waste streams must be acknowledged, which brings the company into new territories. This is evident within a new anti-aging facial product that uses fish waste, or more specifically fish skin

from Sanford's largest fishing catch by volume (Sanford, 2018). Collagen is the main structural protein that is extracted from the fish skin, and it is bonded with other natural extracts to create an innovative and sustainable product (Sanford, 2018). Influenced by Sanford's past track record in using their waste streams in new sustainable products, it may be possible to extend their existing sustainability agenda into new territories to upcycle their plastic waste into eco-innovative designs.

Brainstorm 1

Sanford is proud to have created a safe and high-performance culture for their workplace, but can we push the idea of creating a safe and high-performance culture further? By ensuring that communities are enjoying the coastlines and using it to its full potential. Design ideas could then be linked to a user and the ocean.

Figure 22. Initial design ideas for creating a safe and high-performing culture with the ocean

Figure 23. Initial design ideas for supporting enduring communities and partnerships

Brainstorm 2

Sanford is partnered with existing New Zealand foundations and groups, while also striving to give back to the community by sponsoring certain sports clubs, St Johns, and Fire brigades. How could design push these efforts further? To create a product, service or system that benefits these partnerships or truly gives back to the community.

Brainstorm 3

Sanford is dedicated to working with people, customers and suppliers to ensure they maximise resource utilisation, minimise their carbon footprint and enhance/protect the environment. Can 3D printed designs enforce these ideals further? By using a discarded material to benefit the environment and its inhabitants.

Figure 24. Initial design ideas for protecting and enhancing the environment

INITIAL RESEARCH CRITERIA

The initial research undertaken within the first stage of the project has informed initial research criteria, as seen in figure 25. The initial criteria ensures that development for materials, systems and designs within stage 2 follows a cohesive structure and meets specific objectives. Overall, the criteria helps in achieving the goal of upcycling a range of plastic fishing gear into eco-innovative designs through distributed manufacturing technologies.

OUTPUT	CRITERIA
Materials	<ul style="list-style-type: none">- Materials should consist of a range of significant plastic fishing gear waste streams, obtained from Sanfords, Havelock and Timaru facilities in New Zealand.- Material quality needs to be recovered or consist of a hybrid mix that can be upcycled within a circular closed-loop system.- Materials should inform design decisions and must be applicable to its chosen design.
Systems	<ul style="list-style-type: none">- Systems are required to be localised within New Zealand.- Systems should be situated around upcycling plastic fishing gear.- Systems must be circular and distinguish why 3D printing is used as the manufacturing method.
Designs	<ul style="list-style-type: none">- Designs should be high quality, apply sustainable attributes proposed by Sherin (2017), and be inspired by Sanford’s sustainability agenda to identify innovative areas of implementing upcycled plastic fishing gear.- Designs must utilise the unique capabilities of the 3D printer, to ensure minimum energy and material consumption, and offer customisation across all concepts.

Figure 25. Initial research criteria

Chapter 4:
MATERIAL PROCESSING

PROCESS AND TECHNOLOGIES

The process used in this research to upcycle plastic fishing gear into filament for 3D printing follows an extensive circular cycle that includes collecting, cleaning, melting, granulating, formulating and 3D printing. Each stage in this process is significant within the circular cycle and requires specific procedures and technologies to succeed. The initial four stages of the process, seen highlighted in figure 26 are some of the most fundamental for this research, as each of them must work correctly for the following stages to succeed. Plastic fishing gear is not the cleanest form of plastic waste. So the material processing stage of the research is crucial for removing impurities, maintaining material quality and ensuring

the materials can be upcycled into filament for 3D printing. To ensure each initial stage of the circular cycle is completed to a high standard, a range of cleaning tools and technology that is accessible within Victoria University’s recycling lab is used. While the technology used within this research is a collection of separate machines and not an ‘all in one’ system, they are used in conjunction with one another in one location. Therefore, the use of these technologies and tools will exemplify the distributed recycling in this research and stand as some of the essential equipment used to upcycle plastic fishing gear through distributed manufacturing technologies.

Figure 26. First four stages of the circular upcycling process

Figure 27. Cleaning equipment

The cleaning equipment is predominantly used to remove impurities from the materials and consists of equipment for hand cleaning. No technology is used within this stage.

Figure 28. Contherm thermotech 2000 (Wellington, New Zealand)

The industrial-grade oven can reach 300 degrees celsius and is used for melting the aquaculture ropes and fishing nets into homogeneous slabs of plastic that can then be granulated. It is also commonly used to remove moisture from filament, which can aid in improving the 3D printing success rate.

Figure 29. Conair 8 series granulator (Cranberry Township, USA)

Hard plastics and melted plastic are fed into the granulators hopper where it is then launched into large rotating blades and granulated down into small plastic granules.

COLLECTING

Material samples were collected from Sanford's facilities in Havelock and Timaru. The plastic fishing gear samples consist of buoys, aquaculture ropes and fishing nets, and are the predominant range of plastic fishing

gear used throughout this research. While each material sample is unique, they are all processed through the same circular cycle.

Buoys

Figure 30. Buoy material samples

Obtained from Sanford's aquaculture facilities in Havelock, the buoy samples were covered in sea debris and were cut into rectangular pieces to be transported to Wellington. Being the only solid plastic samples in this research, the buoys do not need to be melted for granulation and can

skip that stage of the cycle. Additionally, the large surface area of the buoy samples creates ease in terms of cleaning as there are no small sections for sea debris to latch onto. Therefore, processing the buoy samples is quick, and material purity can be restored.

Aquaculture Ropes

Figure 31. Aquaculture rope material samples

Collected from Sanford’s aquaculture facilities in Havelock, the rope samples were the most contaminated samples used within this research as the majority of them were covered in sand, sea debris and small broken seashells. As seen in figure 31, the rope samples ranged from small ropes labelled as Lashings and 18/24mm rope, and large ropes marked as Crop Rope and Lead Rope. Each rope is made from synthetic fibres. The large Crop and Lead Rope commonly have sea debris weaving in and out

of them, proving to be a problematic sample of plastic fishing gear to clean. Once they are cleaned, the ropes will have to be melted into solid forms to be granulated, as the fibres would otherwise tangle and clog the granulator. Therefore, cleaning, melting and granulating are crucial procedures for upcycling the aquaculture ropes into material that can be implemented within 3D printing technologies.

Fishing Nets

Figure 32. Fishing net material samples

Gathered from Sanford’s fishing facilities in Timaru, the fishing net samples range in colour, size and cleanliness. While the net samples are considerably cleaner than the aquaculture rope samples, some of the nets have a large amount of sand weaved throughout the fibres. As seen in figure 32, the nets range between yellow, green and blue colours and are all synthetic and monofilament nets, which makes their plastic combination

challenging to define. However, as identified throughout the field research, the aquaculture ropes and fishing nets are a collection of type 2, 5 and 7 plastics. Similar to the aquaculture ropes, the net samples are cleaned, melted and granulated so that they are ready for the next stage of the research.

CLEANING

Cleaning is an essential stage of the upcycling process for plastic fishing gear because unlike other plastic waste, this gear has been in the ocean for a considerable amount of time and has a lot of sea debris latching onto it. Each material sample is cut into a smaller sample to be cleaned by hand using water and an eco-friendly cleaning agent. When finished, the water is poured through an old fabric sheet to separate it from any fallen sea

debris or microplastics. While handwashing the plastic fishing gear may not be the quickest form of cleaning, it can be effective, as small pieces of waste can easily be removed from the fishing gear. Additionally, the use of soap is not mandatory; however, if the material is to be upcycled well into new designs, it may be necessary to remove any unpleasant odours attached to the gear, specifically the aquaculture ropes.

Figure 33. Cleaning process

Cleaning Experimentation

Every piece of plastic fishing gear is different. While many have similar structures and materials, some have singular characteristics, such as unique monofilaments as seen in figure 34, that must be addressed for it to be cleaned. Therefore, this cleaning experiment includes small samples of buoys and different sized aquaculture ropes, in a series of three different cleaning methods for each material sample. These experiments are used to create one finalised cleaning method for the entirety of the plastic fishing

gear samples in this research project, and acknowledge what additional cleaning methods must be attributed to specific gear.

