

A Design-driven approach to 3D printing textiles from recycled polyester

Emma Grain, University of Huddersfield

Abstract

Polyester is aligned to the industrial cycle and as such needs to be preserved as a recyclable resource. (Goldsworthy, 2009). In the last 50 years alone plastic production has increased by 500% and when discarded often ends up in the rivers and sea creating 'plastic soup'. Finding new ways to recycle this into new things is infinitely better than creating new as it saves on CO2 emissions and the ever decreasing resource of oil it starts out as. C.A. Griffiths et al (2016) noted this means that the design stage must consider constraints of time and cost and to furthermore consider sustainability and the need to seek to reduce scrap. Due to the nature of 3D printing, it only uses the material needed for a product with exceptions of small supporting pieces during additive manufacturing, rather than the subtraction approach in manufacturing which involves controlled material removal but involves a lot of waste. 3D printing has been known as a throw away fad and one which can produce lots of waste itself as with both novice and amateur makers there are often mistakes which end up in the bin. While, plastics are still recycled at low rates in centralized recycling facilities, distributed plastic recycling to produce filament for 3DP could help increase this rate at a lower economic and environmental cost (Kreiger et al., 2014). However, at present the market in raw materials for 3DP remains highly concentrated. Even though 3DP plastic is processed into filament by a range of both small and large companies, feedstock is supplied by a handful of large polymer producers (Despeisse, M., et al 2016). There are a number of stakeholders already involved in this unique area, from the reprocessing companies to the manufacturers of the filament and the grinders of the virgin material, fashion brands, 3D printing companies and charitable foundations involved in sustainability issues regarding plastics and finally, designers. This paper seeks to outline these stakeholders in detail and showcase the current work of the researcher where by in developing the '2 Way Closed Loop Cycle', new textile structures have been designed and printed using recycled polyester. Using a design driven approach the structures of existing 3D Printed textiles were analyzed and new structures were designed based on the properties of the recycled material. From a subject only in its infancy, the researcher aims to show the potential of such an experimental idea and how it could change future maker markets and give the fashion industry another route to take in order to close the loop.

Polyester is aligned to the industrial cycle and as such needs to be preserved as a recyclable resource. (Goldsworthy, 2009). In the last 50 years alone plastic production has increased by 500% and when discarded often ends up in the rivers and sea, creating 'plastic soup'. Finding ways to recycle this into new things is infinitely better than creating new as it saves on CO2 emissions and the ever-decreasing resource of oil it starts out as. C.A. Griffiths et al. (2016) noted that this means the design stage must consider constraints of time and cost, and to furthermore consider sustainability and the need to seek to reduce scrap. Due to the nature of 3D printing, it only uses the material needed for a product with exceptions of small supporting pieces during additive manufacturing, rather than the subtraction approach in manufacturing which involves controlled material removal, but also involves a lot of waste. 3D printing (3DP) has been referred to as a passing Fad by Kelleher (2015) and one which can produce lots of waste itself, as with both novice and amateur makers there are often mistakes which end up in the bin. While, plastics are still recycled at low rates in centralized recycling facilities, distributing plastic recycling to produce filament for 3DP could help increase this rate at a lower economic and environmental cost (Kreiger et al., 2014). However, at present the market in raw materials for 3DP remains highly concentrated. Even though 3DP plastic is processed into filament by a range of both small and large companies, feedstock is supplied by a handful of large polymer producers (Despeisse, M et al., 2016).

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Fashion companies big on recycled poly

Both North Face and Patagonia have been leaders in using recycled polyester in their ranges for many years and each has developed this into their ranges more and more, each season gaining more momentum with the popularity of this concept of closed loop design. Polyethylene Terephthalate (PET) is the most common thermoplastic polymer resin of the polyester family and is used in fibers for clothing, containers for liquids and foods, thermoforming for manufacturing, and in combination with glass fibre for engineering resins. The prefix (r) to rPET is recycled.

Both companies have used polyester made from recycled PET bottles in their ranges and more recently polyester made from recycled polyester, which has been helped by 'take back' schemes, using customers' returned items and reusing them into new garments.

Following in the footsteps of these giants, Paramo, a British retailer of outdoor clothing is always looking for the path of least environmental impact (Paramo, 2017). If you send your used Paramo garment back to them, they will either repair and sell on in their second hand EBay store, or strip the garment of its components and branding and send it for chemical recycling. Their garments are all 100% Polyester, providing the highest quality of this material and ensuring the garment isn't down-cycled to a lesser quality.

Other initiatives in the UK include Trash 2 Cash (T2C) a European-funded project bringing together a cross-disciplinary consortium of designers, researchers and manufacturers (Trash 2 Cash, 2016). Using a chemical recycling process conserves the quality of the original materials and ensures no down-cycling. T2C use a Design Driven Material Innovation (DDMI) methodology throughout this 3.5-year project. T2C hope that this new way of working will outline how science, design and industry can input into the process from beginning to end (Trash 2 Cash, 2016).

