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Circular Ocean WP3.1: Potential applications of 3D Printing (3DP) in the recycling of Fishing Nets & Ropes (FNR's)

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In pursuit of innovative and sustainable solutions for marine plastic waste, the Circular Ocean project seeks to inspire enterprises and entrepreneurs to realise the hidden opportunities of discarded fishing nets and ropes in the Northern Periphery & Arctic (NPA) region.

As increasing levels of marine litter is particularly pertinent to the NPA region, the Circular Ocean project will act as a catalyst to motivate and empower remote communities to develop sustainable and green business opportunities that will enhance income generation and retention within local regions.

Through transnational collaboration and eco-innovation, Circular Ocean will develop, share and test new sustainable solutions to incentivise the collection and reprocessing of discarded fishing nets and assist the movement towards a more circular economy.

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Circular Ocean WP3.1: Potential applications of 3D Printing (3DP) in the recycling of Fishing Nets & Ropes (FNR's)

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1. Background

As a technology that is becoming increasingly accessible to individuals and SME's, 3D Printing (3DP) or additive manufacturing presents a number of unique 'print-on-demand' or 'print-as-a-service' opportunities for localised product manufacture. The technology enables on-demand and on-the-spot production, almost limitless customisation and supports the use of a variety of compatible materials including, metals, ceramics, resins, polymers, rubberised plastics and even food and human cells. As an emerging technology gaining popularity, there is considerable experimentation exploring new applications and processes afforded by the flexibility of 3DP. Current uses include rapid prototyping, on-demand components, custom-made prosthetics and hobbyist figurines as well as replacement parts for the repair and upgrading of existing products (e.g. www.endlessobjects.com). 3D printers themselves are also rapidly improving with efforts geared towards increasing efficiency, quality and printing speed along with expansion of the range of printable materials. Supporting industries, such as digital design libraries and filament retailers are also growing in number, broadening the available catalogue of downloadable designs.

Whilst 3DP using Recycled Plastic Filaments (RPF), such as Acrylonitrile Butadiene Styrene (ABS) and High Impact Polystyrene (HIPS), has only recently emerged onto the market, the ubiquitous availability of plastic waste in today's society presents a potentially attractive business opportunity for further development. Where there are steady and consistent streams of plastic waste there exist significant opportunities to convert these otherwise discarded materials into valuable products using local eco-innovation and 3DP technology. Fishing ports are one such example, with as much as 640,000 tonnes (UNEP, 2009) of fishing nets and ropes (FNRs) dumped at sea each year. Not only do these materials pose a serious threat to marine ecosystems, but they also present a significant waste stream of valuable plastic materials. Opportunities may therefore exist for encouraging existing SMEs (or to stimulate start-up enterprises) to create, develop and commercialise selected 3D printed products from recycled FNRs.

This working paper will provide an overview of the current 3DP industry and an assessment of the available 3DP technologies. Each technology will be evaluated in relation to its potential for processing Recycled Plastic Filaments (RPF) and, more specifically, recycled FNRs. To date, FNRs have not yet been recycled for use with 3D printers; however, they have successfully been processed into consumer products by other means. This paper will therefore use the lessons learned from a number of relevant case studies in order to compile a desk-based review of the potential opportunities and challenges to FNRs being successfully recycled into valuable products using 3DP.

2. 3D Printing Technology Overview

3DP involves modelling a three-dimensional (3D) object using computer aided design (CAD) software. There are a number of online libraries containing ready-to-use open-source product files, which can be downloaded and printed; either as they are or following modification (e.g. www.thingiverse.com, www.myminifactory.com). There are also a number of available software packages, such as Google Sketchup, which allow entrepreneurs and/or designers (product/engineering) to create and manipulate their own 3D rendering. Note that, whilst basic versions of Google Sketchup and some other 3D modelling programs are free, upgrade and license fees may apply if used for commercial purposes. There have also been several developments in the use of CAD to actually generate designs, as well as model them. Examples include Michael Hansmeyer's 'unimaginable shapes', whereby algorithms turn a simple cube into immensely complex 3D designs that would otherwise be near impossible to imagine (Hansmeyer, 2012), and the algorithmic design of a partition for the Airbus, which is both stronger and lighter thanks to its biomimetic structure (Nilsson, 2015). It's possible that down the line, designers will be able to specify the performance parameters of a product that computer systems will develop into a number of possible designs from which to choose (Moss, 2015).

Once a product has been modelled using 3D CAD software, the file needs to be converted into a Standard Tessellation Language ('.STL') file, imported into the slicer software which dissects the object into numerous layers that can then be sent to a 3D printer in the form of GCode, a commonly used numerical control programming language designed for computer aided manufacturing (CAM); in this case it allows the automated control of the 3D printer. It's currently possible to print using a personal, desktop 3D printer, send files to a commercial 3D printer or even send them to another, nearby individual with a desktop 3D printer via online platform, 3D Hubs.

There are several variations of 3DP using different types of 3D printing technologies, which lend themselves to certain materials and applications. Some of the more popular include:

2.1 Fused Filament Fabrication (FFF)

This process involves heating plastic filament as it passes through the nozzle of a 3D printer. The print head moves according to the .STL file, depositing layer upon layer of melted plastic, building up the model as the print bed is gradually lowered with each layer (Feeney, 2013). Once complete, models are typically ready to use. The only exception is in the case of complex prints, e.g. those with overhanging elements, as these require support structures during printing, which need to be removed manually post-production (See Figure 1).

