COTTON RAPID CUSTOMISATION FEASIBILITY STUDY

Queensland University of Technology

CSIRO

Australian Government
Cotton Research and Development Corporation

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Acronyms and Abbreviations

ABS	Acrylonitrile Butadiene Styrene
AM	Additive Manufacturing
ASA	Acrylonitrile Styrene Acrylate
BD	Beam Deposition
BJ	Binder Jetting
CAD	Computer Aided Design
CAGR	Compound Annual Growth Rate
CAM	Computer Aided Manufacturing
CLIP	Continuous Liquid Interface Production
CN	Cellulose Nanofiber
CNC	Computer Numerical Control
CRDC	Cotton Research and Development Corporation
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DLP	Digital Light Processing
EBM	Electron Beam Melting
FDM	Fused Deposition Modelling
HVAC	Heating, Ventilating and Air Conditioning
LMJP	Liquid Metal Jetting
LOM	Laminated Object Manufacturing
MJF	Multi Jet Fusion
PBF	Powder Bed Fusion
PC	Polycarbonate
PLA	Polylactic Acid
PMMA	Poly (Methyl Methacrylate)
Polyjet/PJ	Photopolymer Jetting
QUT	Queensland University of Technology
RC	Rapid Customisation
SDL	Selective Deposition Lamination
SHS	Selective Heat Sintering
SLA	Stereolithography
SLM	Selective Laser Melting
SLS	Selective Laser Sintering
UAM	Ultrasonic Additive Manufacturing
UV	Ultra Violet
WTVR	Water Vapour Transmission Rate

Executive Summary

This study aligns with the competitive futures theme outlined in the 2014 CRDC report 'Designing a Future for Australian Cotton'. One of the potential areas of development identified in this theme is rapid customisation. Due to the growth in additive manufacturing, rapid customisation is identified to have potential impact on the textiles and cotton industries.

This report forms a vital first step in exploring rapid customisation as an area of potential for the Australian cotton industry. It aims to establish the technical and economic feasibility of using cotton-derived feedstock in rapid customisation processes. Given there are many possible ways to process cotton as a feedstock, there are a number of diverse opportunities for end-user applications. Therefore, this report also focuses on identifying application areas where cotton has a clear advantage over other synthetic and non-synthetic materials due to its inherent material qualities and characteristics. Through achieving these aims, this report targets four different opportunities outlined within the competitive futures theme: novel treatments for cotton, rapid customisation, supply chain diversification and supply chain optimisation.

Cotton Materials and Processing Technologies

To provide contextual information, the properties of cotton that make it a high-demand and versatile raw material are outlined. Subsequently, the most prominent techniques used to process cotton are described, including spinning, weaving, knitting, nonwoven manufacture, laser cutting and finishing.

Three future trends are identified which affect the development of cotton materials and their application: technology innovation, value-added cotton textiles, and next generation cotton materials. Each of these trends is discussed with potential candidate cotton-derived materials and applications suitable for rapid customisation processes identified. These include: novel cotton treatments, intelligent textiles, cellulose hydrogels and aerogels, and cotton-derived bioplastics and composites.

Additive Manufacturing Technologies

A detailed survey of additive manufacturing technologies is presented in order to evaluate their potential for use with cotton-derived feedstocks. A total of nineteen individual additive manufacturing technologies are surveyed from six categories: material extrusion and deposition, material jetting, sheet lamination, vat photopolymerisation, powder bed fusion and binding, and electrospinning.

Future trends are discussed which are determined to influence the continued development of additive manufacturing technology and its broader impact to society and the economy.

Technology trends detailed are the development of low-cost technologies, and the move toward advanced materials and end-use part production. Social and economic trends focus on the disruptive potential of additive manufacture and potential impacts it has on manufacturing, supply chains and consumer empowerment.

Technical Feasibility

A criteria assessment is presented which evaluates each of the surveyed additive manufacturing technologies. Evaluation is informed by three criteria: the maturity of the technology, application potential of the technology, and the technology's potential for integration with cotton-derived feedstocks. Collectively, the criteria analysis discusses the broad application of each technology, and identifies eleven candidate cotton-derived materials with applicability to rapid customisation.

This criteria analysis is a vital step in ranking the rapid customisation technologies and identifying those with the greatest potential for future research. The five most promising rapid customisation technologies identified are: fused deposition modelling, robocasting, electrospinning, vat photopolymerisation processes, and sheet lamination processes.

Application Analysis

Building on the technical feasibility assessment, an application analysis details potential application ideas that are promising for cotton rapid customisation. Twenty-seven application ideas are outlined from five broad application areas: lifestyle, health, industrial, architecture and design, and automotive and aerospace. Further development of these application ideas informed the design visions for cotton rapid customisation.

Design Visions

Five design visions are proposed that encapsulate the results of this study. Design visions are presented as product and system concepts that emphasise the versatility of cotton-derived materials and their potential impact as rapid customisation applications. Although focused on specific application contexts, the diversification of these design visions to other applications and markets is emphasised. This is facilitated by an outline of the design visions broader impact and potential areas for future research.

1

INTRODUCTION

Rapid customisation is a way of creating physical products directly from digital design files through computer-controlled manufacturing. It is an area of sustained research and development in various industries due to its growing use in the generation of 3D products. Although rapid customisation can introduce disruptive technologies to existing business models, it also has significant potential for new business ventures. According to Wohlers Associates (2015), the worldwide market for additive manufacturing, one of the more commonly utilised techniques, is expected to grow from $3 billion in 2013 to close to $13 billion in 2018. However, identifying the most promising areas for application is difficult, given the wide array of approaches to rapid customisation, and the various processes and technologies that it can involve. Moreover, present approaches to rapid customisation are limited by the choice of available feedstock. Subsequently, one of the key challenges (and potential opportunity) in moving forward is to broaden the range of materials that can be used in production.

In the 2014 CRDC Report "Designing a Future for Australian Cotton", rapid customisation was identified to offer potential opportunities for the cotton industry. These opportunities arise from "the increasing demand for customised products delivered on a mass scale and could fit well with 'design at home' and 'print at home' trends where the final products are textile replacements for the emerging soft-tech market" (Barnett, 2014). In such applications, cotton has several inherent beneficial properties for use as a feedstock in rapid customisation. Its advantages lie in the following characteristics: (i) high cellulose content; (ii) biodegradability; (iii) capacity to be produced at scale; (iv) unique fibre qualities; (v) marketability as a natural fibre (which is attractive to both customers and manufacturers); and (vi) availability in a wide range of forms that have the potential to be adapted for rapid customisation.

Of the three key themes identified in the 2014 CRDC Report – Profitable Futures, Sustainable Futures and Competitive Futures – the opportunities offered by a cotton-derived feedstock for rapid customisation aligns most strongly with CRDC priorities concerning Competitive Futures. The Competitive Futures theme highlights the need for continued innovation in the cotton market and aims to "…transform the way in which consumers demand Australian cotton products and continue to make it competitive" (Cotton Research and Development Corporation, 2015). This supply chain transformation necessitates the development of new products and markets, taking into account interactions from manufacturing processes through to end-user consumption and disposal or recycling (Barnett, 2014). Key factors for consideration with regards to innovation, and therefore the future competitiveness of Australian cotton, are: increasing connectivity in the supply chain, reverse logistics, migration of production to low-cost economies and new business models creating new markets (Barnett, 2014).

This report provides a vital first step in establishing the feasibility of using cotton-derived feedstock in rapid customisation processes, and as such, offers a foundation for effectively targeting future research in this area. It responds to four different opportunities outlined within the Competitive Futures theme, as follows:

i. Novel Treatments for Cotton: identification of new combinations of materials to enhance competitiveness within the man-made fibre market through feasibility assessment of using cotton-derived feedstock in rapid customisation processes.
ii. Rapid Customisation: evaluation of the development potential for new forms of rapid customisation and associated intellectual property to be applied to the production of novel cotton-derived products, along with licensing opportunities for these techniques and their adoption in the global cotton industry.
iii. Supply Chain Diversification: exploration of new applications for cotton and cotton-derived products that allow any part of the cotton plant to be used as input in addition to recycled cotton materials, including lint derivative substrates.
iv. Supply Chain Optimisation: investigation of the potential for increasing the value-add to cotton products before export, as well as improving the efficiency of the supply chain to local consumers.

In providing an assessment of the technical and economic feasibility of using cotton-derived feedstock in rapid customisation processes, this report has significance for both the industry and community sectors. For industry, it signposts areas for future research into rapid customisation, and the most promising avenues to pursue in terms of increasing the demand for cotton against that for man-made fibres in the global textile market. For the community, there is the potential for new cotton-derived products, in addition to traditional textiles, which deliver niche goods or services to specific target demographics, such as Asian mega-niches (Barnett, 2014). Together these opportunities point towards transformational business models that combine complementary services with traditional cotton markets to create new industrial ecosystems for the Australian cotton economy.

This potential for new industrial ecosystems holds significance for the future profitability and sustainability of the Australian cotton industry as well as its competitiveness locally and internationally. The use of cotton-derived feedstock in rapid customisation processes has the potential to make Australian cotton growers more profitable by increasing productivity, improving input efficiency such that limited virgin material is required, and expanding market opportunities for cotton-derived products. It also holds future possibilities with respect to extracting greater value from traditional areas of agricultural research through the development of new manufacturing processes and technologies (Barnett, 2014). In addition to this increased profitability, there is significant potential for increased sustainability through the recycling of existing end-of-life cotton artefacts and production of alternatives to petroleum-derived feedstock for rapid customisation. This in-turn contributes to further competitiveness as market demand for sustainable materials increases and brands increasingly choose cotton-based fibres for their products based on lifecycle analysis and capacity for reuse (Barnett, 2014).

The success of strategies for competitiveness, profitability and sustainability depend greatly on the cotton industry's capacity to adopt new technologies. Key risks to this success are resistance to change, new methods of manufacturing not gaining traction, failure to determine and address limitations in current skillsets, or the trigger of undesirable structural change within the industry (Barnett, 2014). As well as assessing the suitability of cotton-derived feedstock for different manufacturing techniques, this report touches on a number of these risks through commenting on the disruptive potential of different rapid customisation technologies. In doing so, it identifies areas of capability within the cotton industry that require further development in order for adoption of new technologies to be possible. This reflects changes in how mainstream growers, not just innovators in the industry, might engage with technology to take advantage of new knowledge that adds value and certainty to everyday decision-making processes, as well as influencing development strategies for the technology itself.

In the medium to long term, rapid customisation promises to have far-reaching impacts on the cotton industry and everyday life. While current digital manufacturing processes such as computer-controlled pattern cutting, sewing, looming, spinning and fabric printing are value adding to traditional textile goods, the shift from 2D fabrication methods to 3D rapid customisation techniques offers a new generation of nonwoven cotton products. Of the various approaches, 3D printing, otherwise known as additive manufacturing, has the greatest potential to "significantly reduce the length and complexity of the supply chain in almost all existing cotton markets, and at the same time accelerate market cycles and deliver the means of mass customisation or agile manufacturing" (Barnett, 2014). Already in 2011, total industry revenues for 3D printing had grown to $1.7 billion USD, including both products and services, and over the 24 year history of this industry, the compound growth rate has been over 25% (De Jong & De Bruijn, 2013).