Closed loop methods in 3D printing

Refil, founded by Rotterdam based design agency Better Future Factory (BFF) formed by five alumni from the Delft University of Technology. BFF is a multi-disciplinary design and engineering company. BFF finds and develops creative yet realistic and sustainable solutions by incorporating the essential principles of a circular economy. They have many projects running but most famously the recycled filament for 3D printing called Re-filament. Refil produce two types of 100% recycled filament, the first (ABS) Acrylonitrile Butadiene Styrene filament made from car dash boards and PET filament made from old PET bottles, each sold on their website. They believe: '3D printing is today's trendiest industrial revolution. At Refil we aim to make is a sustainable one as well. Why continue to use new plastics, when there is so much old plastic we can re-use?'

In a wholly collaborative move towards sustainable fashion, Will.i.am has teamed up with Coca-Cola to make new things, in part from recycled materials (Ekocycle, 2015). This high-profile collaboration brought together some of the biggest names in fashion and retail, and products ranging from clothing by Adidas and Ecoalf to lifestyle products by Globe Trotter and footwear by Keds sold online and in the prestigious Harrods, London. The products are all made from partly-recycled materials, mainly including a percentage of PET bottles. This information is clearly displayed on their website, adding transparency to the brand's impressive attributes. In an interview with GQ, Will.i.am stated that the project planned to continue launching new products throughout the year, from everyday pieces to luxury items. Will.i.am would be at the helm as creative director, producing the type of recycled clothing we could actually get on board with (Conner, 2015). The quest for making sustainable living 'cool' does not stop with clothing, but reaches over into 3D printing. Using an average of 3 post-consumer PET bottles per printing cartridge, consumers can use their 3D Systems Ekocycle Cube printer for home use with sustainability in mind. Will.i.am explained that the goal is to partner with the most influential brands around the world and use technology, art, style and inspiration to change an entire culture. "We will make it cool to recycle, and we will make it cool to make products using recycled materials. This is the beginning of a more sustainable 3D-printed lifestyle. Waste is only waste if we waste it". (3D Systems, 2014)

B-PET is another recycled filament manufacturer based in Argentina who has produced 100% recycled filament from PET bottles and claims to have 100% recycled PET powder for use on selective laser sintering (SLS) machines in the near future, which will mean a greater clarity of print and an ability for much finer detailing in designs.

On a consumer level, the PROTOCYCLER is a new innovative tool which allows makers to recycle their own plastic waste, from PET bottles to unwanted 3D prints, by using the built-in grinder. This then extrudes the newly recycled filament onto spools ready to 3D print again. Previous machines have been available in recent years, but none so consumer friendly that does the job from start to finish with such ease of use. Such a machine allows for an industry driven by creation and not driven by consumption. ReDeTec.com explains that current extrusion of ABS and PLA is fully supported, but PROTOCYCLER hardware is able to extrude any non-toxic plastic within the melting range of 260, and while PET and plastic bottles are not fully tested they should be possible within the manual use guidelines of the machine.

PROTOPRINT is a social enterprise based in Pune, India that works collaboratively with urban waste pickers co-operatives, using low-cost technology to produce 3D printer filament from the waste plastic they collect (PROTOPRINT, 2014). It recycles 100% post-consumer High-density polyethylene (HDPE) and even its spools are made from plastic flakes – collected from the waste pickers then injection-moulded into the shape.

In collaboration with Parley for the Oceans, Adidas 3D-printed the midsole of a trainer using material made from recovered finishing nets found in the sea and setting a new industry standard using sustainable materials with innovative technology and design to solve design problems. It builds on the brand's Future craft technology, which allows the midsoles to be tailored to the exact contours of the owner's feet (Howarth, D, 2015). On their website, Adidas state that they are working with Parley to transform marine plastic pollution into high performance sportswear, spinning the problem into a solution. The threat into a thread (Adidas, 2016).

Current polyester recycling manufacturers

Through detailed and intensive research using the manufacturers websites, a table was collated to demonstrate whether the manufacturer produced yarn or 3D printed filament from recycled PET. Different companies use different technical methods to process and produce the final materials. Some of the issues identified include warping, and also limitation on the type of the 3D printer manufacturers that can be used. The filament recycling companies generally work in collaboration with the manufacturer, such as Refil with MAKERBOT – if they aren't already developing their own machine. Interestingly, compared to recycling PET into yarn for the clothing industry, initially utilized in 2002 by Teijin, the application to 3D printing is relatively new, with the earliest examples into filament around 2012. Recycled PET is still not as established in the 3D printing industry yet as other virgin materials. The Ekocycle Cubify 3D printer utilizes filament only 25% from recycled materials, and others use 90 to 100% PET. But increasing the percentage of the PET usage can lead to more technical difficulties.

Japanese company Teijin's mission statement is 'Human Chemistry, Human Solutions', in response to various global issues and needs, focusing on technological innovation in their strength of high-performance materials (Teijin, 2014). They are the global leader in chemical recycling of materials into fabric, including polyester. The current global annual production of major fibers is approximately 78.11 million tons. Synthetic fibers account for more than half of this amount, approximately 45 million tons, of which approximately 80% is polyester (Teijin, 2014). The two main materials which Teijin have developed from post-consumer PET or polyester products are as follows:

ECO PET, a mechanically recycled polyester fabric which is made from 100% recycled PET bottles which was first established in 1995. Teijin had already begun manufacturing recycled PET bottles into new bottles, so this was naturally the next step.