Figure 1. A complete Fused Filament Fabrication print prior to removal of support structures (left) and after (right) (3Dprintr Magazine, 2015)

Typical materials used for FFF filament are:

- Polylactic Acid (PLA)
- Acrylonitrile Butadiene Styrene (ABS)
- High Impact Polystyrene (HIPS)
- Polyvinyl Alcohol (PVA)
- Polyethylene Terepthalate (PET)
- Polyamide / Nylon (PA)
- Polycarbonate (PC)

(Matterhackers, 2016)

This technology uses relatively simple, accessible and affordable components (i.e. no lasers required). As such, FFF printers have grown rapidly in popularity amongst hobbyists since the expiration of the patent on FFF printers in 2009 (Lancker, 2015). The ability for numerous companies to develop and start selling their own versions of FFF printers has also helped to bring prices down considerably. Likewise, the number of filament retailers has also increased significantly.

The key limitations determining filament compatibility with any given FFF printer are namely filament diameter and melting point. Whilst there has been no strict 'standardisation' imposed on 3DP filament producers or FFF printer retailers, filament and nozzle diameters are commonly set to either 1.75mm or 3mm, providing compatibility between the vast majority of available filaments and printers. Melting point simply comes down to the material composition of the filament. The ideal printing temperatures of polymers commonly used to make 3D printing filament typically range from 180°C to 310°C (Matterhackers, 2016). Maximum print (extrusion) temperatures vary between 3D printer models and can be as low as 230°C, which may limit print material options for some printers.

An alternative to using ready-made filament is to simply purchase the raw materials in pellet form and pass these through an extruder set to the required filament diameter (Cocomeri, 2015). A number of extruders are available for purchase and open-source blue prints for DIY versions are also becoming widely available (Pearce, 2011; Peels, 2014; Millsaps, 2015), including this 3D-printable example below (Figure 2):

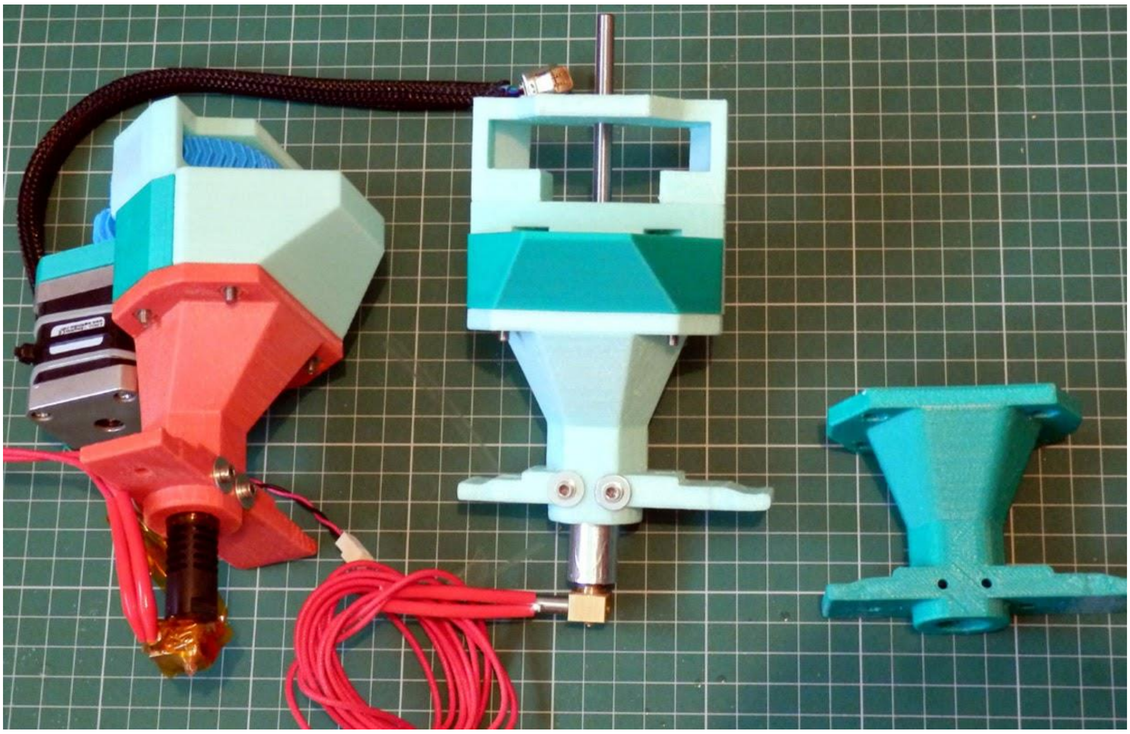

Figure 2. DIY filament extruder with 3D printed housing

Source: https://www.youmagine.com

This method is considerably cheaper compared to the purchase of ready-made filament and also benefits from the option to adjust the diameter of the filament being produced. Additionally, it opens up potential for the on-site recycling of plastic wastes and discarded prints into new printing filament with the addition of a simple shredding device. Plastic waste can then be broken down into small pieces and fed into the extruder to create spools of recycled filament ready for 3D printing (Peels, 2014). Provided the plastic waste used is homogenous in its composition (e.g. 100% ABS), the filament produced will melt at a consistent temperature. Note, however, that this may only be repeated a limited number of times before the polymer starts to depolymerise where it may become brittle and unworkable.