The impacts of 3D printing for the Australian cotton industry are twofold. First, the cost of 3D printers has been steadily decreasing, while their range has been increasing. They are not only more accessible but are trending towards being as inexpensive, reliable and compact as desktop inkjet printers are today. The result is that end consumers could soon be printing objects at home rather than having to purchase them in-store. Second, there are a number of companies currently developing products that use cotton fibre as a substrate material for 3D printing, taking advantage of the flexible and lightweight characteristics of cellulose and nanocellulose to create products that were not previously feasible or technically possible. For example, cotton is now being used as a key material in electronics applications like batteries, which could have wide-ranging benefits for electricity management in the city grid, home and vehicles (Barnett, 2014).

1.1 Project Scope

The aim of this report is to assess the technical and economic feasibility of using cotton-derived materials as feedstock in rapid customisation processes. Given there are many possible ways to process cotton as a feedstock, there are a number of diverse opportunities for end-user applications. The focus of this report is therefore to identify application areas where cotton has a clear advantage due to its inherent material qualities and characteristics. To do so, it delivers the following:

- A survey and description of current available rapid customisation processes and technologies.
- An assessment of these techniques with respect to their potential for using cotton-derived feedstock.
- An outline of the inherent qualities of cotton advantageous for rapid customisation technologies and applications.
- A discussion of the technical feasibility of the possible treatments and processing methods for cotton to prepare it as a feedstock material.
- A matrix mapping of rapid customisation techniques against potential cotton feedstock treatments.
- A series of design visions for potential end-user applications of cotton-based rapid customisation approaches.
- An indicative assessment of potential market opportunities and economic feasibility based on these design visions to support the development of alternative and high-value cotton products.

By mapping out the space of potential rapid customisation approaches and assessing their technical and economic feasibility with respect to using cotton as a feedstock, this report will identify the most promising areas for future targeted research. This will provide direction for future investigation into the most suitable ways in which the Australian cotton industry might benefit from emerging manufacturing processes and technologies to take advantage of new transformational business models.

1.2 Project Method

This project report is the result of a nine-month collaborative project led by Queensland University of Technology (QUT), with the assistance of partners from the Commonwealth Scientific and Industrial Research Organisation (CSIRO). The project was interdisciplinary in nature, leveraging expertise from the respective organisations. The research team from QUT primarily provided expertise from the fields of industrial design, and interaction and visual design. In the context of this project, experience from these domains contributed technical knowledge of currently available rapid customisation techniques, and design expertise in adapting emerging technologies for the design of new end-user products. Complimenting this expertise, CSIRO partners contributed a broad knowledge base from the domains of material science and polymer chemistry. Supporting collaboration and discourse between organisations assisted in realising the key focus of this report: providing a feasibility assessment of using cotton-derived feedstock for rapid customisation processes, and identifying compelling application areas where cotton has a clear advantage over alternative materials. To achieve these outcomes, the project was comprised of three primary stages (Figure 1):

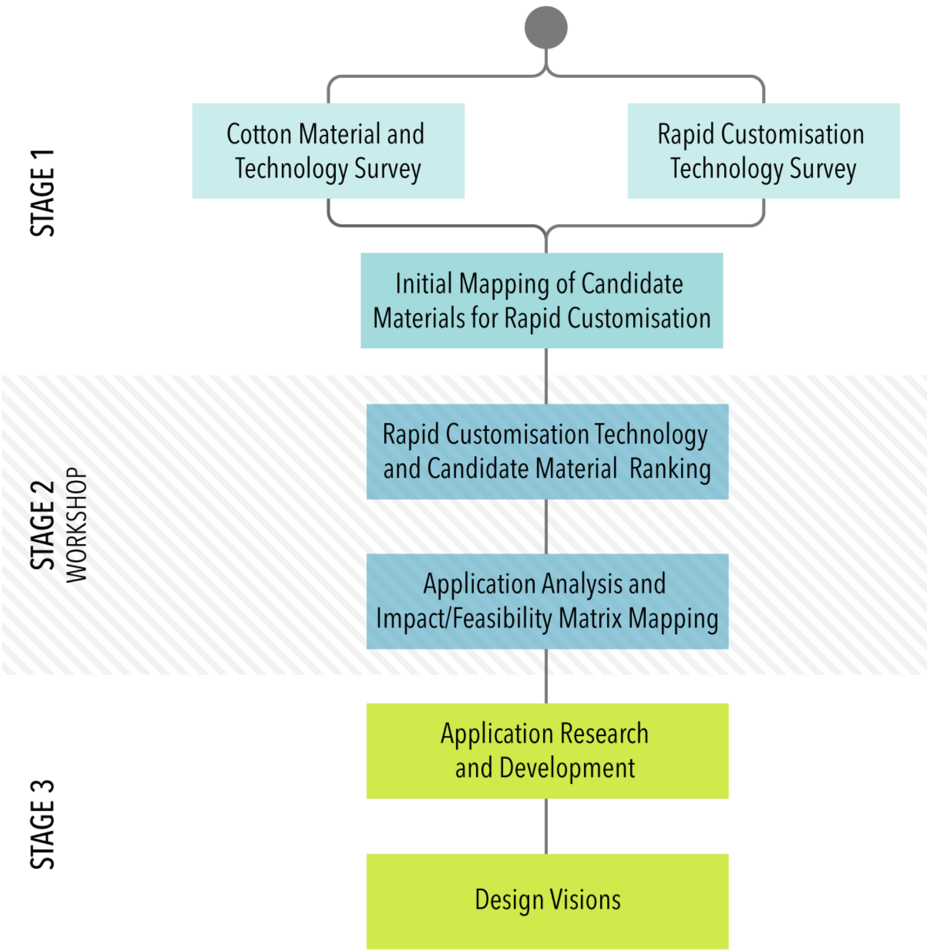


FIGURE 1. PROJECT METHOD

Stage 1

There exist several recent surveys of rapid customisation technologies. However, there exists no survey of the potential use of cotton-derived feedstock for rapid customisation. Therefore, it is not possible to identify which rapid customisation technologies are most suitable for cotton-derived feedstock. To address this, two concurrent literature surveys were conducted:

i. The first literature survey investigated the material properties of cotton, current processing techniques and emerging trends for cotton manufacture and material development. This led to the identification of a range of cotton-derived materials that have the potential for use with rapid customisation processes and applications.
ii. The second literature survey investigated current and emerging rapid customisation technologies, and future trends in the space of additive manufacturing. A criteria analysis evaluating the maturity and application potential of each rapid customisation process was performed in order to identify key benefits and barriers for their use in the development of new cotton products.

From these literature surveys, an initial matrix was developed, mapping rapid customisation technologies to candidate cotton-derived materials. This mapping provided an initial step to establish the processes and technologies most suited for cotton-based applications.

Stage 2

The second stage of the project involved a collaborative workshop between QUT and CSIRO held at the CSIRO research facility in Clayton, Victoria. This workshop comprised of two main activities:

i. A group discussion was facilitated to synthesise the findings from the literature surveys and expand on the initial mapping of potential candidate cotton-derived materials for rapid customisation processes. Subsequently, each rapid customisation technology was ranked based on suitability for use with the identified candidate cotton-derived feedstocks. The aim was to rank the most promising technologies in the context of rapid customisation, as well as provide considerations for the development of candidate cotton-derived materials.
ii. A brainstorming session was facilitated to develop potential rapid customisation applications utilising cotton-derived feedstocks. Brainstorming helped accelerate the formation of a broad variety of potential applications. Subsequently, each application area was discussed with the purpose of evaluating and visually mapping potential impact and projected feasibility.

Stage 3

The third stage of the project focused on the selection of application areas with the most potential, and developing design visions based on these areas. The resulting design visions assist in communicating the outcomes of this study, and provide an indication of possible applications of cotton-derived feedstock applied to rapid customisation processes. Using these visions, opportunities for future research investment are highlighted, identifying those with the most potential to affect increased competitiveness, profitability and sustainability for the Australian cotton industry.

2

Cotton Material and Processing Technologies

Cotton is a versatile natural material with many current and potential applications. As a raw material, cotton is a sustainable and renewable resource that is “biodegradable, non-petroleum based, carbon neutral and has limited environmental, animal/human, health and safety risks” (Moon, Martini, Nairn, Simonsen, & Youngblood, 2011, p.3941). For these reasons, cotton is desirable to both consumers and industries, and continues to be a high-demand raw material on a global scale. This section aims to provide key information regarding the material properties and diverse application potential of cotton. It is intended that this information will provide essential contextual information for this feasibility study. It begins with an overview of the properties of cotton, followed by an outline of the key technologies used for processing cotton. It concludes with a discussion of future trends shaping the uses of cotton, including, technology innovation, value-added cotton textiles, and next generation cotton materials.

2.1 Cotton Properties Overview

The cotton plant is comprised of a number of usable parts, including the linters, lint, cottonseed, stalks and seeds. The two main materials derived of the cotton plant used to produce products are cotton seeds and cotton fibres. Cotton seeds are predominantly used to make cotton seed oil, which is used in products such as soap, margarine, cosmetics and plastics. In contrast to cotton seeds, cotton fibres, are more extensively used and make up approximately 85% of the profit generated from the cotton crop (Cotton Australia, n.d.). The end use applications of cotton fibres vary considerably and largely depend on the different qualities of fibre. Long staple cotton fibres (2.5-6.5cm) are fine and lustrous, and tend to be used for high quality textiles, such as hosiery and bed sheets. Medium staple cotton fibres (1.3-3.3cm) are very versatile and have a wide range of uses in the textile industry, predominantly clothing and furnishings. The short (1-2.5cm) and coarser fibres tend to be used for carpets and blankets, and are often blended with other fibres for use in disposable nonwoven products such as cotton buds and absorbent pads.

Enabling the broad range of applications in which cotton fibre is suitable is its structure and unique properties. Cotton fibre is composed predominantly of cellulose (80-90%), with water (6-8%), hemicellulose and pectins (4-6%), ash (1-1.8%), waxes and fats (0.5-1%), and proteins (0-1.5%), making up the rest of the material. The structure of cotton fibre is comprised of six parts arranged in concentric layers (Figure 2). The outermost layer is the cuticle, a waxy layer containing pectins and proteins that serves as a water protective layer. Below this layer is the primary wall, comprised of a network of layered cellulose fibrils. Following the primary wall is the winding layer, which is also comprised of cellulose fibrils, but which have a different arrangement to those in the primary wall. Below this is the secondary wall, which forms the main part of the cotton fibre. The second wall is similar to the primary wall in that it is comprised of closely packed cellulose fibrils, however, the secondary wall is thicker due to being comprised of several consecutive concentric layers of fibrils. Behind the second wall is the lumen wall, which functions as a barrier between the secondary wall and the lumen. The lumen is a hollow canal which runs the length of the fibre (Cotton Incorporated, 2016).