In 1999, ECO CIRCLE™ utilised Teijin Fibers' innovative chemical recycling technology for polyester products. Its unique recycling technology is a world first in this field. The technology enables decomposition of used polyester products through chemical recycling, followed by reproduction of new polyester fibers. The process can be repeated multiple times (Japan for Sustainability, 2009). This method can produce fabrics that are so purified through the process that the quality is equivalent to that of freshly produced polyester from petroleum (Teijin, 2014). This method is popular with both Patagonia and The North Face, and allows a totally closed loop cycle.

Repreve by Unifil is an American-based leading producer and processor of multi-filament polyester and nylon textured yarns providing innovative, global textile solutions and unique branded yarns for customers at every level of the supply chain. (Repreve & Unifil, 2009). Under the Repreve label, two types of recycled polyester are produced, Repreve filament fibers and Repreve staple fibers. The latter is further

processed to produce the physical properties required of a spun yarn, and the former is in the form of yarn. Both these types of Repreve polyester are used by brands such as The North Face, Quicksilver, Patagonia, Timberland, and New Balance to name a few. These top brands are safe in the hands of a certified sustainable fibre manufacturer and can rely on 100% traceability in their products composition.

Two way closed loop model

Figure 1 shows a two-way closed loop system developed in this research. In the two-way closed loop apparel cycle below, the researcher has theorized that by recycling all PET products, whether bottles, clothing or 3D prints, the existing recycling process of clothing and bottles into textiles can be mirrored but into 3D printing filament and visa versa. This stands to reason through exploring the methods existing polyester recyclers use and noting the early stages up to the pellets stage is identical to that of recycling into printing filament.

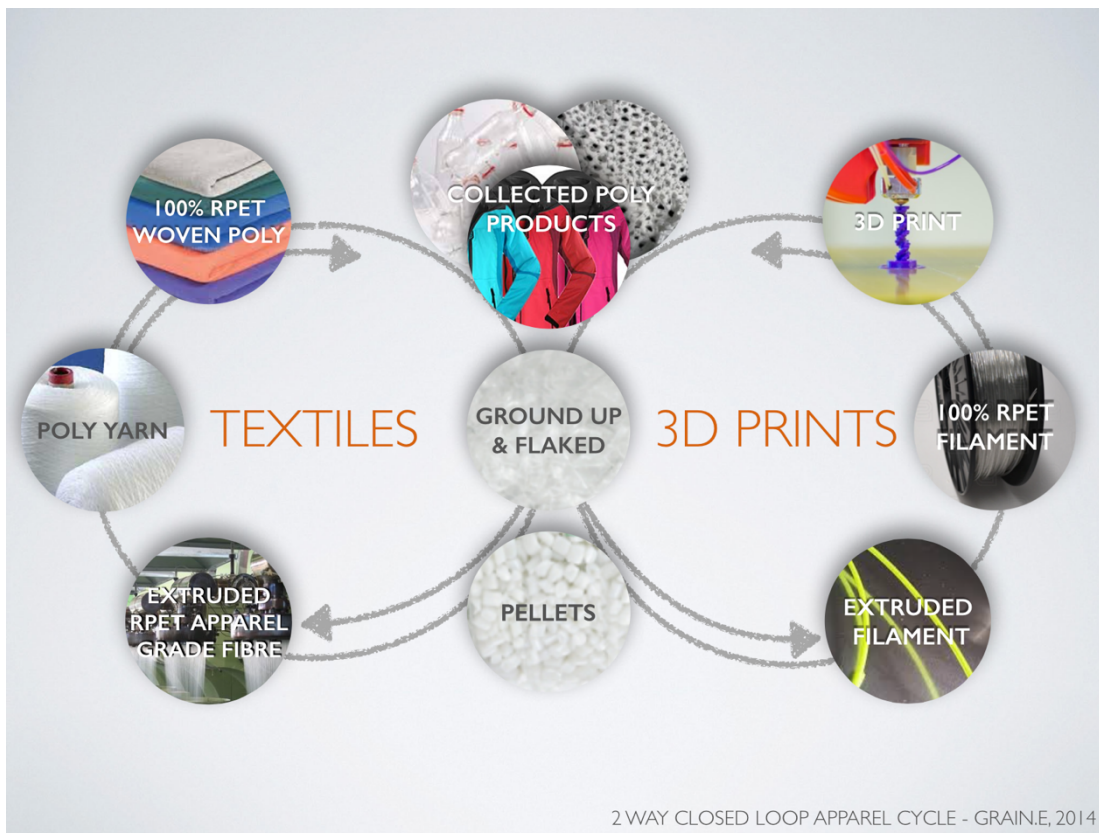


FIG.1 TWO WAY CLOSED LOOP APPAREL CYCLE (GRAINE 2014)

- From this a number of outcomes can take place:
- Polyester clothing > recycled = new polyester yarn > new clothing
- Polyester clothing > recycled = rPET filament
- Polyester clothing > recycled = rPET bottles/packaging
- PET 3D prints > recycled = new polyester yarn > new clothing
- PET 3D prints > recycled = rPET filament
- PET 3D prints > recycled = rPET bottles/packaging
- PET bottles > recycled = new polyester yarn > new clothing