2.1.1 Case Study: Recyclad3d

Finalists in the 2016 iteration of the Plastic Fantastic Challenge, Recyclad3d, proposed the set up of a plastic recycling and 3D-printing museum on the island of Syros, Greece. The idea behind this was to encourage both tourists and local residents to collect and recycle plastic (PET) bottles before they end up in the marine environment. It was proposed that the recycled bottles could then be processed locally by means of shredding, re-extruding and FFF 3D printing to create unique consumer products to be displayed in the museum, generating interest in plastic recycling and 3D printing capabilities (Tsirepa, 2016). Whilst FNR materials have not been considered in this particular instance, there may be interesting parallels to be drawn as the Recyclad3D project involves both the creative use of localised, plastic waste streams and 3DP technologies to facilitate small-scale, localised polymer recycling in a coastal community.

2.1.2 Case Study: Precious Plastic

Launched by Dutch designer, Dave Hakkens, Precious Plastic is an open source guide for the construction of four DIY plastic re-processing machines, including a shredder, extruder and injection and compression moulders. The blue prints have been designed so that the machines may be made simply and cheaply from widely available materials and will then be able to process common plastic waste streams, including but not limited to, bottles and packaging. Whilst the technology behind the machines is relatively simple (i.e. applying heat to remould thermoplastics), the Precious Plastics project represents an accessible means of obtaining and sharing the information needed to build small-scale machines on a local level (Hakkens, 2016). Whilst the Precious Plastic project does not include a 3DP element, the shredder and extruder hold potential for use in an FFF 3DP context. The open source blue prints for the machines provide a DIY alternative to 'off-the-shelf' recycled plastic filament devices currently available, including the Felfil, Recyclebot, Lyman Filament Extruder, Noztek Pro and ProtoCycler to name but a few.

It is therefore evident that there exists considerable and growing interest in Recycled Plastic Filaments (RPF) for the purpose of FFF 3DP. It not only offers cost savings in relation to the raw materials but also appeals to those concerned about the amount of plastic waste generated by the 3DP industry. As extruding RPF from a variety of thermoplastic waste streams is a relatively straightforward and cost effective process, it is likely that FNRs, which are also made from thermoplastics, will be able to follow the same process with some success. There are, however, several considerations and challenges specific to FNRs that will need to be addressed before this can be considered a commercially viable option. For further details refer to section '*4. 3D Printing Options for FNR's'.*

2.2 Selective Laser Sintering (SLS)

In this process a thin layer of powdered material, typically nylon (polyamide 12), metal or ceramic, is spread over the print bed. A laser then fuses sections of the powder as it traces its path according to the .STL file. The layering of the powder and subsequent tracing of the laser continues until the print is complete (Feeney, 2013). The product then needs to be removed from the surrounding un-fused powder material and cleaned using air jets. A polishing service is typically available, creating a smooth finish to the final product.

2.2.1 Case Study: Digits to Widgets and Defiant Laboratory

London based 3D printing service provider, Digits to Widgets, and technology and innovation agency, Defiant Laboratory, recently hosted a workshop focusing on the commercialisation of SLS 3D printed products. It was explained that SLS 3DP is able to produce superior results in terms of both print strength and resolution, when compared to FFF printing, although SLA printing continues to produce prints with the least stratification (visible layers). Additionally, by printing different lengths and thicknesses of the nylon powder using SLS, prints acquire different properties, such as increased flexibility, rigidity or strength. For example, London based designer and architect Ron Arad was able to produce single-component sunglasses frames by simply including perforations in the print where the hinges of the glasses would traditionally be located.

Another benefit of SLS printing is that the accumulative layers of powder provide support to thinner sections of the object being printed throughout the process, removing the need for support structures, which are often necessary in FFF and SLA printing.

In terms of the potential for using recycled polymers, SLS is limited as the process currently uses a very fine and uniform grade of nylon (polyamide 12) powder, which is not currently reclaimed for reprocessing into new powder. Further to this, the heat generated by the laser emanates from the print area throughout the printing process and results in the distortion and morphing of the surrounding powder particles, lowering their quality. This means that the excess powder that remains following the production of a print cannot be directly returned to the printer for subsequent prints. Instead, it must be cut 50/50 with virgin powder, which raises the quality to a high enough standard that successful prints may be produced. It should be noted, however, that should the popularity of SLS 3DP continue to grow to a level whereby discarded prints and degraded polyamide 12 powder are produced in sufficient quantities, recycling programmes for the material are likely to arise (Rowley & Michaels, 2016).

Whilst SLS may not be a suitable technology for the localised reprocessing and 3DP of FNR polymers the potential for SLS products to out-compete those made by the FFF process in terms of quality, resolution and strength is an important point to consider when formulating business plans and deciding on the types of products to be manufactured.

2.3 Stereo Lithography (SLA)

This form of 3DP uses a vat of ultraviolet (UV) curable polymer resin, which is layered onto the print bed. A UV light is then projected onto each subsequent layer, tracing a path determined by the .STL file (Feeney, 2013). The model is then built up layer by layer as the print bed is gradually lowered or raised. Once complete, the finished product is removed from the unreacted resin and cleaned before being ready to use.