Fishing nets are not amongst the experiments because they were not obtained until later on within this study, and have similar structures and characteristics to some of the aquaculture ropes used in these experiments.

Figure 34. Monofilament fishing net

Buoy Sample Experiments

The buoy samples were simple to clean, and all three methods were effective. It did not necessarily need the cleaning agent to get rid of the sea debris; however, it did remove the smell. When cleaned, each piece had considerable amounts of scratches from the cleaning process; however,

this does not matter once they are granulated. The singular attribute that must be applied to this sample of plastic fishing gear is the use of steel wool to remove sea debris.

	EQUIPMENT	METHOD	RESULT	BEFORE	DURING	AFTER
BUOY SAMPLE 1	<div><ul style="list-style-type: none">- Bucket- Hot Water- Brush- Gloves- Mask</div>	<div>Place a piece of the HDPE buoy in the bucket of hot water and scrub them until you see the excess waste fall off.</div>	<div>The sea debris came off the piece of buoy, however, small pieces of sea debris is stuck in small gaps and it still smells.</div>
BUOY SAMPLE 2	<div><ul style="list-style-type: none">- Bucket- Water- Steel Wool- Gloves- Mask</div>	<div>Place a piece of the HDPE buoy in the bucket of water and scrub them until you see the sea debris fall off.</div>	<div>The steel wool worked very nicely and better than the brush as it got the smaller pieces out from the buoy's cracks.</div>
BUOY SAMPLE 3	<div><ul style="list-style-type: none">- Bucket- Small amount of water- Eco-friendly cleaning agent- Gloves- Mask</div>	<div>Dampen pieces of the HDPE buoys in the bucket. Apply the eco-friendly cleaning agent, and scrub off with a brush or steel wool. Rinse off excess soap and waste.</div>	<div>A little bit more difficult not using a lot of water, although the process did work and the buoy piece came out clean. A lot of water was used to rinse off the cleaning agent.</div>

Figure 35. Buoy cleaning experiments

Small Aquaculture Rope Sample Experiments

The small aquaculture ropes were simple to clean as most of the samples only had sand on them. Similar to the fishing nets, these samples are thick and are not used for crops, so they do not necessarily have to be unravelled to be cleaned. However, if the rope or net has considerable amounts of

sea debris and can be unravelled, then it should be. Single attributes that must be applied to this sample of plastic fishing gear includes knocking it in an empty bucket before scrubbing it, to get the excess sand off, and not unravelling it unless it is needed.

	EQUIPMENT	METHOD	RESULT	BEFORE	DURING	AFTER
SMALL AQUACULTURE SAMPLE 1	<ul style="list-style-type: none">- Bucket- Hot water- Eco-friendly cleaning agent- Mask- Gloves	Place pieces of small rope (3 max) in a bucket of hot water. Add the cleaning agent and stir in the bucket. Stir for 15 minutes, then let the ropes soak in the water.	The soaking did not do anything for the ropes. Pieces of sea debris were still attached, and scrubbing should be used.
SMALL AQUACULTURE SAMPLE 2	<ul style="list-style-type: none">- 2x Bucket- Water- Brush- Eco-friendly cleaning agent- Mask- Gloves	1 at a time smack the rope into the bucket to see if any sea debris comes off. After, place ropes in the second bucket full of water & cleaning agent and scrub them until they look clean.	This method was successful for pieces that only had sand on them, however, for pieces with more sea debris, the ropes should be untangled before cleaned.
SMALL AQUACULTURE SAMPLE 3	<ul style="list-style-type: none">- Bucket- Water- Eco-friendly cleaning agent- Mask- Gloves	Place rope in the bucket and unravel them. With a small amount of water and cleaning agent, start to scrub the unraveled pieces to get rid of excess waste and smell.	Unravelling the rope made the cleaning process easier. Once unravelled, each separate strain came out and the cleaning process was great.

Figure 36. Small aquaculture rope cleaning experiments

Large Aquaculture Rope Sample Experiment

The large aquaculture ropes samples were the most challenging plastic fishing gear samples to clean within this research project. Since the majority of these ropes were used for growing crops, a severe amount of sea debris and shells were tangled between the singular synthetic fibres and were near impossible to get out. For this material to be used within this project,

all impurities had to be removed and additional time spent cleaning this sample must be added. Single attributes that must be applied to this sample of plastic fishing gear includes scrubbing the sample as a whole before unravelling and rewashing it and separating the synthetic fibres as the lead was found within the centre of some of the ropes.

	EQUIPMENT	METHOD	RESULT	BEFORE	DURING	AFTER
LARGE AQUACULTURE SAMPLE 1	<ul style="list-style-type: none">- Bucket- Hot water- Brush- Eco-friendly cleaning agent- Mask- Gloves	Place pieces of large rope (3 max) in a bucket of hot water. Add the cleaning agent and unravel in the bucket. Stir for 15 minutes, then let the ropes soak in the water.	The hot water and cleaning agent did get rid of some waste material although by unravelling it, it was difficult to get rid of all of the waste that was wrapped around the rope.
LARGE AQUACULTURE SAMPLE 2	<ul style="list-style-type: none">- 2x Bucket- Hot Water- Brush- Mask- Gloves	Pick up a few pieces of rope, unravel them and 1 at a time smack the rope into the bucket to see if any excess comes off. After, place ropes in the second bucket full of hot water and scrub them until they look clean.	Again by scrubbing the rope, some waste material came off, although without the cleaning agent there was a distinctive difference between experiment 1 & 2, as 2 had more waste still latched onto it.
LARGE AQUACULTURE SAMPLE 3	<ul style="list-style-type: none">- Bucket- Water- Brush- Eco-friendly cleaning agent- Mask- Gloves	Place pieces of rope in the bucket and scrub them with water and the cleaning agent. Then unravel the rope and continue to scrub the pieces to get rid of excess waste and smell.	By scrubbing the rope before unravelling it, more waste material came off. The soap and hot water definitely helped.

Figure 37. Large aquaculture rope cleaning experiments

Finalised Cleaning Method

Using the successes from the cleaning experiments, one finalised equipment list and cleaning method for all materials samples in this research was created. Additional actions that focus on the disposal of water and waste within the cleaning phase were implemented, and singular attributes for cleaning specific gear was applied.

EQUIPMENT	METHOD
<ul style="list-style-type: none">- Large Bucket- Hot Water- Brush or steel wool- Gloves- Eco-friendly Cleaning Agent- Small Buckets- Old Sheets- Towels	Select a piece of plastic fishing gear and one at a smack it around the bucket to remove sea debris. Then scrub it in the large bucket full of hot water and eco-friendly cleaning agent. Using the brush, clean the exterior of your piece, and if necessary or possible, unravel the piece and clean again. Each part of the plastic fishing gear should be exposed and cleaned. After, place the plastic fishing gear on the towel and pat dry then lie them out to air dry. Grab the small bucket and place the old sheet over top of it and pour the excess water left over from the large bucket. drain the water out and collect the excess waste. Empty the small bucket of waste water in the garden and leave the old sheet with excess waste out to dry for later use.

Figure 38. Finaled cleaning method

Figure 39. Finalised cleaning process

Cleaning Buoys

Before

After

Figure 40. Cleaning buoy material samples

Before

After

Figure 41. Cleaning buoy material samples

Cleaning Aquaculture Ropes

Figure 42. Cleaning aquaculture rope material samples

Figure 43. Cleaning aquaculture rope material samples

Cleaning Fishing Nets

Figure 44. Cleaning fishing net material samples

Figure 45. Cleaning fishing net material samples

MELTING

For the aquaculture ropes and fishing nets to be granulated, they first must be melted. Each rope and net sample is separated by colour within multiple trays and placed within the 'Contherm thermotech 2000' to be fused into homogeneous slabs of plastic. Temperatures ranging between 190 to 210 degrees celsius were chosen after extensive melting experiments were conducted. These temperatures were used for all ropes and nets within 90 minute periods to form each slab. The high temperatures used within the melting stage, burnt impurities that may have still been in the material; however, the Lead and Crop aquaculture ropes still had sea

debris weaved within the fibres which had to be separated after they were granulating. The vast majority of ropes and nets melted successfully, as they each formed large slabs of plastic that were ready to be granulated. Unfortunately, the mustard coloured fishing net did not melt as well as the other nets, resulting in burnt material that could not be used within further stages of this research. The burning could be attributed to the nets unknown materials, which were likely to be very different from the other net samples.