Existing 3D printed structures

There has been extensive research into the design and manufacturing of 3D-printed textile structures since the earliest form was produced in 1999 by Jiri Eivenhaus, in its chainmail like state. This was perhaps the most obvious route to begin with, having seen it work with metal originally. There are designers who have designed textiles alone to be 3D printed, and there are designers who have designed garments but not textiles. Thus, limited by the material itself and often being more structural like Iris Van Herpen's and Julia Koerner's 2012 collaboration for their Hybrid Holism collection, where stereo lithography was used to create the sculptural dresses. Polar opposite to this are the textile structures designed by Nervous Systems, and their Kinematics hinged dress (2014) which has a flowing movement when worn and acts more closely to traditional fabric. Bingham et al. (2007) state that through the utilization of Rapid Manufacturing (RM) it is entirely possible to manufacture a structure that incorporates drape and free movement properties directly comparable with conventional textiles. Using the most sophisticated level of 3D printing SLS we can achieve great quality and intricacy, which is why this is the chosen method for most high-end fashion designers and for those trying to achieve the most fabric-like attributes. In Figure 2 the researcher has collated all existing 3D printed textile structures and plotted them in a timeline infographic, outlining the designer, material and process, year of manufacture and the category of structure.

A TIMELINE OF
3D PRINTED TEXTILES
BY EMMA GRAIN

DESIGNER	MATERIAL/ PROCESS	STRUCTURE
JEN EVENKUS & JANE KITTA BIODEGRADABLE CHEMICAL STRUCTURE	SLS NYLON 2000	DRIVE DRESS
CONTINUAUM ALGORITHMIC CIRCULAR PESH	SHAPWAYS SLS NYLON	WED DRESS
FRANCE BIONTI & MICHAEL SCHROET CELL ARTICULATED	SHAPWAYS SLS NYLON	WED DRESS
BRADLEY ROTHENBERG / VICTORIA SECRET SCULPTURE STRUCTURE	SHAPWAYS SLS NYLON	WED DRESS
BRADLEY ROTHENBERG / THREE ASFOUR SAFER DRESS WITH STRUCTURAL WEAVE	SHAPWAYS SLS NYLON	WED DRESS
NERVOUS SYSTEMS EMBEDDED WIRELESS TEXTILES	SHAPWAYS SLS NYLON	WED DRESS
ANDREAS EASTMAN REED FOR PRINT	HYBRID FDM HDMI	HEXOSTRUCTURE
JASON MILLER INSPIRED BY LEE STRUCTURE	SLS PEEK 90 HDMI	HEXOSTRUCTURE
NEGAR KALANTA FLORELL STRUCTURE	SELECTED MATERIALS QUANTUM MATERIALS	HEXOSTRUCTURE
NEGAR KALANTA UNITED STRUCTURE	SELECTED MATERIALS QUANTUM MATERIALS	HEXOSTRUCTURE
BRADLEY ROTHENBERG / KATIE GALLAGHER SCULPTURE STRUCTURE	SLS NYLON HDMI	HEXOSTRUCTURE
OLETT UNIVERSITY GREEN KEY PATTERNS FROM MULTIPLE DIRECTIONS	PLA FORM Ullimaker	HEXOSTRUCTURE
ALBERTO CABELLA REPRODUCING LEAF TO CREATE FROM POWDER	FDM PARABOOT HDMI	HEXOSTRUCTURE
FABRICATE 3D SYSTEMS FORM PRINT OR TO FABRICATE (STRETCHMENT)	FDM FORMITY HDMI	HEXOSTRUCTURE
D3W ALTERNATIVE CHAMPANEL	SLS NYLON HDMI	HEXOSTRUCTURE
CHANEL REWEAVE CAGING	SLS NYLON LINDOMEN	HEXOSTRUCTURE
LOUGHBOROUGH TEXTILE GEOMETRIES	SLS NYLON HDMI	HEXOSTRUCTURE
CHESTER BOSS INTERLOCKING STRUCTURE	MULTI-COLOR PRINTED SLS PLASTIC shapeways	DRIVE DRESS
BRADLEY ROTHENBERG / THREE ASFOUR	SLS NYLON shapeways	DRIVE DRESS
TRAVIS FITCH & THREE ASFOUR INTERLOCKING PANELS	MULTI-COLOR MULTI-MATERIAL Stratays	DRIVE DRESS
TRAVIS FITCH & THREE ASFOUR	MULTI-COLOR MULTI-MATERIAL Stratays	DRIVE DRESS
TRAVIS FITCH & THREE ASFOUR	MULTI-COLOR MULTI-MATERIAL Stratays	DRIVE DRESS
ALEXIS WALKER & BOSS LEON ASYM TRIANGULAR SEGMENTS	SLS NYLON shapeways	DRIVE DRESS

NOT THE END
e.e.grain@hud.ac.uk

FIG.2 A TIMELINE OF 3D PRINTED TEXTILES (GRAIN.E 2016)

In the following sections the researcher has categorized structures into six main areas: messo, linked, hinged, flexible, generative and hybrid structures.

Function analysis of structures

Combining this methodology traditionally used in historical fashion archives with a methodology borrowed from engineering, Object Process Methodology (OPM) (Dori,2002), will work well in analysing new textile structures as the function as well as the look needs to be noted. Using a function analysis diagram (FAD), we can see which textile structures have certain properties and abilities below in figure. 3. The five categorized structures have been plotted against properties including material, cost and movement attributes. Here we can see more clearly which existing 3D fashion textile structures have which properties and compare them.