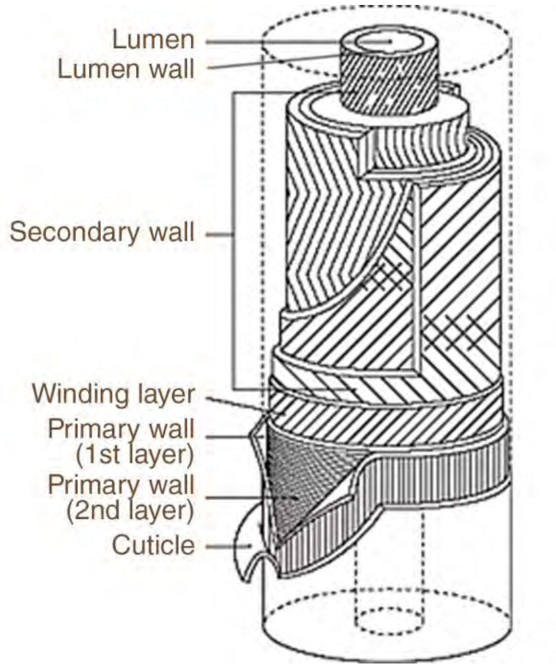


FIGURE 2. STRUCTURE OF COTTON FIBRE

When observed in its entirety, the cotton fibre is a flat twisted ribbon, with 50-100 convolutions per inch. “The fibre is tapered on one end and fibrillated on the other, where it was joined to the cottonseed. This provides the fibre with a soft touch or feel, because it has no sharply cut ends, as do synthetic staple fibres” (Cotton Incorporated, 2016). The softness of fibres means that there is limited skin irritation and makes it an ideal material for close to the skin applications (Avila & Hinestroza, 2008). Throughout the fibre structure, the closely packed cellulose fibrils result in a complex porous structure, which makes cotton fibres highly breathable and accessible to liquids and vapor. These properties make cotton garments extremely comfortable to wear in warmer climates, and an ideal material for products designed to absorb liquid. Through capillary action the fibrils pull liquid in, where it is held in pores between the fibrils. At saturation point, cotton can hold up to 27 times its own weight in water (Cotton Incorporated, 2016).

Cotton exhibits higher fibre strength than other natural forms of cellulose, such as that derived from wood pulp. The superior strength is attributed to the closely packed and parallel arrangement of fibre molecules. When wet, the strength of cotton fibres is generally found to increase due to "intermolecular hydrogen bonding between cellulose chains and their degree of crystallinity" (Cotton Incorporated, 2016). A potential limiting factor of cotton is its mechanical properties in response to heat. "At elevated temperatures, cotton decomposes instead of melting. Long exposure to dry heat above 300°F (149°C) causes cotton fibres to decompose gradually, and temperatures above 475°F (246°C) cause rapid deterioration" (Cotton Incorporated, 2016).

The unique fibre properties of cotton that result in softness, low irritation, high absorbency, strength and breathability, make cotton an extremely diverse material used in a variety of applications. The majority of the world's cotton harvest (60%) is used to make clothing, with the remainder used in various applications including home furnishings, medical, cosmetics, technical and industrial (Cotton Australia, n.d.).

2.2 Cotton Manufacturing and Processing Technologies

In order to facilitate the broad variety of cotton products available, a diverse range of manufacturing and processing technologies are required. These range from technologies used purely to work with raw cotton material, to chemical treatments used to enhance the properties of finished cotton products. This section will provide a brief overview of prominent techniques used to manufacture and process cotton material.

2.2.1 Spinning

Spinning is an integral cotton processing technique that is required to turn individual staple cotton fibres into cotton yarns. The general process of spinning involves twisting the relatively short cotton fibres together to form a continuous yarn (Elhawary, 2015, p191). To enable this, a number of stages are required:

i. Opening and cleaning is required to break down bales of cotton into small tufts, and to remove natural impurities, such as leaf, seed, trash and dust.
ii. Blending is performed to combine fibres with variable properties (maturity, length, strength and elongation), resulting in a consistent yarn quality. Blending may also be used to mix cotton with other fibres, such as polyester.
iii. Carding is performed to convert blended tufts into individual fibres. This process involves straightening the fibres so they become oriented in a common direction. Carded fibres are then reassembled into a 'twistless' rope of disentangled fibres held together by inter-fibre friction. This rope is known as a carded sliver.

iv. Combing is an optional step performed when a finer yarn is required. Fibres undergo further orientation by means of a comb-like device that arranges the fibres into an even stricter parallel form. This process also removes short fibres, fibre hooks and any impurities that remain.

v. Drawing has the purpose of elongating slivers to reduce the linear density to a level that is suitable for spinning. Elongation is achieved by a series of rollers rotating at different speeds to produce a single, uniform strand.

vi. Roving is the final stage before spinning and involves the drawn sliver being fed into a machine called a roving frame. In the roving frame, the strands of the fibre are lengthened further by a series of rollers. Lengthened fibres are wound onto bobbins, where they are twisted slightly to hold the fibres together. This twisted strand is called the roving.

After these steps, spinning is required to produce a strong fibre that will allow for fabric manufacture. Spinning involves three main operations. First, attenuation of the roving is performed to achieve the specified linear density. Second, a twist is imparted to produce a cohesive yarn. Third, the yarn is collected on an appropriate package. There are a number of techniques that perform these operation, but the most commonly used are ring spinning and rotor spinning (Elhawary, 2015).

2.2.2 Weaving

Weaving uses continuous yarn to create sheets of fabric that can be plain or decorated with patterns. The process of weaving is performed using a loom to interlace two sets of threads: warp threads which run the length of the fabric, and weft threads which run horizontally across the width of the fabric. There are many types of looms, both hand operated and machine operated, that can be used for weaving. Despite this variety, all looms perform the same basic function. The warp yarn is held under tension and the weft yarns are inserted between the warp and then forced into place to create the fabric (Stankard, 2015, p. 255).

Computerisation has had a significant effect on the weaving process. CAD packages (for example, APSO, AVL and Scotweave), have effectively eliminated the need to produce designs by hand. They allow the user to input basic information to specify weave structures, face fabric simulations and colour combinations. The most common computerised loom used today is the jacquard loom. The jacquard loom has individual computer-controlled heddles, which lift the warp yarn and allows weft yarns to be inserted. Because each heddle and corresponding warp yarn can be individually controlled, complex and intricate designs are possible (Stankard, 2015).

2.2.3 Knitting

Knitting is a process that uses continuous yarn arranged in a series of intermeshing loops (stitches) to create a variety of textile fabric structures. Traditionally, knitting was done by hand using hand, pin or needle knitting, but now most commercially produced knitwear is produced by using computer-controlled machinery. Compared to woven fabrics, knitted fabrics are less stable, but offer much greater flexibility and drape qualities (Power, 2015).There are two primary types of knitting technologies: weft and warp.

Weft Knitting

Weft knitting is the most common knitting method. It utilises one continuous end of yarn which is fed through consecutive loops to produce three main types of fabric structures: plain, rib, and purl. Within each of these types are a number of variations that can be achieved by altering knit stitches. Weft knitting structures provide good flexibility in all directions, have good elastic recovery, excellent formability and drape, good thermal insulation and resistance to creases. Disadvantages include poor shape retention, and susceptibility to pilling and laddering (Power, 2015).

For the manufacture of weft knitted fabric, there are three different types of machinery: i. circular, ii. fully-fashioned and iii. flatbed.

i. Circular knitting machines use a circular arrangement of needles that feed yarn from multiple sources around the circumference. The fabric output from a circular knitting machine is a continuous tube of knitted fabric that is then cut to produce a flat piece of fabric (Power, 2015). To produce a garment from this material, panels must be cut from the sheet material and then sewn together. Consequently, there tends to be a large amount of material wastage (Larsson, Peterson, & Mouwitz, 2010).
ii. Fully-fashioned machines can be either circular or flat machines and are able to create pre-shaped pieces of fabric, such as front or pack panels of a garment, or sleeves. The pieces are either sewn together with seems or the links of the garment are sewn together to form the full garment. As material cutting and sewing is kept to a minimum, fully-fashioned machines result in less wastage than cut and sew methods (Larsson et al., 2010; Power, 2015). Fully-fashioned processes can also utilise integral knitting which means that pockets, buttonholes and other trimmings are directly knitted in the fully-fashioned produced panels (Larsson et al., 2010).
iii. Flatbed machines are the most versatile weft knitting machines as they can produce complex fabric structures, different pattern options, pattern shaping and are capable of integral knitting. Some flatbed machines are capable of knitting complete garments that do not require additional processes. The two major companies producing complete garment machines are Shima Seiki with their Whole Garment machines, and Stoll with their Knit & Wear machines (Power, 2015). The advantages of complete garment technology include: the elimination of waste as all material used contributes to the garment; labour is reduced due to limited post-processing and, comfort and durability is enhanced as there are no seams (Larsson et al., 2010; Power, 2015).

Warp Knitting

Warp knitting is less common than weft knitting, however it provides a number of advantages. Warp fabric structures are more stable, less prone to ladders but lack drape properties. Warp knitted structures are used in lace, open work, underwear, sportswear and technical applications (Power, 2015). A warp knitting machine consists of multiple needles that extend across the width of the machine. Each individual needle is fed from an independent yarn source, delivered by a guide that directs the yarn around the needle during the knitting action. The fabrics produced from these machines are continuous sheets. The types of machines vary from those with small width for creating scarves, to those up to 5m in width for the production of industrial fabrics (Power, 2015).

2.2.4 Nonwovens

Nonwovens are engineered assemblies of staple cotton fibre that have been formed into webs and then bonded together (Mao & Russell, 2015). Web formation and bonding are usually high-speed continuous processes delivering long lengths of sheet fabric wound into rolls. Rolled goods are further processed using mechanically and/or chemical means to convert them into end-use products. "Mechanical processing includes cutting, folding, slitting, and layering. Chemical processes include chemical impregnation, spraying, heat treatment, laminating, printing and other operations depending on the end use" (Mao & Russell, 2015). The resulting fabric structure is different from many other textile structures as they are anisotropic, are not completely uniform in weight or thickness, and are highly porous and permeable (Mao & Russell, 2015).

Owing to versatile formation and finishing processes, nonwovens can be produced with distinct structural properties that can be tailored to a variety of applications. They are essential to the functional performance of single-use and disposable products used in diverse medical, consumer and industrial applications. Nonwovens are commonly produced for domestic uses. For example, hygiene products such as wipes, diapers, personal care and liquid retention layers, and household products such as cleaning cloths, adhesives and filters. They are also commonly used in industrial and agriculture applications, such as building wrap, filtration, crop covers and weed control fabrics. Uses even span into fashion, with nonwovens used as linings, labels, and disposable garments used for protection and sanitation (Mao & Russell, 2015).