Figure 46. Melting process

Aquaculture Ropes

Lashings

18/24mm Rope

Figure 47. Melting aquaculture rope material samples

The Lashing and 18/24mm rope samples had minor amounts of sea debris throughout their synthetic strands. This attribute made the material samples purer than other aquaculture ropes used within this research.

Crop Rope

Lead Rope

Figure 48. Melting aquaculture rope material samples

While some impurities burnt away, many remained within the Crop and Lead ropes. As the ropes were initially used to grow mussels, it is tough to remove all impurities as the sea debris latches onto every single synthetic fibre. Therefore, the Crop and Lead rope samples are hybrid combinations of rope and contaminants, which may enforce unique 3D printing qualities.

Fishing Nets

Figure 49. Melting fishing net material samples

The fishing nets melted well into plastic slabs. However, as the nets were not unravelled within the cleaning stage, they were challenging to melt together as they were quite dense. As a result, some slabs of plastic had

some unmelted pieces of the fishing net which can granulate into fibres instead of granules and disrupt its overall recyclability through 3D printing.

Figure 50. Melting fishing net material samples

While it was predicted that all of the fishing nets were combinations of the same material, each slab had unique characteristics such as glossy or rough surfaces. While it is unclear on whether or not this can disrupt the

recyclability of the material, it undoubtedly has different qualities that may appear through 3D printing.

GRANULATING

All buoy, aquaculture ropes and fishing net samples were processed using the granulator. This non-adjustable machine uses three large rotating blades to transform large materials into minuscule granules. This research is the first to put plastic fishing gear into the granulator at Victoria University; therefore, some precautions were made before using the machine. Due to the fact the homogenous slabs of plastic fishing gear and buoy samples

are quite large, they were cut on the bandsaw into smaller, 15mm long strips of plastic as a precaution, and by doing so, the machine did not get clogged by any of the materials. Each sample was granulated on its own, and the interior blades had to be cleaned thoroughly after every material sample so that no contamination amongst batches occurred.

Figure 51. Granulating process

Buoys

Figure 52. Granulated buoy material samples

Aquaculture Ropes

Figure 53a. Granulated Lashings

Figure 53b. Granulated Crop Rope

Figure 53c. Granulated 18/24mm Rope

Figure 53d. Granulated Lead Rope

Figure 53. Granulted aquaculture rope material samples

Fishing Nets

Figure 54a. Granulated yellow net

Figure 54b. Granulated light green net

Figure 54c. Granulated dark green net

Figure 54d. Granulated dark blue net

Figure 54. Granulated fishing net material samples

Overview

The initial four stages of the circular cycle performed throughout this stage of the research were significant starting points, as without them the plastic fishing gear samples cannot be successfully upcycled into 3D printing filament and eco-innovative designs. While each processing stage

was experimental and time-consuming, the majority of plastic fishing gear samples were successfully processed into plastic granules for filament formulations and productions.

Chapter 5:
MATERIAL EXPERIMENTATION

PROCESS AND TECHNOLOGIES

The remaining stages in the circular process seen highlighted in figure 57 include formulating and 3D printing. Both of these concluding stages of the process require extensive experimentation as the plastic fishing gear samples consist of unique material combinations which makes it difficult to predict their overall ability to produce filament and 3D print successfully. The results from this experimental phase determine what filament formulas can be developed, what material samples have to be removed from the

remaining research and what unique qualities the materials offer through 3D printing.

High-end equipment made accessible through Victoria University's recycling lab, and masters of design innovation studio are used within these stages to ensure the materials are experimented with to their utmost potential.

Figure 55. Last two stages of the circular upcycling process

Figure 56. Thermoscientific Process 11 twin-screw extruder & Spooler (Karlsruhe, Germany)

Working in conjunction with one another, the extruder and spooler offer adjustments in speed, diameter and temperature throughout the entire making process. Inside the extruder's barrel are twin-screws and a set of temperature stages that are perfect for unprecedented materials as they unify material combinations into a single strand of plastic filament. The filament is then collected at a controlled speed on the spooler to ensure the diameter of the filament remains consistent.

Figure 57. Ultratech digital calipers

The digitalised calipers allow the user to measure the diameter of the filaments fast and accurately throughout the making process.

Figure 58. Ultimaker 3 Extended (Geldermalsen, Netherlands)

Operating through G-code exported through Cura software, the Ultimaker uses fused deposition modelling to extrude material precisely layer by layer into a 3D model. Significant attributes including temperature and speed can be adjusted before and during the making process to ensure 3D prints are successful.

FILAMENT FORMULATION AND PRODUCTION

Initial formulas consisting of 100% buoy, aquaculture ropes and fishing nets were formulated and produced, using the Thermoscientific Process 11 twin-screw extruder and spooler (Karlsruhe, Germany). The overall process requires a small number of granules being placed within a hopper to undergo a series of temperature changes and be extruded consistently at a 2.85mm diameter. The material is then collected at a precise speed, measured by hand and spooled into a roll of filament ready for 3D printing.

Due to unpredictable characteristics and having impurities throughout materials, the produced filaments were not always consistent, which resulted in the filaments inability to 3D print. Therefore, continuous adjustments in temperatures and speed are required throughout the formulating and producing process or additional materials need to be introduced to the filament formulas.

Figure 59. Extruding and spooling filament process

Additional Material

Figure 60. Granulated recycled polyethylene bottles

Due to inconsistencies across a variety of filaments, it was decided that polyethylene bottles would be granulated and added to buoy and aquaculture rope formulas. Polyethylene bottles were chosen as the additional material as they are classified as type 2 plastic, which is found within the buoys and is predicted to be within the aquaculture rope samples. Therefore, it was hypothesised that by adding recycled polyethylene granules to buoy and aquaculture rope formulas, they might be able to improve consistency across the spooled filament. While the

recycled polyethylene granules are not from plastic fishing gear, the use of them was inspired by other forms of plastic waste recorded within the commercial fishing operations. Reflecting on the field research in Timaru, it was found that there was a considerable amount of plastic waste from vessel living quarters and kitchens that were collected and disposed of in a landfill. Therefore, the use of polyethylene bottles is not entirely separate from using plastic fishing gear as they are another form of plastic waste that can be incorporated into filaments from the commercial fishing industry.

Buoy Filament

Inconsistent

Figure 61. 100% buoy filament

A series of buoy formulas were tested using an extruding temperature of 220°C. The 100% buoy formula was inconsistent as its diameter varied between 1.9mm to 3.2mm. 50% buoy granules and 50% polyethylene

Consistent

Figure 62. 50% buoy with 50% recycled polyethylene

granules were mixed to create a consistent filament. Fortunately, the mix made a more consistent roll of filament that had a charcoal colour tint and a glossy finish.

Aquaculture Rope Filament

Lashings

Inconsistent

Figure 63. 100% lashings filament

Consistent

Figure 64. 80% lashings with 20% recycled polyethylene

All aquaculture rope formulas were extruded at 210°C. The initial 100% lashings formula was inconsistent as the material would fold over itself, which resulted in a warped and squished roll of filament. A new formula consisting of 80% lashings and 20% recycled polyethylene was created

to ensure consistency. The new filament was far more controlled than the previous filament and had limited fluctuations within its diameter as well as a matte black finish.

18/24mm Rope

Inconsistent

Figure 65. 100% 18/24mm rope filament

Consistent

Figure 66. 70% 18/24mm rope with 30% recycled polyethylene

The 100% 18/24mm rope formula was inconsistent as large bulges of plastic exceeding 2.85mm formed throughout the strand of filament. The new formula was 70% 18/24mm rope and 30% recycled polyethylene. This

formula created a consistent spool of filament that had a matte dark grey finish.