2.3.1 Case Study: Olo Smartphone 3D Printer

Olo is the world’s first smartphone 3D printer, which recently found success on crowd-funding site, Kickstarter. The device comprises a blacked-out box with a transparent base, which uses light emitted from a smartphone screen to set photo-curable resin; essentially creating a ‘desktop’ SLA 3D printer. The Olo is affordable, starting from $79.00, and is complemented by a range of compatible resins with a selection of colours and varying degrees of flexibility. The limitations, however, include print size restrictions and the fact that the smartphone must remain inside the device for several hours whilst printing takes place. Additionally, recycling for photo-curable resin, once printed, is not currently readily available (Yusuf, 2016).

Whilst it may not be possible to print with recycled FNR polymers using SLA technology, it is important to understand the other methods of 3D printing and how accessible and prevalent they are. With the high quality achieved by SLA printing, the range of different resin options available (flexible, rigid, transparent, opaque) and now the accessibility of the technology through desktop devices, such as Olo, it may be difficult to compete when selling products printed using FFF technology and recycled FNR polymers.

A summary of each 3D Printing method’s performance can be found below:

Table 1. Common 3D Printing Technologies and their Performance:

Performance Criteria	FFF	SLS	SLA
Print Stratification (visible layers)	Significant, visible	Visible, can be reduced through polishing	Barely visible
Print Strength	Fair	High	High

Surface Detail	Fair	High, although polishing can remove some finer surface details	Exceptional
Supports Required	Yes, in some instances	No	Yes, in some instances
Material Selection	Wide, including most thermoplastics and a range of other materials (e.g. food)	Limited to very fine, ubiquitous powders of either PA12, metal or ceramic	Fair, confined to UV curable resins, however, these include translucent, opaque, flexible and rigid variations
Recycled Materials Available	Yes, RPF currently available and in use	No, although there is scope for recycling discarded prints in future	No
Set-up Costs	Low	High*	High*

*Professional-grade equipment typically very expensive, however, desk-top versions have now been, or are in the process of being, released

Source: Adapted from: (De Maria, 2014), (Thu, 2014), (Anusci, 2016) and (Lumb, 2013)

3. Typical Materials in Fishing Gear

Fishing Nets and Ropes (FNR's) are typically made from a variety of polymers

- Polyamide / Nylon (PA)
- Polyester (e.g. PET)
- Polyethylene (PE)
- Polypropylene (PP)
- Aramid (e.g. Kevlar)
- HDPE (High Density Polyethylene)

(Oxvig & Jansen, 2007)

4. 3D Printing Options for FNR's

Fishing ports are therefore potentially localised sources of high quality plastic waste materials in the form of FNRs, which could hold potential in fostering coastal markets for 3DP products. Some examples are listed below, including a unique 3D printed surf fin that mimics the structure of a humpback whale flipper for superior performance (Halterman, 2015).

Link: http://3dprint.com/54948/3d-printing-surfboard-fins/

In addition to commercial products, it may also be possible to use 3DP and RPF to produce fishing related tools and accessories for local use. Examples include a netting needle and fishing lures.

Link: http://www.thingiverse.com/thing:5019

Netting Needle by TimB
Published on December 3, 2010
www.thingiverse.com/thing:5019

Link: http://www.thingiverse.com/thing:25437

Fishing lures by sirmakesalot
Published on June 21, 2012
www.thingiverse.com/thing:25437

However, there are a number of considerations to bear in mind when evaluating the success of FNR polymers in 3DP applications and further research and experimentation is needed. Some key points have been included below.

4.1 FFF Printing with Recycled FNRs

Positives

- FFF 3DP may be the most feasible option for SME's due to the relative ease and affordability of the initial FFF 3DP set up. The technology enables the manufacturing of customisable products on a local scale, including replacement parts, on-demand products (e.g. crampons in snowy conditions) and specialty materials for use in construction (e.g. strong, lightweight structures)
- FFF 3DP therefore holds potential for remote areas where there are long lead times for on-demand product manufacture
- Currently FFF 3DP holds the most potential for the use of recycled plastics to print products, as it simply requires thermoplastics extruded into filament as the raw material. SLA on the other hand requires ultraviolet (UV) resins and SLS uses a very fine, uniform powder material that is difficult or impossible to achieve by processing any available waste plastic streams.
- The extrusion process is fairly simple, involving sorting plastic waste by polymer, shredding it and then forcing the material through a nozzle equipped with an adjustable heater.
- In the case of FFF 3DP businesses, individuals and groups are already experimenting with shredders and extruders to produce RPF for use in FFF 3DP, with good results. For example, Dave Hakkens has recently launched open source blue prints for DIY plastic reprocessing machinery as part of his Precious Plastic project (http://preciousplastic.com), which includes both a shredder and filament extruder.
- In addition to localised DIY filament extruders, commercial recycled filament (ABS, HIPS, PET & PLA) producers have surfaced

Issues

- For FFF 3DP, a pure and consistent supply of filament, consisting of one single material is needed as the composition determines melting point and thus the temperatures set. Caveat: it may be possible to suspend a ground-up plastic with a high melting point within a polymer with a lower melting point; this is possibly the process used by Adidas in producing their 3D printed trainer mid sole prototypes made from fishing line.