2.2.5 Laser Cutting

Laser cutting is a method for cutting and decorating sheet material based on input from a CAD file (Gibson et al., 2010). A highly focused (0.1mm – 1mm) beam of light capable of melting material is used to produce complex and highly accurate cuts and patterns (Lefteri, 2007; Thompson, 2007). A wide range of materials are suitable for laser cutting, including metals and non-metals. It is particularly suitable for materials that require intricate and precise patterns that may be difficult to achieve using other methods (Lefteri, 2007).

Laser cutting is being used increasingly for fabric and textiles such as cotton, silk, fleece and leather. Although the cut is generally very clean when used on fabrics, the process can leave burn marks on some materials (Lefteri, 2007). There are a number of different lasers used for laser cutting (CO2, Neodymium (Nd) and Neodymium yttrium-amuminum-garnet

(Nd-YAG) (Lefteri, 2007; Thompson, 2007), however, CO_2 lasers are the typical choice for cutting fabrics as the light is easily absorbed by organic material (Williams-Alvarez, 2014)

2.2.6 Finishing

Finishing methods are applied to cotton to enhance the natural properties of the material, provide additional functionality and overcome limitations of cotton textiles. For example, stentering and sanforising are used to reduce shrinkage of cotton garments. Treatments such as permanent press provide resistance to wrinkling, while aesthetic treatments including gassing and calendaring are used to improve the surface finish or textiles. Bleaching and dying is widely used to create textiles with a range of colours and a variety of chemical treatments are available that endow cotton textiles with resistance to water, fire, stains and mildew. Cotton can also be napped, a process that endows a downy finish to the textile surface and improved heat insulation.

While these finishing methods have been applied in the textile industry for many years, continued innovation in textile finishing and treatments, particularly nanotreatments (Avila & Hinestroza, 2008; Liu, Wang, Qi, & Xin, 2008) and active materials (Thompson, 2007) offer exciting opportunities for improving cotton products and producing high-value and innovative products.

2.3 Future Trends

Three key areas of future trends have been identified for the processing and applications of cotton material: technology innovation, value-added cotton textiles, and next generation cotton materials. These areas are discussed in the following subsections.

2.3.1 Technology Innovation

The development of technology and the introduction of digital processes has influenced almost every aspect of the textiles industry, from processing raw materials through to the design, manufacture and distribution of finished goods (Burke & Sinclair, 2015). One of the most prominent effects of technology is its facilitation of increasingly shorter lead times between concept and market (Kennedy, 2008). For instance, fast fashion retailers such as H&M and Zara are capable of transforming a 2D pattern design to a finished garment on a store shelf in as little as 3 weeks (Power, 2015, p. 299). This efficiency is predominantly enabled by the availability of diverse digital design tools that are closely integrated with manufacturing processes (Burke & Sinclair, 2015). Using sophisticated software, designers are able to simulate complex stitches, provide garment sampling and generate virtual simulations of an entire garment before it is physically prototyped for real-world testing. These processes empower designers with detailed information about the garment, which can improve the design, avoid material wastage and decrease garment production times (Burke & Sinclair, 2015; Power, 2015).

As technology development continues the textile and clothing industries will increasingly be transformed into high-tech, demand-driven and knowledge-based industries (Walter, et al. in Power, 2015). Some of the key areas for research and development include the virtual supply chain, mass customisation and automatic pattern extraction methods (Kennedy, 2008). Of the different textile technologies, complete garment flatbed knitting machines offer significant potential for development in these areas. . The technology behind complete garment knitting systems is a core focus of textile innovation and has advanced significantly in the last decade. It is being used right across the fashion market, from designer and luxury ranges (e.g., John Smedley, Max Mara, DKNY Jeans, Versace, Burberry, and McQueen) to high street and supermarkets (M&S, George, and Oasis). Production of complete garment knitting products is set to gain market share as the technology continues to improve. In particular, sportswear and casual wear is expected to grow due to the production of fine gauge machines which are able to produce high quality functional garments (Power, 2015, p. 297).

A key technology related to complete garment knitting systems, and a driver of automatic pattern generation and rapid customisation, is 3D body scanning. With 3D body scanning, it is possible to quickly obtain an unlimited number of linear and non-linear measurements of the human body. Measurements can be altered and updated in seconds, offering a more precise alternative to physical measurements (Istook, 2001). Combined with garment manufacturing, 3D body scanning has the potential to create better fitting products that are responsive to an individual's body shape (Istook, 2001). Combining these technologies also has the potential to create a seamless link between pattern development and subsequent garment manufacture (Istook, 2001; Kennedy, 2008). Realising this connection is viewed as a key milestone for the mainstream adoption of the mass customisation model (Kennedy, 2008). The mass customisation model presents the opportunity to define new markets, facilitate a new supply chain, and increase sustainability by reducing standing inventory and unsold garments (Istook, 2001).

The integration of complete garment processes and 3D scanning will facilitate the entire design and manufacture of a garment to be completed quickly at a single location from a single machine (Larsson, Mouwitz, & Peterson, 2009; Power, 2015). Although this type of model has been explored in both a research and commercial capacity, it has not yet achieved mass success. For example, the Scan to Knit project used a 3D scanner to capture the shape of the leg, which was then translated into a knitted program and fed directly to a fine gauge knitting machine to create compression garments (Power, 2015, p. 301). Shima Seiki also experimented in this area with their shop Factory Boutique Shima, in which customers were able to co-design garments that were then manufactured on-demand, in-store (Peterson, Larsson, Mujanovic, & Mattila, 2011). Despite these promising developments, the primary limiting factor is the "level of communication between different software and hardware providers, and the skilled personnel required to operate the systems which are largely multidisciplinary in nature" (Power, 2015, p. 301).

As this technology integration continues to progress, it is expected that there will be a shift in the format of the retail environment. Exhausted by the fast fashion movement, consumers will look for unique and custom garments designed specifically for their needs and wants. Rather than rack after rack of incrementally sized garments, shops will be fitted with 3D scanning booths and sophisticated visualisation software. Customers will be able to co-design garments based on various pre-sets and custom options, then view life-like representations of their finished garments. Garments will be manufactured in-store for same day pickup, or shipped directly to the customers home (Power, 2015). These types of capabilities will not be limited to textiles, extending to an entire range of lifestyle and specialised products. This can be seen in the footwear industry, where a number of major brands are experimenting with custom 3D printed shoes (Robarts, 2014, 2015), and in the fashion accessories category with companies like nervous system (n-e-r-v-o-u-s.com), who make user-customisable jewellery.

2.3.2 Value-added Cotton Textiles

Beyond the technology used to produce textiles, there is substantial interest in cotton material innovation for the development of novel and high-impact products. Of particular interest is the development of wearable technology and smart fabrics. Perhaps the most recognised example of wearable technology is the burgeoning product category of smart watches. Thanks to high profile product launches such as the Apple Watch and other smart watches from companies like Samsung, Motorolla and LG, smart watches have become a core product range in the tech industry over the last few years. Although this is an exciting area of innovation, current generation products are not considered to deliver a refined user-experience that is suitable to the technology platform (Bohn, 2016). Beyond smartwatches, there are a number innovations that are breaking away from current preconceptions about what personal and wearable technology can be by embedding functionality directly into soft-goods and the garments we wear. This synthesis of textile material and technology has the potential to expand the possibilities of many exciting product development areas including quantified self, health and safety, the internet of things and the smart home.

An important driver in this new space for wearables has been the development of durable conductive inks and miniature sensors to create intelligent textiles. For example, using screen printing, It is possible for solder paste and other conductive inks to be printed directly on textiles to form electronic circuitry that connects a host of sensors and devices (Thompson, 2007). In addition to screen printing, conductive thread has been used to weave touch and gesture interactivity onto any textile using standard industrial looms. The threads used are indistinguishable from standard threads and can be incorporated into a number of objects from jeans, couches and blankets to open up a world of possibilities for intelligent textiles. According to Stacy Burr, managing director of Adidas digital sports, by 2025 near field communication technology and electronic sensors will be embedded in all of our clothing. This will allow smart devices such as smart watches and mobile phones to communicate with the clothes we wear (Fumo, 2015). The beginnings of this trend have already been seen in the fitness apparel market with the commercialisation of a number of smart garments in 2015. Products such as Ralph Laurens Polo-tech shirt, Athos (liveathos.com), and Hexoskin (hexoskin.com.au) use biometric sensors to collect data on heart rate, breathing, andthe speed and intensity of a workout (Charara, 2015). Using biomechanic sensors, some products in development, such as Heddoko, are even able to capture and visualise body movements. This will allow athletes to review their movements in order to increase performance and reduce the risk of injury (Kosir, 2015).

Further afield, a compelling area of textile innovation is the impregnation of textiles with various treatments. For example, conductive polymers such as polyacetylene, polypyrrole and polyaniline to produce conductive textiles. Adding conductivity to fabric creates a number of potential use cases as the garment can be used to sense the environment around it. Depending on type, conductive polymers are sensitive to heat, chemicals, gas and pressure and as such can be used for "applications in the field of sensors, actuators, electromagnetic interference shielding, etc" (Bhat, Seshadri, Nate, & Gore, 2006). Another area of exploration in textile treatments is the use of nanoparticle treatments which to improve the functionality of textiles (Bhat et al., 2006). Various types of nanoparticles have been applied to textiles to enhance "antibacterial properties, water repellence, soil resistance, antistatic, anti-infrared, flame retardant properties, dyeability and strength of textile materials" (Liu et al., 2008). One specific case is the application of carbon-nanotubes to improve the mechanical properties of cotton, while retaining its superior breathability. The nanotubes were applied in the form of a modified nanotube emulsion to the cotton fabrics via a traditional dipping, drying and curing procedure. It was shown that the nanotubes formed a cross-linked network on the cotton fibres, endowing the fabric with substantially improved tear resistance, flame retardancy, UV-blocking and water repellency (Avila & Hinestroza, 2008; Liu et al., 2008). Nanomaterial treatments are also being developed with the purpose of improving functionality of nonwovens. Combining various nanotreatments has the potential to produce highly functional products with enhanced antibacterial, antivirus, hydrophobic and hydrophilic properties (Mao & Russell, 2015).

2.3.3 Next Generation Cotton Materials

First-generation cellulose products, such as paper, textiles and absorbent pads take advantage of the natural properties of cellulose. Although these products have had significant impact on society and industry, the functionality, durability and uniformity demanded from the next generation of cellulose products cannot be achieved with traditional cellulosic materials (Moon et al., 2011). One possible solution for improving the functionality of future cellulose based products is by utilising nanocellulose, a product that is extracted from natural sources of cellulose, such as cotton. By extracting cellulose material at the nanoscale, it is possible to control the hierarchical structure of the material. This enables the removal of defects associated with natural cellulose materials and provides the ability to tailor the properties of the material to specific applications (Moon et al., 2011).

There are a number of different classifications of nanocellulose that can be derived from cotton. These include microcrystalline, nanocrystalline, microfibrilated, nanofibrilated, nanocrystals and nanowhiskers (Moon et al., 2011; Pandey, Nakagaito, & Takagi, 2013). Some of these derivations from natural cellulose require mechanical processing, which is the case for microfibrilated cellulose and nanofibrilated cellulose, while others require more extensive processing. For instance, cellulose nanocrystals have been extracted from microcrystalline cellulose by using acid hydrolysis (Moon et al., 2011).