Lead Rope

Inconsistent

Figure 67. 100% lead rope filament

The 100% lead rope formula included some minor pieces of sea debris, which gave the wobbly spool of filament a rough texture. A second formula consisting of 60% lead rope and 40% recycled polyethylene was

Consistent

Figure 68. 60% lead rope with 40% recycled polyethylene

formulated and produced. This new formula seemed to have stabilised the diameter of the filament and flow; however, material impurities remained and created a hybrid material with unique surface qualities.

Crop Rope

Figure 69. 100% crop rope filament

The 100% crop rope formula had too many impurities that were not removed within previous processing stages. When spooled, the material had a rough quality that made the filament very inconsistent. Due to the

filaments messy structure and the inability to remove the contaminating materials within this research, the crop rope was not developed into a consistent spool of filament and was removed from the remaining study.

Fishing Net Filament

Yellow Net

Light Green Net

Figure 70. 100% fishing net filament

All fishing net formulas were extruded at 220°C. The 100% yellow net formula had minor problems with consistency that was resolved with a decrease in speed while extruding. The filaments diameter was then consistently remaining around 2.85mm, and the material had an intriguing brittle quality. As it is a monofilament net, small blue pieces of fishing line within the yellow net made the filament turn lime green when extruded.

The 100% light green net formula extruded a consistent spool of filament ranging around 2.85mm in diameter. The filament seemed to be less brittle than the yellow net filament and had a slight gloss finish with a unique sea-green tint.

Dark Green Net

Figure 71. 100% fishing net filament

The 100% dark green net formula created a consistent spool of filament with a diameter slightly fluctuating around 2.85mm. The dark green filament was the glossiest of all, as its surface quality almost looked slippery against its jade green colour.

Dark Blue Net

The 100% dark blue net was the most consistent fishing net filament with almost zero diameter fluctuations. Similar to some aquaculture rope samples, the dark blue net had sand weaved throughout its fibres. When extruded, the material had a unique surface texture that reveals small white dots throughout its dark blue colour.

Incorporating the Water Bath

While the majority of plastic fishing gear samples were successfully formulated and produced into 3D printing filament, they were all fabricated at a slow speed. To boost material production, the water bath was introduced to the filament making process. The water bath is placed

between the extruder and spooler to allow material to cool instantly after extruding so that it may be spooled at a faster speed. This additional process allowed for more filament to be made in a shorter timeframe and was used for every material formulation.

Figure 72. Water bath

Figure 73. Water bath next to extruder and spooler

3D PRINTING

All 3D printing experiments were performed on the 'Ultimaker 3 Extended.' The 3D printing procedure consists of installing the largest nozzle offered through this printer which is the 0.8mm nozzle, this large nozzle size is used to avoid any clogging within the printer. After installation, a chosen filament is fed into the back of the printer and extruded at a set temperature. Due

to the unpredictability of the plastic fishing gear within the 3D printing process, adjustments in speed, temperatures and material flow can be made if necessary throughout the process to ensure the model is printing correctly.

Figure 74. 3D printing process

Test Forms

3D printing tests establish the overall printability of plastic fishing gear filaments under a series of variables and encourage design outputs that are suitable for the characteristics of the materials. The variables that include, height, detail, flex, infill, strength and overhang are tested over a collection of different 3D models, as seen in figure 75. Each model was influenced by the marine environment, tests 1 to 2 variables and helps in acknowledging small attributes that future 3D printed models should have to successfully 3D print.

Figure 75. Digital drawing of final test models

Figure 76. 3D printing test form

Buoys

The 50% buoy and 50% recycled polyethylene filament consistently 3D printed throughout all test models. Gradual geometries ensured the printed layers formed together well, while a temperature ranging around 225°C guaranteed well-established infill patterns, material flow and detail. The material successfully reached a 55-degree angle overhang and

became highly flexible when print layer gaps were consistently distributed throughout the form. Minor inconsistencies within the filament resulted in small separations between layers and larger surface areas on the bottom of the prints contributed to slight warping.

Figure 77. 50% buoy with 50% recycled polyethylene test prints

Figure 78. 50% buoy with 50% recycled polyethylene test prints

3D Printing Settings for Buoys

MATERIAL	ULTIMAKER NOZZLE	INFILL	PRINTING TEMP	BUILD PLATE TEMP	SET SPEED	ADJUSTED SPEED	PRINT QUALITY
50% Buoy + 50% PE Granules	AA 0.8mm	15% Lines (If used)	225°	85°	15mm/s	50% to 100%	Good

Figure 79. 50% buoy with 50% recycled polyethylene 3D printing settings

3D printed trials for the buoy and recycled polyethylene filament distinguished its overall success, as the material exhibited promising qualities around strength, flexibility and detail. While all five models 3D printed well, minor faults establish alterations that should be considered when designing with this material. Complexity around 3D forms should be controlled, and low bottom surface areas could be implemented within future designs to minimise warping and reduce layer separation. Additionally, the use of adhesive tape and an enclosed chamber for the 3D printer can aid in reducing these unwanted imperfections. On the other hand, the jet black tones and slight gloss finish throughout the 3D model's exhibit modern and desirable aesthetic qualities that suggest the material could be used within a variety of high-value designs.

Figure 80. 50% buoy with 50% recycled polyethylene test prints

Lashings

The 80% lashings and 20% recycled polyethylene filament 3D printed smooth, detailed and stiff test models. A continuously altered temperature of 230°C and above ensured the filament extruded well and built consistent 3D forms. The forms ranged in unique surface qualities as smooth and wobbly surfaces were detected amongst the different geometries. The low flexibility in the material created dense models, and slight layer separation resulted in the material reaching a 40-degree angle overhang before failing.

Figure 81. 80% lashings with 20% recycled polyethylene test prints

Figure 82. 80% lashings with 20% recycled polyethylene test prints

18mm and 24mm Ropes

The 70% 18/24mm rope and 30% recycled polyethylene filament varied in 3D printing quality. While the material can print continuously to create detail, finished models and an overhang angle of 45 degrees, there was a collection of imperfections recorded throughout the test models. Layer separation and minimal material distribution created fragile forms that would easily break and inconsistencies within the filament resulted in the creation of incomplete models. That being said, the filament was the most flexible out of all aquaculture ropes filaments and bestowed sleek surface qualities when successful.

Figure 83. 70% 12/24mm rope with 30% recycled polyethylene test prints

Figure 84. 70% 12/24mm rope with 30% recycled polyethylene test prints

Lead Ropes

The 60% lead rope and 40% recycled polyethylene filament effortlessly and consistently 3D printed each form. The material was inherently unique as its hybrid mix of synthetics and sea contaminants created rough and slightly bumpy surface textures. The high melting temperature of 240°C made the material fairly malleable, resulting in layers resembling a clay-like aesthetic. While there were minor splits within some models, the material created strong and fluid forms, and successfully reached an overhang angle of 50-degrees.

Figure 85. 60% lead rope with 40% recycled polyethylene test prints

Figure 86. 60% lead rope with 40% recycled polyethylene test prints

3D Printing Settings for Aquaculture Ropes

MATERIAL	ULTIMAKER NOZZLE	INFILL	PRINTING TEMP	BUILD PLATE TEMP	SET SPEED	ADJUSTED SPEED	PRINT QUALITY
80% Lashings + 20% PE Granules	AA 0.8mm	25% Cubic Subdi- vision (If used)	230°	85°	15mm/s	60% to 100%	Good
70% 18/24mm Rope + 30% PE Granules	AA 0.8mm	25% Quarter Cubic (If used)	235°	85°	15mm/s	70% to 100%	Average
60% Lead Rope + 40% PE Granules	AA 0.8mm	25% Tri-Hex agons (If used)	240°	85°	15mm/s	40% to 100%	Good

Figure 87. Aquaculture rope and recycled polyethylene 3D printing settings

Aquaculture ropes and recycled polyethylene combinations revealed unique material qualities and satisfactory results when 3D printed. The use of an additional recycled material helped in producing a variety of robust, flexible and detailed models. However, minor defects within models relating to filament diameter resulted in the need to alter material settings. Therefore, throughout the printed tests, adjustments in speed, temperature and material flow were rapidly performed until the models

printed continuously and consistently. The multitude of material ratios used within the tests resulted in a collection of gradual grey shades and unique surface textures. The combination of smooth, sleek and rough surface textures as well as grey shades, moves the materials aesthetic quality away from plastic to resemble something more organic. Therefore this material could be adapted into more natural-looking designs that are used within an environmental setting.