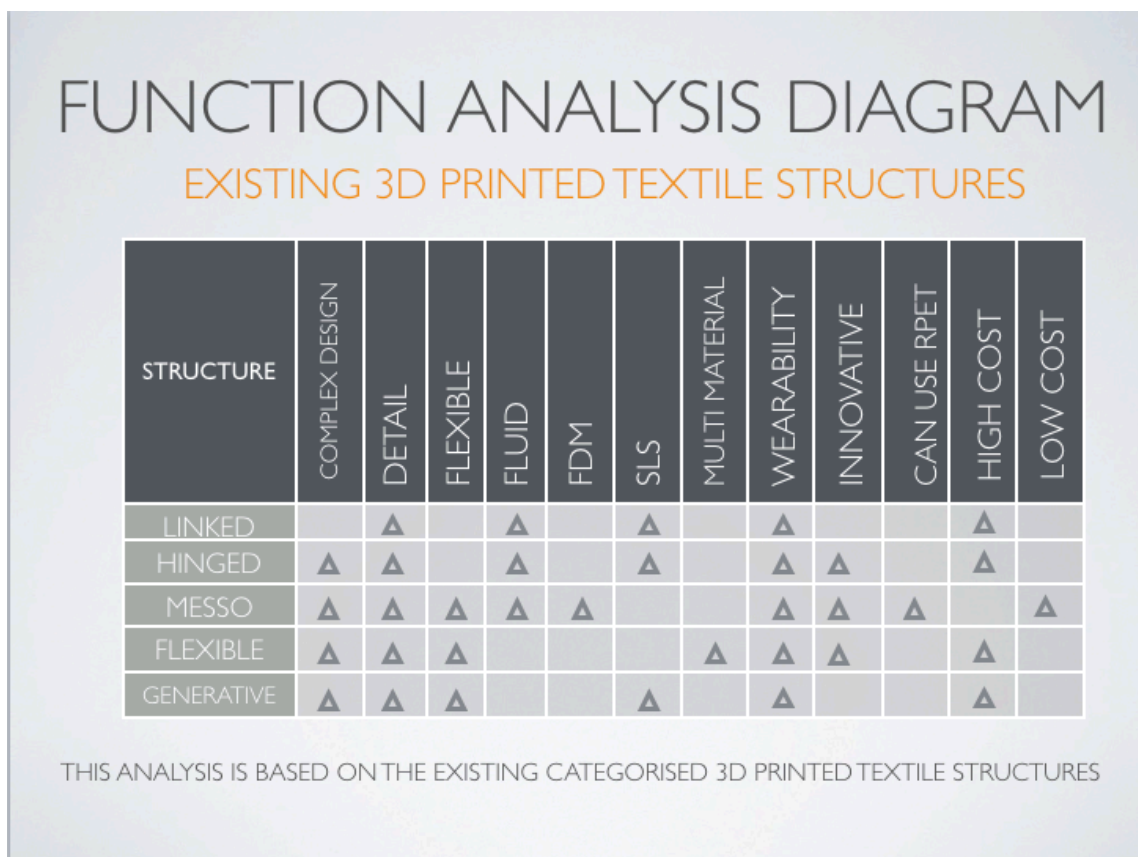


FIG.3 FUNCTION ANALYSIS DIAGRAM FAD (GRAIN. E, 2017)

In the following sections the researcher has categorized structures into five main areas: mezzo, linked, hinged, flexible and generative structures. The sixth category mentioned previously, hybrid, has been left out here as it involves printing onto traditional fabric so can't be compared like for like. Here shown in figure. 4 the properties of each category will be discussed at length with reference to their strengths and weaknesses in relation to design, flexibility, detail and innovation.

ANALYSIS OF PROPERTIES IN 3D PRINTED TEXTILE STRUCTURES

STRUCTURE	DESIGN	FLEXIBILITY	INNOVATION	PROS & CONS
LINKED	BASED ON TRADITIONAL CHAIN MAIL DATING BACK TO THE MIDDLE AGES	THE SMALLER THE INDIVIDUAL COMPONENT THE MORE FLUID THE 3D PRINTED TEXTILE	CHAINMAIL IS AN ALREADY EXISTING STRUCTURE AS IS KNITTED AND WOVEN STRUCTURES	SIMPLE AND KNOWN TO WORK AS MANY PRE EXISTING DESIGNS CAN BE MADE
HINGED	HINGES ARE PRINTED FUNCTIONING, WORKS BEST USING SLS	THE SMALLER THE INDIVIDUAL COMPONENT THE MORE FLUID THE 3D PRINTED TEXTILE	KINEMATICS BY NERVOUS SYSTEMS IS 4D PRINTED AND PRINTS FOLDED UP ALLOWING A MUCH BIGGER ITEM TO BE PRINTED	HAS A SWING LIKE MOVEMENT AS THERE ARE ONLY 2 DIRECTIONS A HINGE CAN MOVE IN
MESSO	COMPLEX DESIGN WITH SPECIFIC WHICH MUST HAVE SYNCLASTIC BENDING AND AUXETIC BEHAVIOR	STRETCHES IN ALL DIRECTIONS AND MORE SO IF PRINTED IN A FLEXIBLE MATERIAL	ANDREAS BASTIAN'S MESSO STRUCTURES HAVE BEEN USED IN FASHION BY DANIT PELEG SUCCESSFULLY	MOST REALISTIC FABRIC MOVEMENT
FLEXIBLE	DESIGNS CAN BE MOULDED OR ANY OF THE OTHER CATEGORIES	THE MATERIAL ITSELF IS FLEXIBLE THEREFORE THE WHOLE STRUCTURE IS.	TRAVIS FITCH COLAB THREE ASFOUR	FEELS BETTER ON THE BODY AND CAN TAKE MORE MOVEMENT THOUGH IT FEELS RUBBERY
GENERATIVE	DESIGN GENERATED BY NUMBERS IN SOFTWARE OR INSPIRED BY NATURE	DEPENDANT ON THE DESIGN AND MATERIAL CHOSEN	ALESSANDRO ZOMPARELLI	DOESNT ALWAYS HAVE FLEXIBILITY IN MIND BUT CREATES UNIQUE SHAPES LIKE NO OTHER