Research investigating the use of cellulose nanomaterials has experienced a resurgence in recent times. This in no small part has been due to the abundance of cellulose as a natural and renewable resource. Moreover, there is an abundance of waste cellulose available, of which only 2% is recovered industrially (Qiu & Hu, 2013). Providing an effective method for using nanocellulose recovered from waste cellulose presents a highly attractive prospect in the space of environmentally sustainable products. However, despite there being great potential for the development of nanocellulose based products, cellulose nanomaterials must overcome many obstacles before they become a viable commercial option. The production of cellulose nanomaterial currently requires time consuming preparation procedures with very low yield, it is highly hydrophilic, has poor dispersion due to high agglomeration tendency, low thermal stability and it is expensive compared to other nanomaterials (Pandey et al., 2013).

Research investigating the use of nanocellulose in practical applications has focused on a number of areas in recent times. Some of the most promising include nanocellulose polymer matrix compositions (Moon et al., 2011), neat cellulose nanomaterial barrier films and membranes (Moon et al., 2011), nanofibre materials made from regeneration of virgin or recycled cellulose (Lavoine, Desloges, Dufresne, & Bras, 2012), cellulose nanomaterial hydrogels and aerogels (Moon et al., 2011), and cellulose smart materials (Qiu & Hu, 2013). In the following subsections, these areas and their current applications will be discussed.

Cellulose Polymer Matrix Composites

Cellulose polymer matrix composites are the product of mixing cellulose nanomaterial with different kinds of polymers, typically thermoplastics. The aim of developing these composite materials is to produce new materials with enhanced functional properties. Cellulose nanocomposites are an attractive prospect for nanocomposites as the nanomaterial itself has excellent properties (Pandey et al., 2013; Qiu & Hu, 2013). Cellulose nanomaterial is highly crystalline, has a regular shape and high aspect ratio (Pandey et al., 2013). Experiments have shown that nanocrystalline cellulose is stiffer and stronger than their natural fibre or organic source. “Crystalline cellulose has a greater axial elastic modulus than Kevlar and its mechanical properties are within the range of other reinforcement materials” (Moon et al., 2011). If cellulose nanomaterials are built into a composite with the proper structure, their properties might translate into excellent composite properties (Moon et al., 2011).

Cellulose nanofibres have the potential to improve the material properties of both synthetic and natural polymer matrixes (Pandey et al., 2013). “Surface functionalisation allows the tailoring of particle surface chemistry to facilitate self-assembly, controlled dispersion within a wide range of matrix polymers, and control of both the particle–particle and particle-matrix bond strength” (Moon et al., 2011). Already, cellulose has been widely utilised as fillers and a reinforcing agent in composite material. The significant reinforcement observed for polymer/cellulose whisker nanocomposites have demonstrated significant reinforcement due to the formation of “rigid whisker networks in which stress transfer is facilitated by hydrogen bonding between the whiskers” (Qiu & Hu, 2013). “Some variety of cellulose nanomaterial composites produced to date can be transparent, have tensile strengths greater than cast iron, and have very low coefficient of thermal expansion” (Moon et al., 2011).

One of the most promising area of scientific and technological innovation for nanocellulose composites is the development of environmentally friendly composites made entirely from natural sources (Song, Xiao, & Zhao, 2014). Cellulose nanomaterials are the ideal material to develop new biopolymers for a variety of commercial applications. Due to the biodegradability of cellulose, composite material would have the potential to degrade fully, “leaving behind unharmful residue biomass with the emission of carbon dioxide and water” (Pandey et al., 2013). One material that has been a popular topic of research for these purposes is polylactic acid (PLA). PLA is a biodegradable thermoplastic that is derived from natural sources such as plant starch. Due to the biodegradability of PLA, it is extensively used in disposable food packaging products such as drinking cups, containers, and wrap (Song et al., 2014). There has been some success producing biodegradable nanocomposites by incorporating modified nanocellulose fibres with a PLA matrix to produce barrier films used in paper food packaging (Song et al., 2014). Tests on this composite material showed that the nanocellulose fibre polylactic acid composite resulted in a lower water vapour transmission rate, This suggest that the nanocellulose fibre polylactic acid composite has promise as a green-based packaging material (Song et al., 2014).

Cellulose Hydrogels and Aerogels

Cellulose nanomaterial has excellent potential to be used for the development of hydrogels matrices. “Hydrogels are, mainly, structures formed from biopolymers and/or polyelectrolytes, and contain large amounts of trapped water” (Chang & Zhang, 2011). As a material, they are soft and wet, and have properties that are similar to body tissue (University of Wollongong, n.d.). Cellulose-derived hydrogels have a variety of potential applications in a range of domains. In particular, the excellent biocompatibility and biodegradability of cellulose hydrogels make them an exciting prospect for drug delivery systems and tissue engineering (Chang & Zhang, 2011). A particular area of development for these applications is tailored hydrogels that are stimuli responsive. An example of a stimuli responsive hydrogel is one that is able to swell or shrink as a function of external stimuli, such as temperature or pH levels. In such instances, “drugs loaded in the hydrogels can be released while they swell to looser structures due to environmental changes in the vicinity" (Qiu & Hu, 2013). Some examples of drugs being explored in these applications include BSA, dextran, insulin, oxaliplatin, and ketoprofen (Qiu & Hu, 2013). Besides their applications in biomedicine, hydrogels have potential applications in the fields of food, cosmetics, agriculture, contact lenses and water purification (Chang & Zhang, 2011; Qiu & Hu, 2013).

In addition to use in hydrogels, cellulose and cellulose nanomaterial can be used to create aerogels. Aerogels are highly porous materials with extremely low density, high surface area and low thermal conductivity (Moon et al., 2011). There are a number of ways to produce cellulose aerogels. One way is to convert cellulose hydrogels into aerogels through a variety of drying processes including regular freeze drying, solvent exchange drying, rapid freeze drying (Jin, Nishiyama, Wada, & Kuga, 2004), and supercritical carbon dioxide drying (Fischer, Rigacci, Pirard, Berthon-Fabry, & Achard, 2006). It is also possible to produce cellulose aerogels from cellulose solution. One of the benefits of this method is that waste cellulose fabrics (e.g., from textiles) or other biomass wastes can be used (Han, Zhang, Wu, & Lu, 2015). Producing aerogels from cellulose solution involves three primary steps: "the dissolution of the starting cellulose (various solvents and cellulose source materials can be used), the precipitation of cellulose, and solvent removal while avoiding cellulose consolidation/agglomeration". This last process can be done by supercritical drying, freeze drying or rapid decompression" (Moon et al., 2011).

The application potential of aerogels is quite diverse, although, they are particularly strong for industrial applications. They have immense potential for use as insulating foams, such as those for houses or in refrigeration. This is due to having thermal conductivity at atmospheric pressure (inferior to 0.030 W/m K) that is comparable with that of typical insulating foams such as polyurethane (Fischer et al., 2006). One limiting factor of cellulose aerogels in such applications is that they are easy to ignite. However, recent research has shown that cellulose aerogels can be modified to provide good flame retardant properties (Han et al., 2015). This ability to modify the chemical structure and nanostructuration of aerogels makes it suitable for specialised applications. For instance, the internal structure of an aerogel can be between microporous to macroporous (Fischer et al., 2006). An example outcome of such tailored materials are highly porous aerogels for use in precision filtration (Jin et al., 2004).

Smart Materials

As discussed with cellulose hydrogels and aerogels, cellulose may be used to create materials that are responsive to specific environmental stimuli. Materials with this type of functionality are broadly termed as 'smart materials'. The functionality of cellulose smart materials can be designed to undergo controlled changes such as "shape, mechanical rigidity/flexibility, opacity, and porosity" (Qiu & Hu, 2013). The activation/deactivation of smart materials can be induced from a variety of stimuli including pH, temperature, ionic concentration, bacteria, chemicals and electricity. In addition to biomedical applications that have previously been discussed, "smart materials based on cellulose have vast applications in the sensing field" (Qiu & Hu, 2013). For example, conductive cellulose materials have been prepared as humidity and temperature sensors (Qiu & Hu, 2013), and biosensors have been added to cellulose membrane filters for microbial sensing in the water treatment industry. (Qiu & Hu, 2013).

2.4 Summary

Cotton is a versatile, sustainable and renewable material, with a broad range of applications. Existing manufacturing and processing technologies have helped shape cotton as a mainstay component in various products. The manufacturing and processing technologies outlined in this section include spinning, weaving, knitting, laser cutting and finishing are used to process raw cotton into usable materials.

Three future trends are identified which will affect the development of cotton materials and their application as end-use products: technology innovation, value-added cotton textiles, and next generation cotton materials. Current technology innovations have resulted in lower lead times for cotton products, and emerging technologies such as 3D body scanning and rapid customization technologies promise to have significant impact on the types of cotton products available and how consumers access them. New material technologies, such as conductive inks and threads, offer significant potential for novel cotton products such as wearable garments and high performance cotton fabrics. It is expected that the functionality of cotton products will continue to advance with the development and introduction of next generation cotton materials. Some cotton-derived materials of particular interest for research development are cellulose polymer matrix composites, hyrdrogels, aerogels and nanomaterials. In addition to demonstrating the future potential of cotton as a raw material, these next generation cotton materials provide a number of potential candidate cotton-derived materials for rapid customisation processes. With this in mind, the following section reviews current additive manufacturing technologies in order to assess their potential for using cotton-derived feedstocks.

3

Additive Manufacturing Technologies

The purpose of this section is to provide a detailed understanding and evaluation of current and emerging additive manufacturing technologies. This forms the basis for ranking each technology's potential for future applications using cotton-derived feedstock.

3.1 Section Method

This section begins with an introduction to additive manufacturing, coving basic principles, advantages and technology classification. Subsequently, a detailed analysis of additive manufacturing technologies is presented. In total, 19 different additive manufacturing technologies, from six technology classifications are discussed (Figure 3).