Figure 88. Aquaculture rope with recycled polyethylene test prints

Yellow Nets

The 100% yellow net filament 3D printed consistently, resulting in the majority of test models having an excellent print quality. The filament 3D printed clean material paths at 230°C which resulted in tidy models with minor disfigurement. One wall models had brittle attributes and could easily break if force was applied; however, the use of infill made the material more assertive and less prone to cracking. By successfully reaching a 45-degree overhang and 3D printing a consistent straight line, the yellow net filament proved to be a prominent material for 3D printed upcycling.

Figure 89. 100% yellow net test prints

Figure 90. 100% yellow net test prints

Light Green Nets

The 100% light green net filament 3D printed well throughout the test models with slight defects. While the material produced strength when infill was applied, it had a fragile distinction that made it susceptible to splitting. Additionally, large bottom surface areas made some models warp, resulting

in inaccurate forms. On the other hand, using a temperature ranging around 235°, the material successfully reached a 45-degree overhang, had little flexibility, produced tiny details and had a satisfying glossy finish.

Figure 91. 100% light green net test prints

Figure 92. 100% light green net test prints

Dark Green Nets

The 100% dark green net filament's quality varied throughout the test models. Simpler geometries and a 240°C temperature allowed the material to build upon itself to reach a 45-degree angle, ensure detail and create glossy models that uniquely transmitted different green tones. Due to a

varying filament diameter, some models had many gaps, and some had unstable surfaces as the material was distributed unevenly. Additionally, the models were very fragile, and distinctive warping amongst forms was detected.

Figure 93. 100% dark green net test prints

Figure 94. 100% dark green net test prints

Dark Blue Nets

The 100% dark blue net filament 3D printed the majority of the test models effortlessly and precisely. While the material didn't print one form so well, other models printed at 245°C displayed promising qualities such as strength, high flexibility, accuracy, detail, and unique surface quality. The models had an irregular texture that made the printed walls slightly rough, which resulted in a dark blue matte finish with small white speckles. The material just reached a 50-degree overhang and has validated its use for 3D printed upcycling.

Figure 95. 100% dark blue net test prints

Figure 96. 100% dark blue net test prints

3D Printing Settings for Fishing Nets

MATERIAL	ULTIMAKER NOZZLE	INFILL	PRINTING TEMP	BUILD PLATE TEMP	SET SPEED	ADJUSTED SPEED	PRINT QUALITY
Yellow Net	AA 0.8mm	20% Zig Zag (If used)	230°	85°	15mm/s	70% to 100%	Good
Light Green Net	AA 0.8mm	20% Triangles (If used)	235°	85°	15mm/s	60% to 100%	Average
Dark Green Net	AA 0.8mm	20% Octet (If used)	240°	85°	15mm/s	50% to 100%	Poor
Dark Blue Net	AA 0.8mm	20% Grid (If used)	245°	85°	15mm/s	70% to 100%	Good

Figure 97. Fishing net 3D printing settings

The fishing net filaments proved to be quite promising when 3D printed, mostly because no additional materials had to be introduced to the formulas to ensure diameter consistency. While some deficiencies were recorded throughout the test models, most of the 3D prints showed great variety in strength, flexibility, accuracy, z height orientation, overhang, and detail. Additionally, the fishing net filaments offer a variety of playful and ocean-like colours as well as glossy and matte finishes. The variation in both functional and aesthetic qualities certifies the implementation of the materials into a diverse collection of design ideas. These may include but are not limited to designs based around the ocean or products for children.

Figure 98. Fishing net test prints

Figure 99. All 3D printed tests

REFLECTION

By following the initial material criteria throughout the filament formulating and 3D printing experiment stages of the circular process, it is understandable that a range of plastic fishing gear collected from Sanford can effectively be upcycled into 3D printing filaments and forms. Additionally, material processing and experimenting results suggest the adoption of distributed manufacturing technologies can assist in generating more localised upcycling initiatives. While each formulated filament constructively responded to the 3D printing process, unique characteristics and qualities were established amongst individual forms. Each of these distinctive 3D printing attributes suggests how the materials can be utilised and implemented within particular scenarios and eco-innovative designs. Moreover, the materials success in 3D printing proposes that customisation can be employed to create a variety of forms, textures

and patterns that can amplify the materials individual qualities. In regards to 3D printing settings, it was found that no universal set of parameters would quarantine the materials success when 3D printed. Therefore, continuous adjustments in temperature, speed and material flow had to be incorporated to ensure the materials worked with the printer. Furthermore, it was recognised that layer separation, warping and inaccurate material distribution was attributed to the inconsistency of a filaments diameter, the orientation and density of a form, and the uncontrollable properties of the plastic filaments. Therefore, setting adjustments and the incorporation of the water bath in the filament production stage is necessary to guarantee a consistent diameter of 2.85mm, and eco-innovative designs must be orientated around the materials capabilities to ensure the models are 3D printed to a high standard.

Chapter 6:
DESIGN EXPERIMENTATION

Outline

By establishing material settings and understanding the characteristics of the plastic fishing gear filaments within the material experimenting stage, a series of three conceptual areas in the context of by Sanford’s sustainability agenda could be developed. Within each conceptual area is a large variety of scenarios and eco-innovative designs, developed from the initial design ideas, that are generated and expressed through a series of drawings. One primary design idea is then refined through computer-aided models and renders, and a range of different plastic fishing gear filaments are suitably chosen to 3D print physical prototypes. Each 3D print is individually analysed to understand further material restrictions and what additional requirements must be added to models in order for them to successfully 3D print.

Conceptual Area 1:

CREATING A SAFE & HIGH-PERFORMANCE CULTURE WITH THE OCEAN

The experimental design ideas developed within this conceptual stage are situated around creating an enjoyable, strong, educational and safe relationship between users and the marine environment. Hypothetically, each design idea would be fabricated through a collaborating scenario between Sanford and other New Zealand based foundations and companies through a circular 3D printing system, as seen in figure 100. The anticipated designs propose the adoption of upcycled plastic fishing gear within existing ocean-based activities to amplify connections between environmentally conscious consumers and the marine environment and to initiate thought-provoking ideas around marine pollution. The exploration of these design opportunities includes watersports equipment, beach cleaning tools and fishing tools for children and replacement parts for old boats. All materials are initially considered for these designs; however, 100% fishing net filaments and 50% buoy combined with 50% recycled polyethylene filament is used to develop physical prototypes.

Figure 100. Conceptual area 1 scenario

Concept 1a - Water sports equipment designed in collaboration with Torpedo7

Figure 101. Conceptual area 1 drawings

Concept 1b - Designing for Children with the Graeme Dingle Foundation

Figure 102. Conceptual area 1 drawings

Concept 1c - Designing High-end Boating and Water Sports Equipment with NZ Marine

Figure 103. Conceptual area 1 drawings

Water Sports Equipment

Designed for environmentally conscious consumers, 3D printed water sports equipment made from used plastic fishing gear offers an effective and sustainable method of enjoying the ocean. Consumers who have a strong passion for the marine environment would have an incentive to support this production, as water sports equipment made from marine plastic waste can tangibly exemplify their values for more sustainable productions and less plastic pollution. Additionally, 3D printing offers an unprecedented degree of customisation; therefore, consumers can modify and adapt specific equipment according to personal preferences and requirements. The use of customisation can enforce deeper attachments

between users and products, resulting in substantial connections between the user and the ocean, and longer-lasting products that do not re-enter the circular upcycling system for an extended period of time.

From the material experimentation stage, it was discovered that the fishing net and buoy filaments are robust materials that can offer aesthetic qualities that are suitable for this design. Therefore, an assortment of forms and patterns are 3D printed to exemplify the materials use within a design context and to establish additional restrictions within 3D printing plastic fishing gear filaments.