  Link: http://www.dezeen.com/2015/12/12/adidas-ocean-plastic-3d-printing-eco-friendly-trainers/

- Out of the available 3DP technologies, FFF's quality is on the lower end of the scale, with visible layers of lamination and poor strength (see Table 1)
- Contaminants (both foreign materials and polymers with different melting points) within the filament can cause blockages and subsequent damage to 3D printers. The material must therefore be cleaned as part of the recycling process and contaminants must be removed; this can be difficult with little or no access to industrial equipment.
- The quality of prints, particularly issues with layer lamination and warping, is highly dependent on the types of materials used. Nylon and HDPE, which are often used in fishing nets, (see *3. Typical Materials in Fishing Gear*) tend to be less common in filaments as they are more difficult materials to work with (e.g. due to warping). This is one of the most significant challenges when developing DIY, recycled filaments. For further information on specific materials, see related forums and YouTube reviews, such as those copied in below:

  Links: https://www.youtube.com/user/TheMakersMuse
  https://www.youtube.com/user/ThomasSanladerer

- Even within polyamides (e.g. nylon), you still have chemical variations e.g. Nylon 6, Nylon 4, 6, etc which all have different physical properties that will impact on the quality of 3DP
- There may be issues related to getting clean and good quality waste FNR polymers due to the potential for contamination with algae, salt and adsorbed/absorbed chemical contaminants. Such contaminants could cause blockages and print failures as well as present potential occupational health risks when the plastics are heated (e.g. inhalation of VOCs and particulates)

4.2 SLS Printing with Recycled FNR Materials

Positives

- Adidas has recently teamed up with Parley for the Oceans (http://www.parley.tv) as part of their Futurecraft 3D project (http://www.adidas-group.com) looking at the incorporation of 3D printing technology into their sporting products
- As part of this project, Adidas has recently produced two sports shoe prototypes that use recycled fishing nets. The first blends filaments and yarns, reclaimed from ocean waste and gill nets, to create the fabric upper. The second shoe incorporates a midsole that has been 3D printed using the SLS method and comprises recycled polyester and gill nets.

Issues

- Currently, commercial grade SLS machines and their set up are prohibitively expensive for small start-ups, although newer, more affordable models, such as the Olo, are becoming available.
- The material input needs to be a very fine and uniform powder which may require additional machinery to achieve from a recycled feedstock

4.3 FFF Printed Tools (Moulds) for Moulding Mixed Plastic Waste

Positives:

Bureo, based in Chile, is currently turning nylon fishing nets into skateboard decks and sunglasses, demonstrating the potential for FNRs to be successfully injection moulded into quality, marketable products (Brooks, 2014). The process involves a common EREMA 1310 TE recycling system, whereby the nylon nets are cleaned, shredded and fed into a preconditioning unit that compresses and warms the material. As the FNR material is then mixed, any small inconsistencies in composition are blended to create a stable, reliable melt. The nylon is then extruded into pellets using minimal heat and pressure, which are applied gradually so as to maintain the high structural integrity of the material. The nylon is then injection moulded pure to produce sunglasses frames or mixed with fibreglass to produce skateboard decks (Breuer, 2016). With 3D printed moulds and tools gaining attention in the 3DP industry, their potential to create custom moulds for the injection moulding of FNR materials could prove valuable, although further testing is needed.

Link: http://www.bureoskateboards.com/net-positiva.php

- Object Form (UK), a recycled filament company, has had some success during trials using FFF 3DP to print tools (moulds) made from Polylactic Acid (PLA), which were then used to mould molten polymers with a lower melting point than the PLA (See Appendix 1)
- Although PLA was used in this particular trial, other materials may be used to produce 3DP tooling. Trials making moulds using ABS, a material with a higher melting point than PLA are currently being carried out.
- Polycarbonate (PC) may hold potential as filament made from this material, has one of the highest melting points of the available filaments on the market. PC might be used to make moulds and then the moulds used to shape heated FNR materials.

Issues:

- The filament used to create the mould, must have a higher melting point that the molten polymers being poured into it to prevent it from warping or distorting
- Nylon has a high melting point compared with most 3DP filaments, therefore, an assessment of the FNR materials and their physical properties would be needed in order to determine which 3DP filaments would be suitable to use for mould or ‘tool’ making
- Printed polymer moulds, such as the PLA examples trialled by Object Form (UK), may be reused a number of times, but are less durable than traditional injection moulds (e.g. steel). This technique would therefore be suited to products involving variation and customisation, rather than a single repeated shape.
- As previously highlighted, potential occupational health issues may be associated with the melting of recycled FNR's (e.g. contaminants and fumes)

4.4 Chemical Recycling of FNR’s into New Materials, Ready for Use in 3DP

Positives:

- Purifying recycled polymers would remove issues associated with contamination and lack of uniformity. Both Aquafil and MBA Polymers have experience of this process with Aquafil producing Econyl – a 2nd life nylon – derived from FNRs.