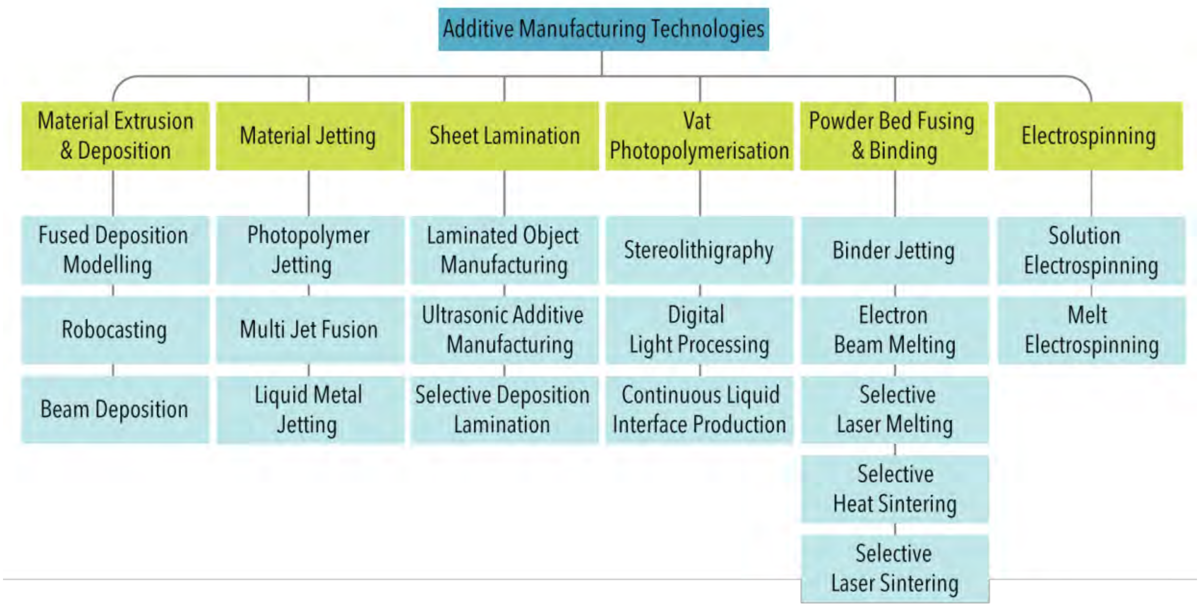


FIGURE 3. ADDITIVE MANUFACTURING TECHNOLOGIES AND SUB-CATEGORIES

For each technology, the basic principles, functionality and unique characteristics are described. A criteria assessment provides a more detailed analysis of the technology and its applicability for use with cotton-derived feedstock. Three key areas are assessed: maturity, application, and feasibility.

Maturity

The criteria used to assess the maturity of additive manufacturing technologies includes: cost, availability, market share, adoption rate, intellectual property, level of current innovation and time since commercialisation. Based on these criteria, each AM technology was evaluated on a maturity scale comprised of five levels (Table 1):

TABLE 1. TECHNOLOGY MATURITY CRITERIA ANALYSIS LEVELS

Level	Description
Innovation	Associated with technology in the early stages of development or technology that has received renewed interest and development at a later stage of development. At this stage, there may be only limited detail of the technology available to the public. The market may be characterised by expiring patents and innovations with the technology.
Introduction	The technology has been commercialised but is yet to establish itself in the market. This technology may still have limited availability and capabilities, and can be coupled with high cost.
Growth	The technology is characterised by incremental development and improvement. This can be associated with expanded product range, release of later generation technology, lower costs, increased availability, and greater consumer awareness.
Maturity	Maturity is associated with a well-established technology the plateau of many of characteristics experienced in the growth stage. The technology has an established product range, technology development has remained steady and technology prices are consistent. At this stage the market may also be characterised by saturation.
Decline	Typically associated with declining sales and profit, technology decline is often caused by saturated market, availability of superior technology, decreased interest, and limited applications.

Application

The criteria used to assess the application of additive manufacturing technologies includes: current applications and industries, material properties, part quality, raw material state and requirements, material cost, material variety, part features, fabrication options, flexibility and fabrication speed. Based on these criteria, each AM technology was evaluated on an application scale comprised of five levels (Table 2 on the following page):

TABLE 2. APPLICATION POTENTIAL CRITERIA ANALYSIS LEVELS

Level	Description
Limited	AM Technology characterised by generally poor performance of parts and limitations associated with the technology. This might include limited material compatibility, poor material properties, poor part accuracy, poor longevity and limited current uses.
Emerging	Characteristic of AM technology with strong, but not proven potential. Alternatively, the technology may be associated with an emerging application - for instance in the medical or aerospace fields where the technology application has been experimental and shown promise but not been adopted at scale.
Specialised	Characteristic of AM technology that has established applications, but isolated to a specific industry or niche market. Common specialised applications may include medicine or aerospace and automotive.
Expanding	Characteristic of AM technology with previously established areas of application, and experiencing increasing applicability, acceptance, and uptake in a broader diversity of application areas.
Widespread	Characteristic of AM technology with well-established and broad applications in a variety of industries.

Integration

The criteria used to assess the feasibility of integrating cotton-derived feedstock with additive manufacturing technologies included: the material requirements of the additive manufacturing technology, existing material characteristics of the additive manufacturing technology, known cotton-derived materials, mass manufacturability of known cotton-derived materials, ease of producing relevant cotton-derived materials, and estimated cost of producing applicable cotton-derived materials. Discussion of these criteria for each additive manufacturing technology took place at the collaborative workshop attended by research staff from QUT and CSIRO. Subsequently, each additive manufacturing technology was assigned a score on an integration feasibility scale comprised of five levels (Table 3 on the following page):

TABLE 3. INTEGRATION FEASIBILITY CRITERIA ANALYSIS LEVELS

Level	Description
Very Low	No current materials are known that are deemed to be compatible with the technology. There may be limited potential to develop compatible materials. However, they may would require extensive development, and may not provide substantial benefit over other materials.
Low	Evidence suggest a compatible material may be viable. However, this is likely to require extensive development and cost, and may not provide substantial benefit over other materials.
Moderate	Cotton can be processed into a feedstock similar to current feedstocks used for the technology. These materials may be difficult or prohibitive to produce due to cost, lead times or poor efficiency. They may also provide limited advantages over current feedstocks
High	Known materials exist that are deemed to be compatible with the additive manufacturing technology. However, these materials may not provide notable benefits over comparable materials.
Very High	Known materials exist that are deemed to be compatible with the additive manufacturing technology. These materials are readily available, are easily produced and low cost.

3.2 Introduction to Additive Manufacturing Technologies

Additive manufacturing (AM) is a term used to describe a broad range of technologies that allow the direct fabrication of physical objects from 3D computer models. The general process employed by additive manufacturing technologies is commonly referred to as 3D printing and allows for physical 3D objects to be created by building up successive layers of material (Figure 4). Layer boundaries are derived from a 3D model by converting the solid volume of the three-dimensional object into a series of two-dimensional cross sections spaced at regular intervals (Gibson, Rosen, & Stucker, 2010; Stucker, 2011). This process is comparable to laying down rows of bricks in the process of building a wall.

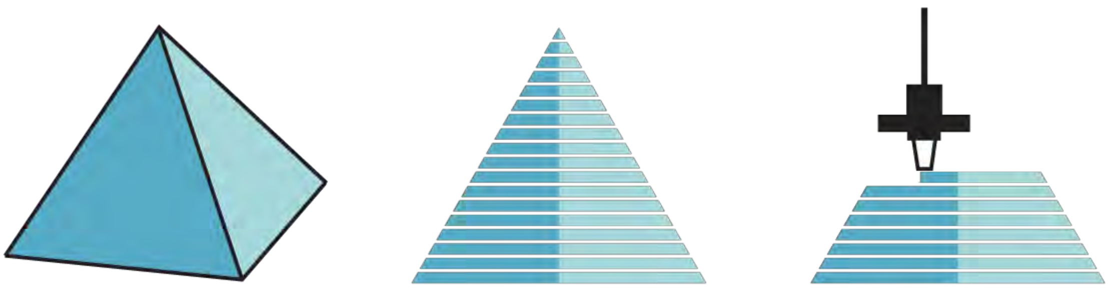


FIGURE 4. LAYER-BY-LAYER CONSTRUCTION.

A key benefit of the layering process used in additive manufacturing is that complex objects are created directly from model geometry. There is no need to adjust for constraints typically encountered in other manufacturing processes because of tooling, undercut and draft angle limitations. For example, subtractive methods of manufacture, like CNC milling, require that the cutting tool have a clear path to the material to be removed. Since AM does not share comparable constraints, forms and details that have not been previously possible are able to be created quickly and easily using a single system of fabrication (Gibson et al., 2010). It is possible to produce an assembled part consisting of multiple elements that does not require any post-processing beyond removing support structures/material from the completed build and refining the surface finish (Warnier, Verbruggen, Ehmann, & Klanten, 2014).

Although AM technologies differ in terms of object layer fabrication and the method of layer bonding, they all adopt a layer-based approach to part production. Subsequently, a similar production process is apparent across the many different approaches to AM, and a series of manufacturing stages common to the use of most applicable technologies can be recognised. Eight general steps are discernible in most AM processes (Figure 5) (Gibson et al., 2010)..

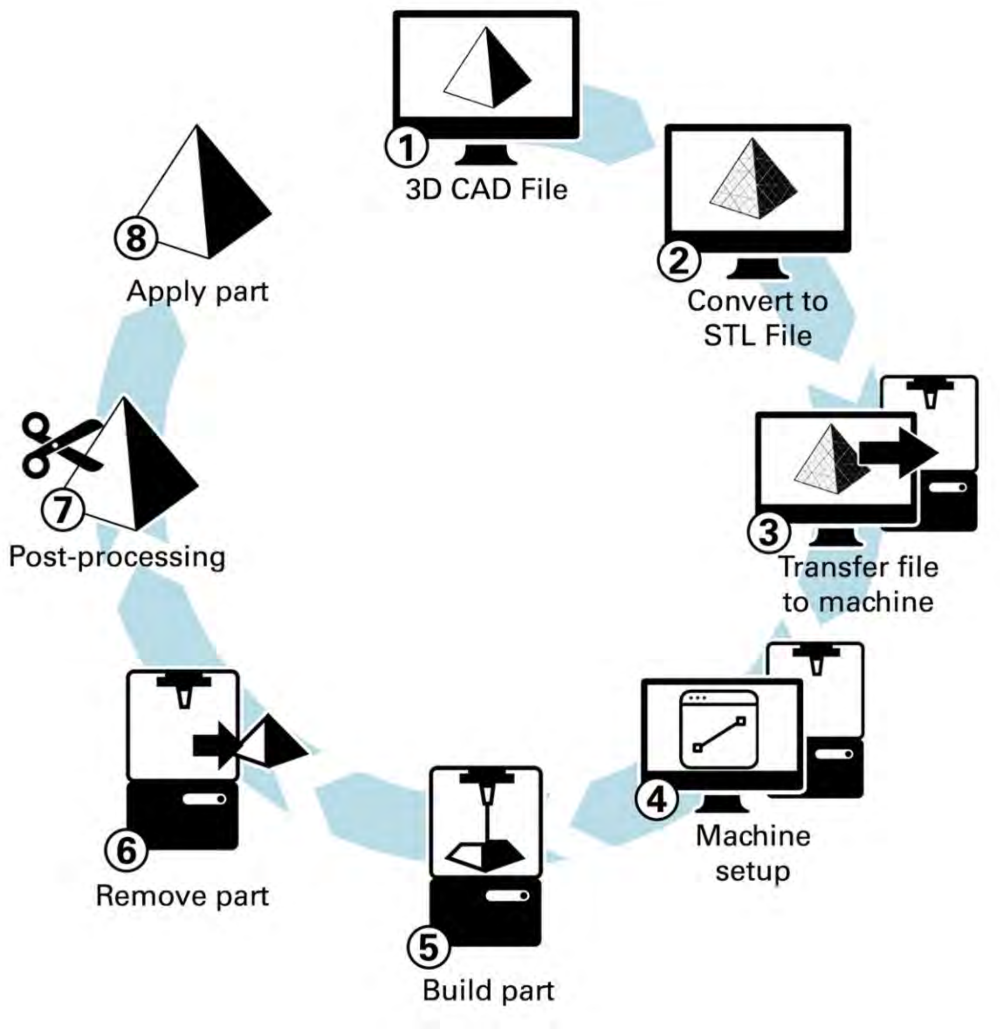


FIGURE 5. THE 8 STAGES OF ADDITIVE MANUFACTURE, ADAPTED FROM GIBSON ET AL., 2010.