FIG.4 ANALYSIS OF PROPERTIES IN 3D PRINTED TEXTILE STRUCTURES (GRAIN. E, 2017)

3D CAD & MODELLING

As well as designing the garment, the researcher had to learn how to use the software in which the garment was designed. Coming from a menswear background, the researcher designed using Adobe Illustrator, a CAD programme used in fashion to draw up flat designs before sending them to a factory to have them made up by the manufacturer. This, however, was not an easy transition, and somewhat of an obstacle for them – alongside the research itself, the 3D software had to be mastered to a point where sufficient designs could be drawn up.

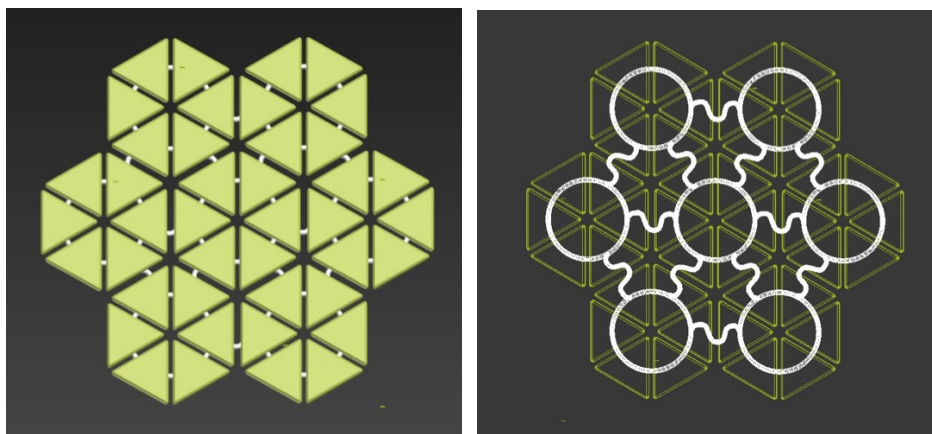


FIG.5, 6 SHOWING THE DESIGN IN SHADED AND WIRE FRAME MODE IN 3D STUDIO MAX

Design development

The conventional design process in textiles and fashion always starts with ideas and design development. The design process started with sketching, then the research team discussed the application of how the 3D shapes can be constructed flexibly enough to fit around the body but to print flat. The decision was made that the printing process would be flat, but the material would be initially hard, so the structure should be designed to bend or fold, therefore, research into folding paper and live hinges were investigated.

It was identified by Yves Weinand and Hani Buri (2008: 2-5) that paper folding gives a very direct and intuitive perception and comprehension of geometry, and rigidity of folded plate structures. By folding and manipulating paper, hands and eyes collaborate in a dialogue – a spontaneous understanding of the potential for such forms. It is with this in mind that folding paper helped realize the potential shapes that could work around the body by allowing the paper to mimic the rigid structure of the 3D prints.

The design development and initial idea started by hand drawing a set of structures inspired by the shapes seen on the skin when seen up close. This then developed quickly into 2D and 3D CAD packages and multiple design iterations, which were developed with ease on the computer where repetition and accuracy is easier than manual methods.