  Link: www.mbapolymers.com
  Link: www.aquafil.com/sustainability/the-econyl-project/

Issues:

- It would be necessary to check the compatibility of the final polymer (following chemical recycling) with 3DP technologies through trials or consultation with a 3DP materials specialist
- Costs associated with the transportation of FNR's to and from processing facilities may be economically prohibitive depending on the distance and mode of transportation used and the quality and volume of material in each location and will need to be assessed on a case by case basis
- Removing FNR materials for chemical recycling for use by other industries would see the value held in the material removed from the local community, however, it may still be a solution to issues associated with the dumping of FNRs at sea, landfilling or incineration. Plastix Global in Denmark (http://plastixglobal.com) are currently leading the EC funded Retrawl 2 project, (http://plastixglobal.com/retrawl-brief/) which aims to implement an upscaled mechanical FNR recycling facility. However, some key points have been highlighted during the initial stages of the project, including varying degrees of FNR contamination (sand,

fatty acids, algae, copper salts) and the need to keep thermal degradation through heat processing to a minimum.

5. Conclusions

As FNR's present a potentially significant volume of polymer waste, there exists an opportunity to turn these materials into value-added products locally through the use of 3DP technology. As an increasingly accessible method for localised production, 3DP holds considerable potential, particularly as the technology lends itself towards the use of polymers. In the case of an FFF 3DP set-up there will be some upfront costs in purchasing cleaning equipment, shredders, filament extruders and an FFF 3D printer, however, if RPF can be successfully made from FNRs then on-going costs associated with the purchase of filament may be avoided. If opting for injection moulding using FFF 3D printed tools, then there would also be the additional cost of filament with a higher melting point than the FNR material in order to create the mould, as well as an injection moulder. Where moulds are created using SLS 3DP (i.e. in PA12 or metal), there would be additional costs involved in having the moulds printed commercially as SLS 3DP isn't available as a 'desk top' processes due to the considerable and expensive infrastructure required. Further tests are needed in order to determine which of these options are successful, before accurate costings can be estimated.

As with any recycled plastic waste stream, it is possible that a number of challenges will be encountered during testing. For example, contaminants and filaments comprising mixed materials with different melting points can cause blockages and damage to FFF printer nozzles, which is something to be considered. There exists concern within the industry as to occupational (indoor) air quality implications associated with the melting and printing of certain polymers. This is due to the possibility of off-gassing of potentially harmful substances, which will depend on the chemical composition of the materials being printed and the presence of contaminants. Additionally, plastics recyclers may be hesitant in considering FNRs for recycling due to the inherent potential for contaminants. The first step in this process should therefore be an assessment of the type, grade, purity and melting point of typical FNR materials, compared to the requirements of common FFF printers.

Alternative options, such as the sorting and bailing of FNR's for sale to chemical polymer reprocessing companies and organisations, such as Nofir (http://nofir.no) (onto Aquafil http://www.aquafil.com) or Plastix Global. The revenue generated could then be used to purchase pure, reprocessed polymers for use in 3D printers to create value added products locally. This would require an estimate of the volume, composition, quality and location of FNR materials and consultation with chemical polymer reprocessing companies to evaluate the economic viability of such a scheme. However, the key potential opportunity in the medium to longer-term is to create and develop businesses using retained waste FNRs as a material resource in the fishing community rather than exporting it into the distribution chain

In summary, there exists potential for the use of 3DP within local fishing communities to create value added products. FNR materials may provide a local supply of viable polymers, however, further research is needed as to the types, quality, purity and volume of materials available and the suitability of those materials in different 3DP applications.

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6. References

Anusci, V. (2016) The 9 Best SLA 3D Printers You Can Buy 2016. *All3DP*, 1 January, [Online]. Available at: https://all3dp.com/best-sla-3d-printers/ (Accessed: 1 February 16).

Brooks, R. (2014) Bureu Launches the World's First Skateboard Made from Recycled Fishing Nets. Inhabitat, 15 March, [Online]. Available at: http://inhabitat.com/bureo-launches-the-worlds-first-skateboard-made-from-recycled-fishing-nets/ (Accessed: 23 January 16).

Breuer, G. (2016) Rescuing the Ocean with Skateboards and Sunglasses *Plastics Engineering Supplement: Recycling 2016* [Online]. Available at: http://s3.amazonaws.com/rdcms-spe/files/production/public/PlasticsEngineering/Images/PENG_APRIL2016_SUPPLEMENT.pdf (Accessed 20 July 2016).

Cocomeri, C. (2015) *How Felfil is Born.* [Online]. Available at: http://blog.felfil.com/index.php/2015/09/03/come-e-nato-felfil/?lang=en (Accessed 10 April 2016).

De Maria, C. (2014) Open 3D Printing. *OS4BME: Open Source for Biomedical Engineering* [Online]. Available at: http://www.slideshare.net/fablabpisa/2014-1222-open-3-d-printing-and-fabrication-technology-cd (Accessed: 23 January 16).

Dezeen (2015) Adidas Combines Ocean Plastic and 3D Printing for Eco-friendly Trainers, *Dezeen*, 12 December, [Online]. Available at: http://www.dezeen.com/2015/12/12/adidas-ocean-plastic-3d-printing-eco-friendly-trainers/ (Accessed: 23 January 16).

Esquivel, B., Mitchell, J., Takalo, K. & Jenkins, J. (2015) *Lyman v5 Filament Extruder.* [Online]. Available at: http://hedron.technology/filament-extruder/ (Accessed 10 April 2016).