1. Almost all AM processes begin with the creation or acquisition of a 3D CAD file of the object to be manufactured. This may be achieved through using CAD modelling software, acquisition of a pre-built model from a sharing website or by 3D scanning a physical object.
2. The 3D CAD file is converted into a file format compatible with the AM technology. For most AM technologies, this is the .STL file format. .STL files contain information of the model surfaces which is used for calculating the 2D planar layers required for the printing process.
3. The STL file is then transferred to the AM machine where the print size, orientation and position may be adjusted.
4. Once the file has been transferred, the model is sliced into horizontal layers, with each layer converted into x and y coordinates. At this stage the specific build parameters must be specified. These parameters may include setting the energy source and strength, layer thickness, quality and speed.
5. The 3D printer reads the x and y coordinates contained in the model to build the part up layer-by-layer. This stage is typically automated and requires no input from the user. However, user input may be required in case of any errors. Additionally, some AM technologies allow for components, such as electronics, to be inserted during build.
6. Upon build completion, the part is removed from the machine. Removal processes vary among the different technologies used.
7. Depending on the technology, post-processing of parts may be required to achieve the final desired result. This may include the removal of excess material, part curing and machining of parts.
8. The final stage is the application of the finished part. The suitability of a part for a particular application depends largely on the technology and material used. Due to the extensive development of additive manufacturing techniques, many final use parts are now directly manufactured using additive manufacture (Gibson et al., 2010).

Although these eight stages provide a good starting point, the nature of each stage and the level of customisation available does vary with each individual technology. Differences in the end product result from variations in 3D printing speed, layer thickness, range of materials, accuracy, and cost (Gibson et al., 2010). This diversity of characteristics can make it difficult to develop a single and accurate method of classification for the different additive manufacturing technologies.

Beginning at a very broad level, additive manufacturing can be categorised by the format in which each layer of material is processed. Material processing classifications include point-wise processing, line processing, layer processing and volume processing (Figure 6). Each of the incremental developments in layer processing provide significant increases in speed of part creation.

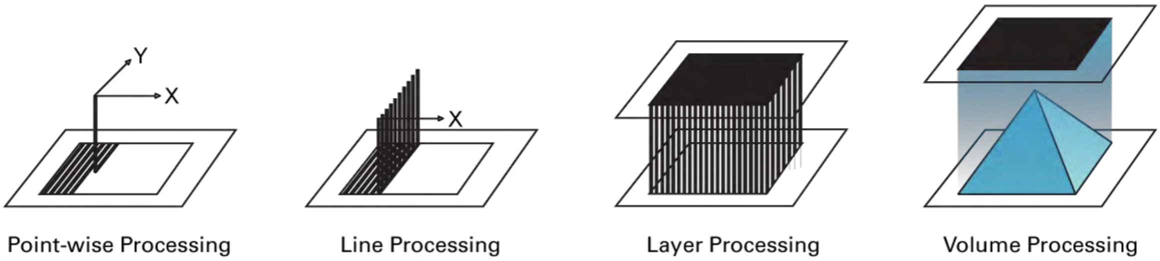


FIGURE 6. CLASSIFICATIONS OF AM PROCESSING METHODS (ADAPTED FROM GIBSON ET AL., 2010)

Point-wise processing is only capable of processing a single location of the layer at one time. Line processing improves on single point processing systems by processing multiple locations on each layer simultaneously. Layer processing provides further advancement by processing an entire layer in one step. Layer processing represents the current state of the art. However, it is possible that future AM technologies will be able to process entire objects in one step. To represent this potential of AM technology, the classification of volume processing is included in the classification, despite not being fully realised yet.

Beyond layer processing format, the classification of individual technologies is based on the types of materials used and the methods for constructing layers. Some common classifications of technology include material extrusion, sintering, melting, jetting and UV curing. For these classifications, there is a close relationship between the type of material and how the layers are constructed. Typically, materials are purposefully designed for the types of technology used to create layers. For instance, material extrusion methods require liquid material or material in the form of filaments that can be melted before extrusion. Sintering and melting technology typically uses powdered material that will melt and bond together when exposed to a heat source. UV curing and jetting technology requires liquid materials that can be solidified upon exposure to a UV light source. This is by no means an authoritative classification of the different technologies, however it provides an indication of how different technologies can be classified. It is also worth noting that 3D printing technology is continually being developed and improved. This can involve the creation of entirely new methods, or it can be in the form of iterative developments that build on previous methods - many of which may not fit directly into these classifications and may require new classifications. The immense variety of different processing methods, technology and materials used translates to unique advantages and disadvantages associated with the various 3D printing technologies. These include variations in surface finish, fabrication speed, layer thickness, mechanical properties, post-processing requirements, material availability, part cost and machine cost (Warnier et al., 2014).

3.3 Material Extrusion and Deposition

Material extrusion and deposition processes apply layers of material directly onto a build platform to build a 3D object. The contours of each layer of the object are traced out with the deposited material. Successive layers are built up until all layers of the object are complete. The objects created are free standing, and as such require construction of support structures for overhanging parts of the model.

3.3.1 Fused Deposition Modelling

Other names: Fused Filament Fabrication; Plastic Jet Printing.

Fused deposition modelling (FDM) machines consist of a movable print head, a build platform and plastic filament material (Figure 7). 3D objects are created layer-by-layer by heating and extruding plastic filament material through the extrusion head onto the build platform. Once a layer is traced out on the horizontal plane, the build platform is lowered vertically and then material is deposited on the next layer (Bogue, 2013).

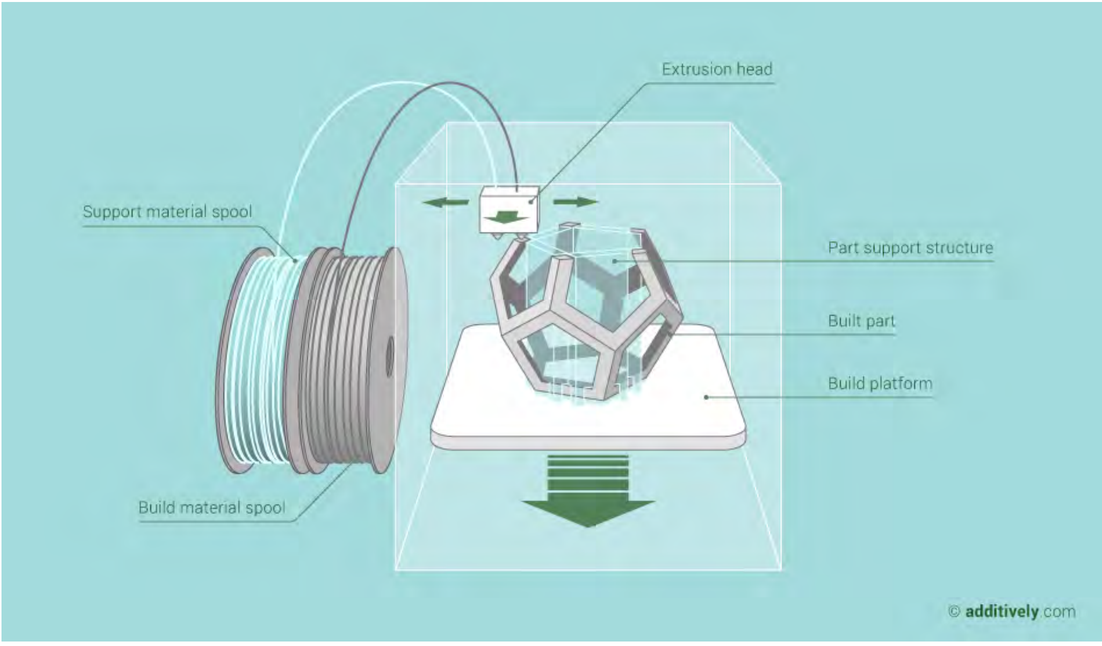


FIGURE 7. FUSED DEPOSITION MODELLING (ADDITIVELY.COM, 2015)

FDM requires two types of material. First, build material is required for the volume of the 3D part. This material is heated slightly above melting point so that it immediately (after around 0.1s) solidifies and cold-welds to the previous layer. Build materials vary substantially and include a number of common thermoplastics. Second, support material is required to be deposited underneath sections of the part volume which are not supported by the build platform. The support material may be the same as the build material, in which case it is removed by hand, for example by trimming it with a craft knife. Alternatively, some FDM printers have a secondary extrusion head allowing the use of alternative support materials. These materials are often water-soluble (e.g. PVA), which results in easier post-processing (Gibson et al., 2010; Pham & Gault, 1998).

Maturity

FDM technology was developed in the 1980s and has experienced continued innovation over its lifespan. A significant part of this innovation has been the attention FDM printer technology has received in open source projects in which they can be built from standard parts and parts printed from other 3D printers (Gibson et al., 2010; Wohlers Associates, Inc, 2015a). This innovation has resulted in the widespread availability of FDM machines to consumers, as well as the development of hybrid systems. For example, current FDM printers on the market are able to print with integrated carbon fibre strands (markforged.com) and integrated electronics (voxel8.com). At a consumer level, the price of FDM printers ranges from $300-$5,000. Sophisticated commercial FDM printers are also available and range from $15,000-$400,000.

Application

FDM is compatible with a large variety of thermoplastic materials, derived from both non-renewable and renewable sources. Common non-renewable thermoplastics include ABS (Acrylonitrile butadiene styrene), ASA (Acrylonitrile Styrene Acrylate), Nylon and Polycarbonate (PC). From renewable sources, PLA (Polylactic Acid) derived from plant starches (including corn, tapioca and sugarcane) is a common material for use with FDM as it is non-toxic and biodegradable (Gibson et al., 2010). The resolution and surface finish of FDM parts is determined by the type of machine, filament thickness and material type. With ABS material, FDM parts can be achieved with 0.127 mm minimum layer thickness, 0.127 minimum feature size and +/-0.27 tolerance. The surface finish of FDM is inferior to Stereolithography and Selective laser Sintering (Additively.com, 2016b).

A key limiting factor for the application of FDM parts is that they are anisotropic. This results in parts that are weaker in the z-axis, which can cause delamination where the bond occurs between layers. To some extent, improvements to part strength can be influenced by material selection. For example, PLA is typically associated with excellent layer bonding, and thus reduced delamination. Moreover, a number of materials are available that provide specialised properties such as improved toughness, and UV ratings. These properties make FDM parts suitable for widespread application in a range of areas including functional models, form and fit testing, prototypes, end use parts, manufacturing tooling and molding, and concept parts (Gibson et al., 2010; Pham & Gault, 1998).