Figure 104. Computer-aided design Water sports equipment

Figure 105. Water sports equipment renders

Figure 106. 3D printed prototypes of Water sports equipment

Figure 107. 3D printed prototypes of Water sports equipment

Figure 108. 3D printed prototypes of Water sports equipment

Figure 109. 3D printed prototypes of Water sports equipment

The water sports equipment prototypes validated the use of net filaments as well as the buoy and recycled polyethylene filament as unique surface qualities that could not be replicated with other materials, enhanced the conceptual designs. Each material proved to successfully 3D print a variety of forms and small detailed patterns, that could be developed to heighten the use of customisation. Additionally, models demonstrated that the materials could reach the full size of the Ultimaker's height of 300mm, suggesting that the upcycled filaments can produce large scale objects.

Cylindrical forms 3D printed better than others, as equal tension between layers when drying allowed the model to stay uniform and accurate. After attempting a large variety of prototypes, it was found that polyethylene-based tape significantly assisted in reducing model warping, which then guaranteed less deformation throughout the entire model. Additional attributes such as model overhang and infill density should be considered to ensure strength and stability throughout future models.

Conceptual Area 2:

SUPPORTING ENDURING COMMUNITIES & PARTNERSHIPS

Giving back to the community, establishing Sanford's sustainable efforts, and introducing society to innovative upcycling initiatives are the main objectives behind the designs within this conceptual area. In a way similar to the first conceptual area, each design idea would be produced through a scenario where Sanford partners with New Zealand community groups, as seen in figure 110, to create designs that are suitable for public spaces. The designed applications are educational and functional items for everyone to enjoy. The proposed design ideas include widespread furniture, playground objects, communal beach showers and modular pontoons. While each material was again considered for these designs, 100% fishing net filament and 50% buoys with 50% recycled polyethylene filament are the materials used to create physical prototypes.

Figure 110. Conceptual area 2 scenario

Concept 2a - Bespoke Designs for the Surf Life Saving Club

Figure 111. Conceptual area 2 drawings

Concept 2b - Designing for Public Places with the city council

Figure 112. Conceptual area 2 drawings

Concept 2c -Designing Equipment for New Zealand Boating Clubs

Figure 113. Conceptual area 2 drawings

Designing for Public Spaces

3D printed furniture and playground objects made from plastic fishing gear have the potential to educate a wide range of society on how local upcycling initiatives can provide a solution to domestic plastic waste streams. They also initiate the use of upcycled materials within functional everyday objects, which can create inspiring and sustainable communal areas. Additionally, 3D printing can incorporate unique textures and forms representative of the marine environment. These representations can express Sanford's sustainable efforts for their plastic waste streams as they depict where the material originated from. The physical prototypes

created within this stage consist of using net filaments because of their robust qualities and ocean-based colours, which can create sturdy and playful objects. Furthermore, buoy and recycled polyethylene filament is additionally used as its strong traits, and dark black tones can create stable and modernised designs that could be implemented within a variety of public spaces. These prototypes establish the use of the materials in another design context and help in identifying further material restrictions within 3D printing.

Figure 114. Computer-aided design playground pieces and public furniture

Figure 115. Playground pieces and public furniture renders

Figure 116. 3D printed prototypes of public furniture

Figure 117. 3D printed prototypes of public furniture

Figure 118. 3D printed prototypes of public furniture

Figure 119. 3D printed prototypes of public furniture

Through design experimentation, it was decided that public furniture would be developed and produced into physical prototypes, rather than the playground pieces. Furniture is a universal design that can be implemented within countless environments, making it the stronger design idea for communicating the upcycling initiative. Each prototype conveyed high-level detail in 3D printing marine-inspired textures such as scales, gills and shell-fish surfaces, which ensures its relation back to the fishing industry and further accentuates Sanford's sustainable efforts. Additionally, each material was strategically placed within the prototypes to ensure strength

within the chairs and to subtly symbolise the origin of the materials again by representing fish fins and tails, as well as shell outlines in the negative space. Small model deformations within these prototypes were attributed to sharp corners that were prone to lifting off from the bedplate as well as the use of thin walls that need infill to reduce model distortion. Future models should gradually flow with curved corners to minimise lifting, and infill density should be thoughtfully distributed to use minimal material while also providing stability.

Conceptual Area 3:

PROTECTING & ENHANCING THE ENVIRONMENT

Design applications within this conceptual area aim to 3D print used plastic fishing gear into products that help the environment and its inhabitants thrive. Conceivably, each design idea expressed within this stage would be produced through a collaborating scenario between Sanford and New Zealand certified charities or government-funded agencies, as seen in figure 120. Each design focuses on how a product and its user can aid in protecting New Zealand’s native wildlife or mitigate further environmental damage. These design ideas include nesting boxes and protective structures for native birds, equipment that minimises the amount of plastic within the marine environment and forms of transportation that reduce carbon emissions. The material used to construct physical prototypes within this stage is the 60% lead rope with 40% recycled polyethylene filament.

Figure 120. Conceptual area 3 scenario

Concept 3a - Designing for New Zealand Native Species with the Department of Conservation

Figure 121. Conceptual area 3 drawings

Concept 3b -Equipment made with sustainable coastlinesthat Prevents more Marine Pollution

Figure 122. Conceptual area 3 drawings

Concept 3c - Designing with GenLess to Reduce Carbon Emissions

Figure 123. Conceptual area 3 drawings

Nesting Boxes

3D printed nesting boxes made out of used plastic fishing gear supports New Zealand's native blue penguins flourish by generating homes for them within their natural habitats. Inspiration for this design idea was taken from a visit to a small beach on the west coast of the North Island, known as Pukerua Bay (Figure 124). At the beach it was discovered that penguins tend to nest under houses due to the lack of protected areas along the coastline; therefore this design idea helps in ensuring the native blue penguins are safe by providing them with secure shelters. Standard nesting box designs are usually made from wood. While these designs are

practical, 3D printed nesting boxes can be designed to mimic landscapes and blend into the natural surroundings. Additionally, the idea provides the opportunity for families, companies or organisations to "adopt" a nesting box to exemplify their commitment to upcycling initiatives and protecting New Zealand's native inhabitants. The aquaculture filament consisting of 60% lead rope and 40% recycled polyethylene is used for the designs physical prototypes, as its grey shade and variety of surface qualities are perfect for 3D printing nesting boxes that mimic rock formations.

Figure 124. Pukerua Bay

Computer-Aided Models

Figure 125. Computer-aided design nesting boxes

Renders

Figure 126. Nesting box renders

Figure 127. 3D printed prototypes of nesting boxes

Figure 128. 3D printed prototypes of nesting boxes

Figure 129. 3D printed prototypes of nesting boxes

Figure 130. 3D printed prototypes of nesting boxes

Using aquaculture filaments within the chosen design was significantly effective as stone-like structures were effortlessly impersonated by the materials colour and surface qualities. The assortment of boxes, lids and tunnels were all successfully 3D printed using the material and further details such as engravings of family names could be implemented within the design. The use of engravings could enhance the “adopting” initiative as it embodies who is responsible for the protection of New Zealand’s native inhabitants. On the other hand, through the creation of different

prototypes, it was found that the thickness of the design can significantly increase how strong the overall model is. By ensuring a robust wall structure around the entire nesting box, the protection of native blue penguins can be reinforced. Several models became prone to cracking throughout the 3D printing stage, and the use of intense curves resulted in layer separations. Therefore, future models should be printed with an enclosed 3D printing chamber to guarantee less cracking, and forms must be strategically modelled to have less intense overhangs.

Figure 131. 3D print warping

REFLECTION

In regards to the initial research criteria, the anticipated scenarios within this stage exemplified systems that were localised within New Zealand, upcycled plastic fishing gear and distinguished the use of 3D printing as a manufacturing method by optimising its customising capabilities. Each design utilised 3D printing customisation by incorporating unique patterns, textures, surface qualities and engravings throughout the models. Additionally, infill densities and precise material distribution throughout models ensured minimum energy and material use. On the other hand, by developing design ideas around Sanford's sustainability agenda, innovative implementations of the materials could be established, and sustainable attributes surrounding collaboration, storytelling, consumption, upcycling materials, and utilising new technologies could be adopted. Therefore, the design experimentation stage conceptually informed how the plastic fishing gear filaments could be used to produce eco-innovative designs within a range of scenarios. However, due to the broadness of concepts within this

stage, further refinement is needed to exemplify how plastic fishing gear can be upcycled contextually into realistic designs and scenarios.