Feeney, D. (2013) *FFF Vs. SLA Vs. SLS: 3D Printing 3D Printing and Rapid Prototyping*. Available at: http://www.sd3d.com/fff-vs-sla-vs-sls/(Accessed: 23 January 15).

Maker's Muse (2015) *What Maker's Muse is all About*. Available at: https://www.youtube.com/user/TheMakersMuse (Accessed 1 February 2016).

Hakkens, D. (2016) *Machines.* [Online]. Available at: http://preciousplastic.com/machines/(Accessed 10 April 2016).

Halterman, T. (2015) Surfer Looks to Whales, Shark Skin & 3D-Printing to Make Surfing a Smoother Operation, *3DPrint.com*, 31 March, [Online]. Available at: http://3dprint.com/54948/3d-printing-surfboard-fins/ (Accessed: 25 February 16).

Hansmeyer, M. (2012) *Building Unimaginable Shapes*. Available at: https://www.ted.com/talks/michael_hansmeyer_building_unimaginable_shapes/transcript?language=en (Accessed 10 January 2016).

Lancker, P. (2015) *The Influence of IP on the 3D Printing Evolution.* [Online]. Available at: https://www.creax.com/en/our-work/the-3d-printing-evolution-insights-on-the-influence-of-ip-on-technology-dev (Accessed 10 May 2016).

Lumb, D. (2013) The Top Nine Consumer 3D Printers for Every Budget. *Fast Company,* 28 August, [Online]. Available at: http://www.fastcompany.com/3016490/9-consumer-3-d-printers-for-every-budget (Accessed: 1 February 16).

Matterhackers (2016) *3D Printer Filament Comparison Guide.* Available at: http://matterhackers.com/3d-printer-filament-compare (Accessed: 23 January 2016).

Mellino, C. (2015) Adidas Unveils 3D-Printed Shoe Made from Plastic Ocean Waste, *EcoWatch*, 10 December, [Online]. Available at: http://ecowatch.com/2015/12/10/adidas-3d-printed-shoe/(Accessed: 25 February 16).

Millsaps, B. (2015) *Protocycler is 3D Printing with Recycled Coffee Cup Lids as they Blow Past Indiegogo Goal*. [Online]. Available at: https://3dprint.com/41288/protocycler-recycled-coffee-cup-lids/ (Accessed 10 April 2016).

Moss, R. (2015) *Creative AI: Algorithms and Robot Craftsmen Open Up New Possibilities in Architecture.* [Online[. Available at: http://www.gizmag.com/creative-ai-algorithmic-architecture-robot-craftsmen/36212/ (Accessed 10 May 2016).

Nilsson, F. (2015) *Design is Behind the World's Largest 3D Printed Aircraft Component.* [Online]. Available at: http://www.engineering.com/PLMERP/ArticleID/11145/PLM-This-Week-Generative-Design-is-Behind-the-Worlds-Largest-3D-Printed-Aircraft-Component.aspx (Accessed 10 May 2016).

Oxvig, U. & Jansen, U. (2007) *Fishing Gears* 2nd ed. [Online]. Skaagan: Fiskericirklen. Available at: http://www.fisheriescircle.com/Home/Educational+materials/Educational+materials/Fishing+gears (Accessed: 23 January 16).

Pearce, J. (2011) *RecycleBot v2.2.* [Online]. Available at: http://www.thingiverse.com/thing:12948 (Accessed 10 April 2016).

Peels, J. (2014) *For Cheaper 3D Printing: A Review of Filament Recyclers*. [Online]. Available at: http://www.inside3dp.com/cheaper-3d-printing-review-filament-recyclers/ (Accessed).

Rowley, J. & Michaels, B. (2016) *3D Printing Workshops: Learn How to Utilise 3D Printing & Commercialise it*. Digits 2 Widgets & Defiant Laboratory. London, 6 April.

Sanladerer, T. (2015) 3D Printing Guides: Going big with solid-state relays. Available at: https://www.youtube.com/user/ThomasSanladerer (Accessed 1 February 2016).

Thu, M. (2014) First Low Cost SLS 3D Printers Hit the Scene*. 3D Printing Industry*, 14 August, [Online]. Available at: http://3dprintingindustry.com/2014/08/14/first-low-cost-sls-3d-printers-hit-scene (Accessed: 1 February 16).

Tsirepa, K. (2016) *Recyclad3d.* [Online]. Available at: https://plasticfantasticchallenge.org/post/173883(Accessed 10 April 2016).

Yusuf, B. (2016) *Olo 3D Printer: Frequently Asked Questions.* [Online]. Available at: https://all3dp.com/olo-smartphone-3d-printer-frequently-asked-questions/ (Accessed 10 April 2016).

Image Sources:

Figure 1. 3DPrintr Magazine (2015) *A complete Fused Filament Fabrication print prior to removal of support structures (left) and after (right)* [Online]. Available at: https://www.3printr.com/polymaker-introduces-easy-to-remove-3d-printing-material-for-support-structures-5530210/ (Accessed 19 July 2016).

Figure 2. Horne, R. (2015) *DIY filament extruder with 3D printed housing* [Online]. Available at: https://www.youmagine.com/designs/universal-pellet-extruder-reprap-3d-printing (Accessed 20 July 2016).