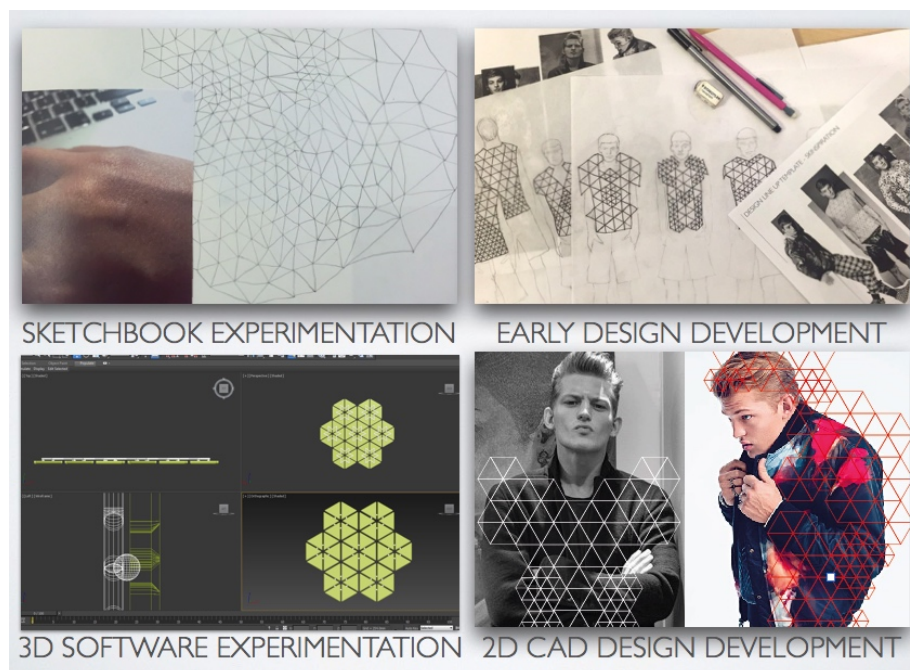


FIG. 7 INITIAL DEVELOPMENTS FROM 2D TO 3D (GRAIN. E, 2015)

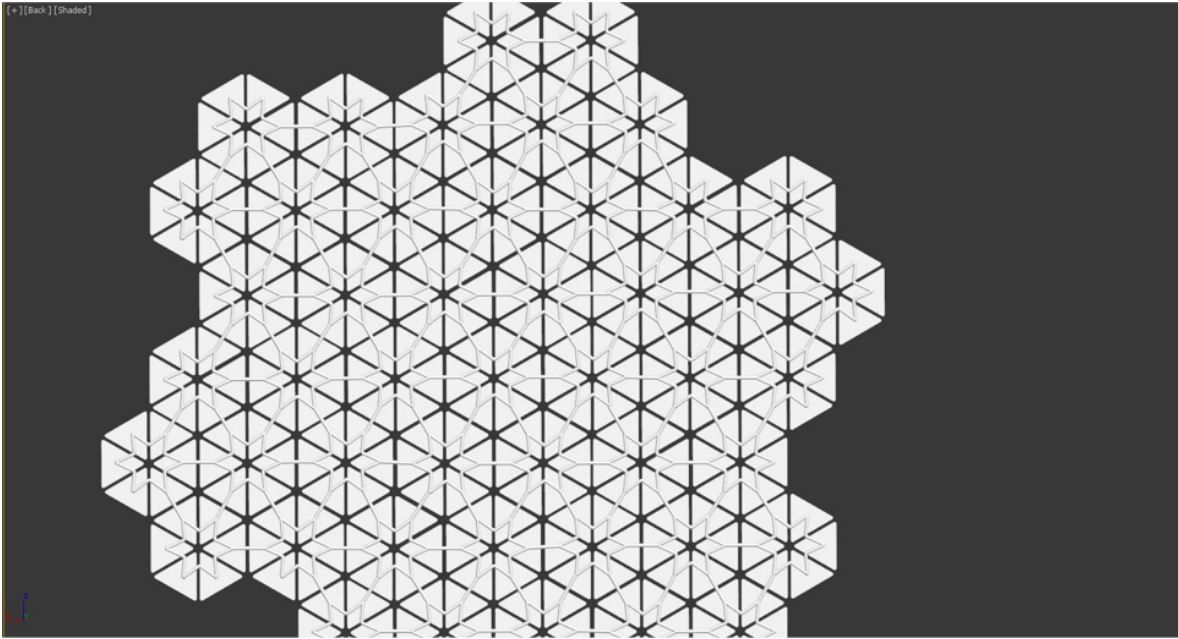


FIG.8 FINAL DESIGN OF TEXTILE STRUCTURE BACK FACE. (GRAIN.E 2016)

The final design shown is a number of repeated geometries with a different structure on the front face compared to back, and is shown here with the back facing up.