While the material experimentation stage found that consistent filament can aid in 3D print quality, the design experimentation phase reiterates the importance of creating forms that work with the materials to ensure high-quality results. Due to rapid cooling and shrinkage within materials, complex models can easily deform, split and warp as the tension between their 3D printed layers is uneven. Some procedures can be enforced to reduce the risk of these malformations; which includes the use of polyethylene tape on the print bed, higher printing temperatures and enclosed 3D printing chambers. However, the computer-aided design models should be appropriately shaped to work with the materials capabilities and guarantee the best 3D printing results.

RESOLVED CRITERIA

Through the material and design experimentation stages, various attributes were found and applied to the research criteria. The resolved research criteria guide the completion of this research as it is used to determine final materials, designs and systems that assist in answering the research question. From material experiments, it was apparent that consistent filaments had to be produced at a precise diameter to ensure high 3D printing quality. Additionally, it was found that the materials had

to work within the printer for accurate models to be produced. Whereas, the design experiments reinforced the idea of working with the materials 3D printing qualities to make sure fewer deformities occurred within models, resulting in higher quality 3D prints. Furthermore, it revealed the need to demonstrate the use of the materials in context, to acknowledge how plastic fishing gear could be upcycled into real-world eco-innovative designs.

OUTPUT	CRITERIA
Materials	<div><div>- Materials should consist of a range of significant plastic fishing gear waste streams, obtained from Sanfords, Havelock and Timaru facilities in New Zealand.</div><div>- Material quality needs to be recovered or consist of a hybrid mix that can be upcycled within a circular closed-loop system.</div><div>- Materials should inform design decisions and must be applicable to its chosen design.</div><div>- Materials must formulate and produce accurate filaments that consistently remain between 2.3mm to 2.85mm in diameter.</div><div>- Materials have to effectively 3D print to ensure high-quality print results.</div></div>
Systems	<div><div>- Systems are required to be localised within New Zealand.</div><div>- Systems should be situated around upcycling plastic fishing gear.</div><div>- Systems must be circular and distinguish why 3D printing is used as the manufacturing method.</div></div>
Designs	<div><div>- Designs should be high quality, apply sustainable attributes proposed by Sherin (2017), and be inspired by Sanford's sustainability agenda to identify innovative areas of implementing upcycled plastic fishing gear.</div><div>- Designs must utilise the unique capabilities of the 3D printer, to ensure minimum energy and material consumption, and offer customisation across all concepts.</div><div>- Designs should work with the properties of the materials to ensure fewer deformations occur within models, and high-quality outputs can be created.</div><div>- Final designs should contextually represent 3D printed upcycling and eco-innovation.</div></div>

Figure 132. Resolved research criteria

Chapter 7:
DESIGN PROPOSITION

Outline

Using the resolved research criteria, one scenario and design idea is developed for each conceptual area to exemplify the use of upcycled plastic fishing gear within a specified context. All resolved designs are 3D printed using the Ultimaker 3 Extended and incorporate buoy, aquaculture rope and fishing net filaments to demonstrate how a range of different

plastic fishing gear can be upcycled into eco-innovative products. Each design aims to exemplify a variety of sustainable attributes and upcycling opportunities that aid in answering the research question from multiple standpoints.

Figure 133. 3D printing finalised designs

Creating a safe & high-performance culture with the ocean

WATER SPORTS EQUIPMENT: PADDLES

Scenario & Design

The final design for the 'Creating a safe and high-performance culture with the ocean' scenario is situated around paddleboarding paddles that embody upcycling productions, identify new markets and deliver compelling stories. Ideally, the paddles would be created through a collaboration between Sanford and the New Zealand-based extreme sports company, Torpedo7. Within this collaboration, local marine waste is upcycled to produce paddles that not only initiate an enjoyable relationship between the user and the ocean but also create a thought-provoking idea on keeping our oceans clean by reusing marine waste within recreational ocean activities. By utilising the unique capabilities of the 3D printer, the paddle designs can additionally look at new markets, more specifically, the growing environmentally conscious consumer market, through the use of customisation. Customisation can ensure each paddle has integrated unique patterns that are inspired by endangered marine species. This addition to the design of the paddles is based on the idea that a small portion of the product's proceeds can be donated to charitable industries that support the conservation of the specified marine species, who are currently endangered due to plastic pollution. The use of upcycled marine waste, as well as charitable customisation, is a strong incentive for environmentally conscious consumers to support this eco-innovative design as it can tangibly symbolise their values for protecting the marine

environment and supporting enduring upcycling initiatives. Furthermore, to complete the sustainable story of upcycling plastic fishing gear into recreational ocean-based products, each paddle can be returned at its end of life to Torpedo7, to be granulated and formulated back into filament to be used again within future productions.

Paddles, grips and handles were all 3D printed using 100% dark blue net filament, 100% yellow net filament and 50% buoy with 50% recycled polyethylene filament. The use of these materials within the organic forms ensured high-quality and robust 3D prints were created. Additionally, each material offered an opportunity to enhance the idea of charitable customisation through distinctive ocean based-colours. The unique green, blue and black colours found on the prints can mimic similar colours found on endangered marine species. In the case of the final 3D printed prototypes, the blue designs represent whale sharks, the green designs represent green turtles, and the black designs represent humpback whales. Beyond these prototypes lies a large variety in unique colours found within other plastic fishing gear that could be utilised through similar recreational concepts to introduce the conservation of a wider variety of endangered marine species to the upcycling initiative.

Figure 134. Finalised paddle designs

Figure 135. Final patterns

Figure 136. Final paddles

Figure 137. Final grips

Figure 138. Final handles

Figure 139. Paddle contextual shots

Figure 140. Paddle contextual shot

PUBLIC FURNITURE: SEATING

Scenario & Design

The final design within the 'Supporting enduring communities and partnerships' scenario is set around public seating that gives back to the community, celebrates its material life story and educates society on localised upcycling initiatives. Hypothetically, the communal seats would be created through a partnership between Sanford and a local community council within New Zealand. Throughout this partnership, 3D printed designs can be co-created by the community and Sanford, to ensure the furniture pieces are suitably incorporated within an environment, while still recognising Sanford's sustainable upcycling efforts by indicating where the materials originated from. The anticipated designs could utilise 3D printing customisation to achieve these goals. Unique forms can be distinguished for furniture pieces to fit precisely into communal areas, while the use of distinctive textures and negative space influenced by the marine environment can subtly reference the origin of the material. Through the implementation of these designs throughout society, the public can be educated on innovative upcycling initiatives that locally process domestic

plastic waste into functional, everyday products. In doing so, the upcycling initiative could receive significant attention and therefore, more 3D printed furniture made from used plastic fishing gear could be designed and introduced to a wide variety of communities throughout New Zealand.

The public furniture piece was 3D printed out of the 50% buoy and 50% recycled polyethylene filament. The use of this material within a curvacious and thick-walled chair resulted in a sturdy and accurate 3D printed model. The materials black tones create a modernised piece of furniture that could fit into a range of environments. Whereas, its glossy finish intensifies the fish scale texture as the light gradually accentuates individual areas of the form. The steep curves on the underside of the chair act as a form of structural integrity, while also visually communicating the origin of the material subtly by embracing the shape of a fish fin within the negative space.