Appendix 1

Object Form Interview

Tuesday 15th December 10:30

Rhiannon Hunt and Scott Knowles

RH: Have you completed trials using recycled nylon into 3DP filament?

SK: There's potential for harvesting nylon for creating recycled filaments as the products that they're typically found in are all around us, for example garden strimmers.

It may be that it [nylon] is less well known as a material within the communities that are early adopters of the [3D-printing] technology, such as engineers, electronics enthusiasts etc, as nylon tends to be used a lot in textiles.

RH: Do you envision any difficulties in introducing these 3D-printing technologies to small, rural communities?

SK: Local conditions, like power surges, can cause damage to the 3D-printing machines and whilst replacement parts are relatively 'cheap', for the people in those communities it could halt production.

There exists a need to consider the knock on effects of introducing [3D-printing] technologies to local economies, ecosystems, communities etc.

Legislation may not be as stringent in these [developing] countries particularly for repairing things, making it easier to integrate [3D-printing parts], which will be beneficial where the existing method is inferior.

However, 3D printing adds value, but this needs to be greater than the costs associated with processing the nets into a material supply along with the set-up of extruders and printers. A cost-benefit analysis is needed.

RH: Are you aware of any VOC testing for 3DP and have you carried out tests for your recycled filaments in use?

SK: There's a report demonstrating that 3D-printing operation isn't hazardous, which I can forward onto you but that does depend on the material being used.

Further research is needed and the industry needs to establish 'ground rules' for each type of printing and material, as is the case with other potentially hazardous substances in the home and workplace.

RH: Are you aware of the advantages or limitations of Solid State Polymerisation (SSP) and Chemical De/Repolymerisation, such as methanolysis?

SK: Not specifically. I have looked into it and chemical method allows for removal of contaminants

RH: Have you attempted to create composite or blended filaments?

SK: It's possible to mix two plastics in a dual extruder, which are not chemically bound, to print out different components of a print.

Blends are possible, but not with powders and plastics, as streaking will affect quality and is difficult to control

Hybrids of PLA & PHA have been successfully developed for added strength and www.colorfabb.com produces true copper & brass blended with PLA

Powderised nylon for SLS and powdered nylon blended with other plastics has potential but needs to be explored.

RH: Have you attempted to create moulds using 3D printing that could be used to shape low quality or mixed ocean waste plastics?

SK: Yes, this is a really promising area even within the UK as there are benefits to being able to rapidly create tools for moulding custom components locally.

You may need to line the inside of the mould, as the linear structure of 3DP can be slightly porous. The surface of the final piece will also be textured if the mould isn't coated or smoothed in some way, such as with acetate and ABS usage.

By altering the deposition speed and flow rate you can prevent leakage, but it takes experimentation.

The plastic used for the mould needs to withstand the temperature of the molten fill plastic without undergoing heat stress, warping and resist chemical interactions.

Object Form (UK) has successfully used PLA for mould making, but it can't take the stresses and strains of being used within machinery. You could successfully print a mould from PLA and use molten HDPE with a lower melt temp of 90-100 degrees or rubberised plastic.

One weakness is that the PLA mould won't last as long as a metal one so they will only suit certain applications where customisation and rapid turnaround are a priority over longevity.

RH: Any additional comments?

SK: PLA recycling is a booming area with more and more businesses investing a lot in research

Appendix 2

Types of materials commonly used and properties of Fishing Nets & Ropes (FNRs)

Chemical Name	**Polyamide**	**Polyester**	**Polyethylene**	**Polypropylene**	**Aramid**	**High-density polyethylene**
Abbreviations	PA	PES	PET	PP		HDPE
Examples of trade names	Nylon, Perlon	Terylene, Dacron, Tetoron, Trevira	Nymplex, Courlene	Danaflex, Mulfiflex, Ulstron	Kevlar	Dyneema, Spektra, Dynex
Shock Load	Good	Acceptable	Poor	Good	Poor	Good
Handling	Good	Excellent	Good	Good	Excellent	Excellent
Durability	Good	Excellent	Acceptable	Good	Excellent	Excellent
Rot, Fungal rot, moisture	Good	Excellent	Excellent	Excellent	Excellent	Excellent
UV Radiation	Acceptable	Excellent	Acceptable	Poor	Acceptable	Acceptable
Acid Resistance	Good	Excellent	Excellent	Excellent	Good	Excellent
Alkaline Impact	Excellent	Excellent	Excellent	Excellent	Good	Excellent
Wearing Resistance	Excellent	Excellent	Acceptable	Acceptable	Poor	Excellent
Storage	Wet/Dry	Wet/Dry	Wet/Dry	Wet/Dry	Wet/Dry	Wet/Dry
Buoyancy (density)	Sinks (1.14)	Sinks (1.38)	Barely floats (0.95)	Floats (0.91)	Sinks (1.44)	Floats (0.97)
Melting point	Approx 250°C	Approx 245°C	Approx 128°C	Approx 150°C	Approx 427°C	Approx 147°C

Source: Oxvig, U. & Jansen, U. (2007), Chapter 2, p11-22, *Fishing Gears* 2nd Edition. [Online] Skaagan: Fiskericirklen. Available at: http://www.fisheriescircle.com [Accessed 23.01.16]


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