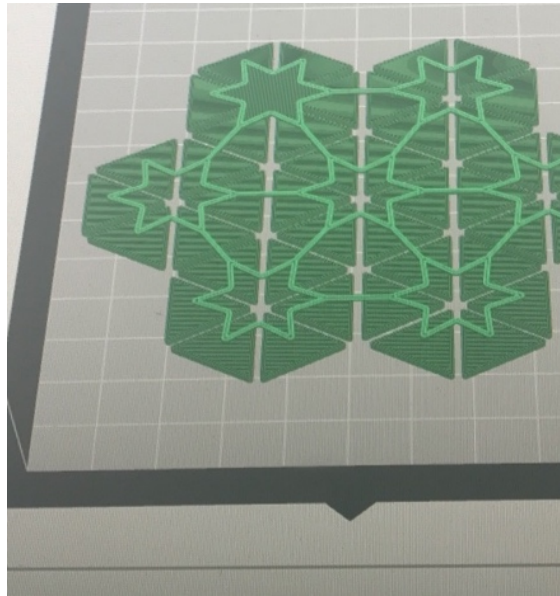


FIG. 9 MAKERBOT MACHINE TO USE

FIG. 10 CURA IMAGE TO SHOW PLACEMENT AND SCALE INSIDE PRINTER

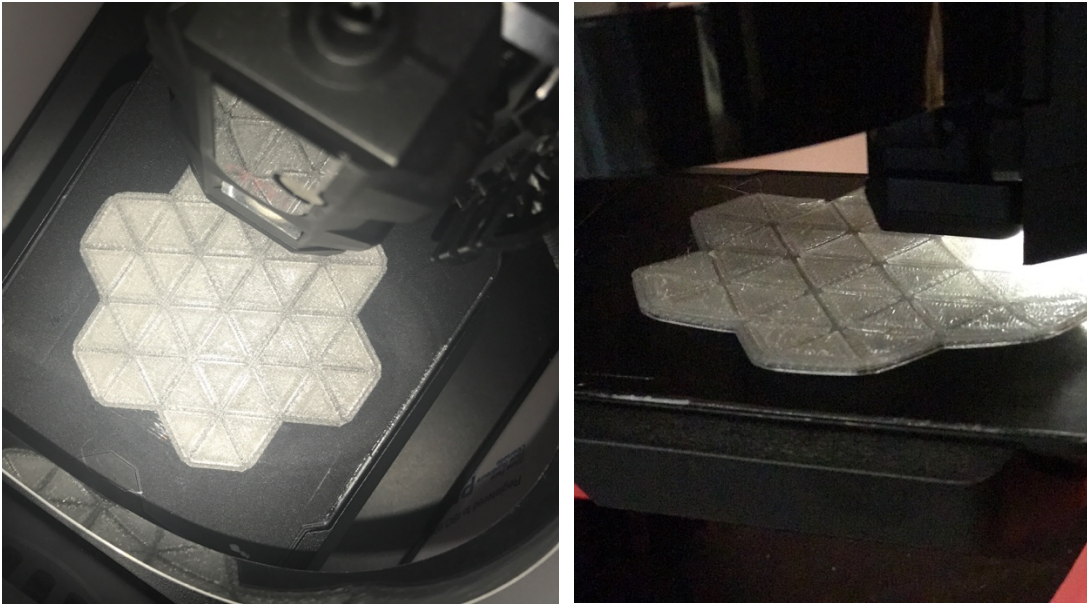
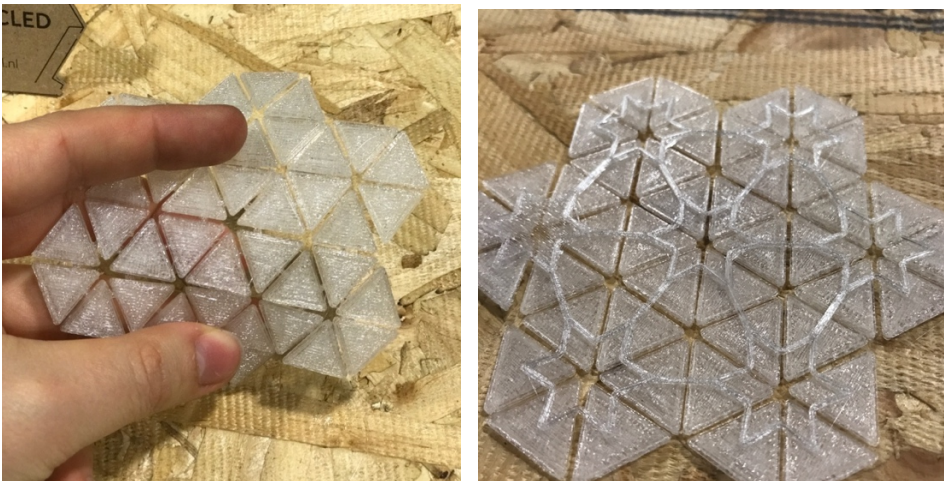


FIG.11 MAKERBOT PRINTING AN RPET TEXTILE DESIGN (GRAIN.E, 2017)



FIG.12a & b MAKERBOT RPET FINAL PRINT (GRAIN.E 2017)



Findings

During this project, a number of findings arose when using the FDM MAKERBOT printer and the rPET material to produce initial prototypes. In Figure 9 is the MAKERBOT machine which was used to print the rPET structure. In figure 10 the design is shown uploaded onto the screen that is connected to the 3D printer, this is called CURA slicing software, and sends the information to the printer after you have altered the settings which include:

LAYER HEIGHT – Measured in 0.1mm, the lower the number the more detail.

SHELL – The outer layers of each detail before it is filled.

RAFT – Base layer thickness.

FAN – Speed of fan to cool down the print.

SCALE – Design can be scaled on the CURA software to the size of the print bed.

FILL – Density of the filament material, the denser the slower the print.

SUPPORT – This is the print material printed to support parts of your design but to be removed post production.

Some obstacles which occurred whilst printing with rPET on this machine were:

Warping, which meant the base/raft layer did not stay flat to the base all the way round, thus interfering with upper layers as the lower layers were stuck up at the edges. To resolve this the fan was turned down to avoid the print drying too quickly, this helped a little.

On the first print in this material, the raft layer was made too thick and during post production it would not come away from the design, so the next design went forward with a thinner raft which worked.

Colours are restricted when using rPET at the moment, as they are directly coming from the original waste materials so the colour is determined by the original waste, whether that is clear, blue or green.

Overall the material produced a clean and flexible structure which could bend around the wrist but there is more work to be done on both material and structure before it could bend around the body. The initial testing with this material on a structure intended to bend and curve was a success, however more design work on particular structures with this material in mind is needed, and possibly the uses of more advanced printers with finer detail capabilities.

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