Figure 141. Final seating design

Figure 142. Final seating design curves and back

Figure 143. Final model textures and side

Figure 144. Finalised seating design close-ups in context

Figure 145. Finalised seating design in context

NESTING BOXES: FOR LITTLE BLUE PENGUINS

Scenario & Design

The final design for the 'Protecting and enhancing the environment' scenario is based around 3D printed nesting boxes for Little Blue Penguins that provide necessary shelter, create captivating collaborations, and utilise hybrid materials within a closed-loop system. Theoretically, the production and implementation of the nesting boxes would be achieved through a partnership between Sanford and New Zealand's Department of Conservation. This localised production of 3D printed nesting boxes out of used plastic fishing gear is significantly noteworthy today, as Little Blue Penguins have been found to nest under houses due to the lack of protected areas along New Zealand's coastline. In order to produce larger quantities of nesting boxes to solve this problem, an additional third-party candidate can collaborate with the project by funding the creation of a Little Blue Penguin nesting box. In doing so, the new candidate would be effectively recognised as a family, company or organisation that is doing their part to protect New Zealand's native species. The use of 3D printing customisation can reinforce this "adopting" scheme, by producing exclusive engravings on the nesting box that represent the third party candidate or the native species they are protecting. Additionally, 3D printing customisation can utilise imperfect hybrid materials within this design idea as unique surface qualities can be exploited to mimic rock formations that are commonly found within the Little Blue Penguins natural habitats.

Therefore, aquaculture rope filament is the predominant plastic fishing gear material that is upcycled and integrated within this design idea.

The nesting box design is 3D printed using the 60% lead rope with 40% recycled polyethylene filament. While the grey tones and rough surface aspect of this material emphasises a rock-like quality, the 3D printed model employs organic curves and rigid corners to impersonate a rock formation further. The idea of resembling rock formations within the 3D printed nesting boxes means that New Zealand's pristine landscape is not disrupted, as the nesting box blends into the natural environment. While the physical design only utilises one aquaculture rope filament, the variety in grey shades and surface qualities found in other aquaculture rope filaments ensures that a collection of different natural environments can be mimicked. Therefore, nesting boxes for Little Blue Penguins are not limited to light grey rock coastlines and can be employed throughout multiple habitats. Kororā is the Maori name for Little Blue Penguin and can be seen embossed on the back of the nesting box with the outline of a Little Blue Penguin next to it. This unique design attribute specifies the protection of Little Blue Penguins and can be customised according to what native New Zealand bird species are being protected by the 3D printed nesting box.

Figure 146. Finalised nesting box design

Figure 147. Final nesting box design close-up and top

Figure 148, Final nesting box design engraving and tunnel

Figure 149. Final nesting box design in context

Figure 150. Final nesting box design in context

Chapter 8:
DISCUSSION & CONCLUSION

DISCUSSION

Overview

Finalised eco-innovative designs each proved to have fulfilled the resolved research criteria as materials, systems and designs were determined to a high standard. However, one criterion based around the minimum energy and material usage within designs was challenging to achieve. Printing times varied depending on the materials success within the 3D printer, resulting in more power being used. Additionally, by using larger quantities of materials within the 3D printing process, more plastic fishing gear waste can successfully be upcycled through 3D printing. Therefore, this criterion

was not fulfilled as it did not coincide with 3D printing upcycled materials. Overall the finalised research established how plastic fishing gear could be upcycled through distributed manufacturing technologies to mitigate commercial fishing waste and create eco-innovative designs.

Throughout the processing, experimenting and developing stages of the research lies a variety of implications that have been separated and categorised within this chapter as impacts, challenges and future research.

Impact

This research established a set of processing stages that following work regarding 3D printing with plastic fishing gear can adopt to effectively upcycle materials step by step into consistent filament for 3D printing. The six-part upcycling procedure that consists of collecting, cleaning, melting, granulating, formulating, and 3D printing has well-determined technologies and processes needed to ensure materials can be recovered. Within this research, the quality of the materials was reclaimed or consisted of hybrid mixes of synthetic fishing gear and sea contaminants that can still be upcycled as long as they remain within the circular closed-loop system. While the implementation and adoption of other procedures may be necessary to apply the upcycling system into commercial use, the research has validated that a range of plastic fishing gear can be effectively and feasibly upcycled through distributed manufacturing technologies.

The tangible outputs of this research include 3D printing filaments and 3D printed prototypes made out of New Zealand plastic fishing gear waste that are encompassed within scenarios that provide long-term models across potential stakeholders, engagement with the community and contextual designs. The implementation of these ideas for upcycling plastic fishing gear has already stimulated interest within the industry before the completion of this research portfolio. Recognising industry-wide potential of this research, the Marine Farming Association Limited in Marlborough, New Zealand, is currently writing an article on this upcycling project to share with the broader members of their association and potentially extensive publishing domains within New Zealand. The rapid industry interest in this research suggests that there is a high possibility that upcycling initiatives for plastic fishing gear could be implemented within a real-world practice.

Challenges

The majority of upcycling procedures executed throughout this research had standard practices that could be used as the starting points for establishing finalised methods for processing plastic fishing gear. However, the cleaning of plastic fishing gear lacks a standard practice. Therefore, an extensive amount of experimentation was needed to develop a unique, sustainable, responsible and effective finalised cleaning method for the range of plastic fishing gear within this research. While the hands-on approach was intensively time-consuming, it was adequate for small batches of plastic fishing gear. For the broader implementation of this upcycling process, further research would be required to productively clean large portions of plastic fishing gear at an excelled rate.

Undisclosed materials within some of the monofilament plastic fishing gear made the melting, formulating and 3D printing stages of this research exceptionally challenging. Extensive experimentation was required to understand the materials melting points, which resulted in some plastic fishing gear samples being eradicated from the remaining research. While many of the monofilament plastic fishing gear samples were successfully upcycled throughout this research, material testing could be utilised to understand what the plastic fishing gear consists of entirely, which would eliminate the possibilities of the materials being susceptible to the upcycling process.

Future Research

While the undertaken research throughout this portfolio laid a significant foundation for upcycling plastic fishing gear at a research-level, the need for large-scale 3D printing upcycling initiatives is substantial for commercial growth. The use of large scale 3D printers, such as the Bigrep and robotic 3D printing arm combined with affordable ‘all in one’ processing technologies distinguish an opportunity to upcycle the substantial plastic fishing gear waste stream locally through large-scaled upcycling initiatives. While these technologies are still within their infancy, continuous developments and overseas adoptions of the technologies, as discovered within the background research, suggest that it is feasible to extend this research into large scale productions.

Moving beyond plastic fishing gear, the validated upcycling procedure used within this research creates transferable knowledge that could be adapted to upcycle other plastic waste streams. The introduction of new plastics within the upcycling initiative could result in unfamiliar material qualities being discovered; therefore, novel 3D printed designs could be created. With extensive plastic waste streams extending well beyond the commercial fishing industry, it is relevant that localised upcycling initiatives are considered for a variety of significant domestic plastic waste streams within New Zealand.

CONCLUSION

Plastic fishing gear is one of the most severe and dangerous forms of ocean plastics that is commonly abandoned, lost or discarded within the marine environment due to the lack of localised recycling options for the commercial fishing industry. Therefore, there is a crucial need for more localised upcycling initiatives that reuse materials within a circular closed-loop system to ensure this problem does not continue Distributed manufacturing technologies, including 3D printing, combined with shredding and extruding technologies can establish solutions to this problem as a range of used plastic fishing gear can be processed through a circular system and upcycled into new eco-innovative designs. Through extensive processing as well as material and design experimentation, a range of plastic fishing gear that includes buoys, aquaculture ropes and fishing nets were successfully upcycled into consistent 3D printing filament using distributed manufacturing technologies. Additionally, a series of 3 conceptual eco-

innovative designs were 3D printed using the upcycled plastic fishing gear filaments. Each contextual design focused on implementing sustainable attributes while looking for innovative applications that reinforced the use of the upcycled filaments. Furthermore, customisable capabilities of the 3D printer were utilised to create unique eco-innovative designs that fortified the use of 3D printing as the manufacturing method. The overall achievements of this research not only establishes how plastic fishing gear can be upcycled through distributed manufacturing technologies into a spool of 3D printing filament and eco-innovative designs. But also identifies the compelling need to shift away from the linear economy, to be introduced to something more circular. Hence the title of this research, 'From Line to Loop'.

Figure 151. From Line to Loop

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From Line to Loop

A circular 3D printing initiative for upcycling commercial fishing plastics

By Matthew O’Hagan