Integration

FDM technology utilises thermoplastic material in a melt extrusion process. Based on these technology requirements, two candidate feedstocks derived from cotton are identified: cotton-derived bioplastic and cotton-derived nanocellulose reinforced polymer matrix composites. These candidate cotton-derived feedstocks are known materials, both used commercially and in a research capacity. Plastics have been developed that utilise both the oil and hulls from the cottonseed, and cotton-derived cellulose fibres have previously been used to reinforce plastics (Pandey et al., 2013). The use of such materials for rapid customisation is promising due to the potential manufacture of fully biodegradable, environmentally friendly products. However, the benefits that they offer compared to already common bioplastics, such as PLA, must be considered.

3.3.2 Robocasting

Other names: Direct Ink Writing; Robotic Assisted Deposition.

Robocasting (Figure 8) is similar to FDM as it works by directly depositing layers of material onto a build platform to build an object. The unique feature of robocasting is the materials that are used and the subsequent application of the parts created. The materials deposited are referred to as 'inks' and exist as colloidal suspensions, which although a liquid, retain their shape when deposited.

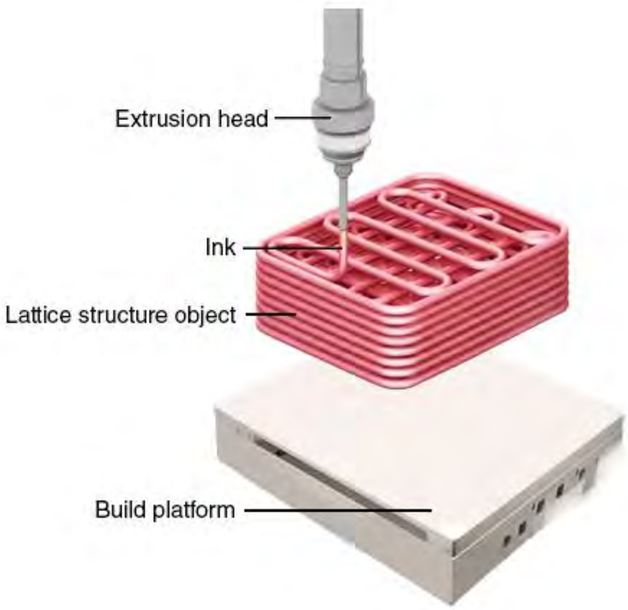


FIGURE 8. ROBOCASTING (ADAPTED FROM INOVENSO.COM, 2013)

A common material used for robocasting inks is ceramic powder, which is formed into a colloidal suspension with a volume of 50-65% ceramic powder (Vaezi, Seitz, & Yang, 2012). However, ink material can extend to any type of nanoparticulate material, so long as their "interparticle forces can be controlled to produce the desired solids concentration and rheological properties" (Lewis, Smay, Stuecker, & Cesarano, 2006, p.2195). The inks have a controlled viscoelastic response that must satisfy two properties. First, they must dry immediately after being deposited so that they retain shape and are capable of supporting their own weight (Lewis et al., 2006). Second, "suspensions must have a high solid volume concentration to minimise shrinkage during drying so that the particle network is able to resist the involved capillary stresses" (Munch et al., 2008). Depending on the material used, and the intended application, printed parts may require a process of drying, debinding and sintering to achieve the requisite strength.

Maturity

Robocasting was developed in 1996 at Sandia National Laboratories. Robocasting machines are not commercially availability for purchase; however, they are available as a service for full-scale manufacturing. The technology has not been characterised by unified development. Instead it has been developed in a variety of diverse industries and application areas, including tissue engineering, drug delivery, industrial filtration and craft (Gibson et al., 2010).

Application

The main factor limiting the application of robocast parts is that they are near-net-shape and not near-net-size. This means that it is difficult to predict dimensional variation and obtain high dimensional accuracy with robocasting. Robocast parts have a rough surface finish and without post-processing, a smooth surface is unobtainable. Beyond these limitations, a key advantage of robocasting is that more than one material can be used at a time. This allows for graded materials, and parts that can seamlessly transition from one material to another without interrupting the printing process. This allows for the printing of embedded materials and fugitive material, which is a key reason why robocasting has received significant interest in medical research (Gibson et al., 2010). In this area, robocasting is used to print 3D hydrogel structures that contain biomaterial to encourage cell growth. Robocasting of hydrogels is gaining interest as a method of drug delivery, where parts are loaded with controlled release drugs to treat chronic illness and disease (Lewis et al., 2006).

Beyond medicine, robocasting also has the potential for more common applications, particularly concerning ceramic parts. Robocast ceramic parts are used for industrial filtration, laboratory equipment, thermal analysis crucibles and medical implants. Robocasting can also be used in more common applications such as household appliances, aircraft and automobile components and computers. Robocast ceramics are advantageous over traditional ceramics as they can be designed with internal cavities and cooling channels; may be free-formed; and dried and baked in less than 24 hours. Traditional fabrication of ceramics can take several weeks to progress from design to finalised part. Common materials used in robocasting include, silica, lead zirconate titanate, barium titanate, aluminia, mullite, silicon nitride and hydroxyapatite (Lewis et al., 2006).

INTEGRATION

The compatibility between robocasting and colloidal suspensions results in a high feasibility for integrating cotton-derived feedstocks with robocasting technology. One candidate cotton-derived material is identified for use with robocasting: cotton-derived nanocellulose hydrogel. Although not widely used in commercial applications, nanocellulose hyrdogels have received substantial interest in tissue scaffolding and drug delivery research (Chang & Zhang, 2011). Cellulose hydrogels also have the potential to be converted into aerogels via rapid freeze-drying. This results in extremely low-density and porous materials with applications such as filtration and insulation (Fischer et al., 2006).

3.3.3 Beam Deposition

Other names: Directed Energy Deposition; Laser Powder Forming; Laser Powder Deposition; Laser Deposition Technology; Laser Freeform Manufacturing Technology; Laser Metal Deposition; Electron Beam Deposition Modelling.

Beam deposition (BD) technologies deposit either a powder or a wire filament material to create objects layer-by-layer. Regardless of the material type, each of the different technologies uses a similar process to form the layers of an object. A focused laser (or other energy source) creates a melt pool on the build surface. As this occurs, material is deposited on the melt pool. For powder systems (Figure 9), a stream of inert gas carries the material through the processing head assembly onto the melt pool. For wire fed systems, the filament material is fed through the processing head assembly onto the melt pool. The material melts as it enters the melt pool and then solidifies as the laser moves away creating a thin track of material deposited on and welded to the previous layer. This process is used to trace out successive layers of a part until the part is complete (Bogue, 2013; Gibson et al., 2010).

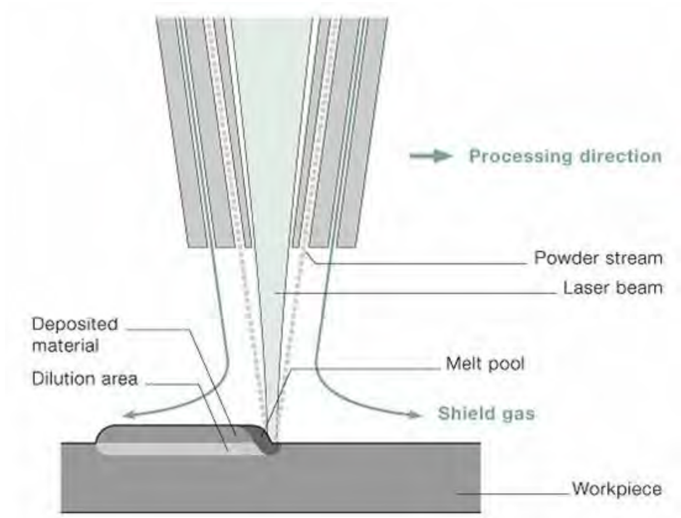


FIGURE 9. DIRECTED ENERGY DEPOSITION (LPWTECHNOLOGY.COM, 2015)

Maturity

The earliest beam deposition machines were developed in the 1990s. Manufacturers of commercial machines include LENS and POM, while other non-commercial systems have been developed by the Fraunhofer Institute, NASA (EBF[3]), and a number of other research groups. BD is a niche technology, and the machines have generally been developed with characteristics and capabilities suited to niche applications. At this stage, BD is predominantly used in the aerospace industry, but has not yet gained widespread acceptance. However, as the technology develops this is likely to occur due to the benefits it provides over other custom part manufacturing processes (Gibson et al., 2010).

Application

Beam deposition is typically used with ceramic or metal material, however, thermoplastics can also be used. The majority of metals can be effectively processed, although metals with high reflectivity and thermal conductivity (e.g., gold, copper) can be problematic. Ceramics are also difficult to process as fewer ceramics can be melted to form a molten pool. Ceramics have a tendency to crack during cooling, and as a result they are usually processed as part of a metal composite. Parts created using BD can achieve extremely high density and excellent mechanical properties. BD processes can also exert excellent control over microstructural features, allowing for varying material compositions and solidification rate. This allows the manufacture of components with gradient material composition variations along all axes (Gibson et al., 2010).

An important capability of BD processes is that they can be used to add features to or repair damaged sections of an existing part (Bogue, 2013). For complex geometries, multi-axis deposition heads and support structures are required. These supports must be accessible so they can be removed during post-processing. An additional drawback of BD processes is poor accuracy and surface finish. Most processes are unable to achieve accuracy better than 0.25mm and a surface finish less than 0.025mm. Due to these limitations parts cannot achieve the same level of complexity as other AM technologies (Gibson et al., 2010; Stucker, 2011). BD processes are used in a number of industries including aerospace, biomedical and other heavy machine industries to create limited run custom parts or for the repair of existing parts.

INTEGRATION

The compatibility of thermoplastic materials with BD processes results in a moderate feasibility for the integration of cotton-derived feedstocks. Two candidate cotton-derived materials are identified: cotton-derived bioplastic, cotton nanocelulose reinforced polymer matrix composite. As discussed with FDM, these are known materials. As BD is currently used in niche industries for limited run applications, the applicability of cotton-derived bioplastics for these applications must be considered.

3.4 MATERIAL JETTING

Material Jetting uses a process similar to inkjet printing where droplets of material are deposited onto a build platform layer-by-layer to build a 3D object. Material jetting systems originally used a photopolymer liquid to produce objects, however, innovation has resulted in machines capable of printing wax like materials for the creation of investment casting patterns (lost-wax casting) (Stucker, 2011), liquid metal jetting systems (Wang & Liu, 2014b) and Multi Jet Fusion (Hewlett-Packard, 2016).

3.4.1 Photopolymer Jetting

Photopolymer jetting (polyjet) machines use ink-jet style print heads to deposit microscopic droplets of liquid photopolymer material onto the build platform to create 3D objects (Figure 10). The print head is equipped with a UV light which immediately cures the deposited photopolymer material. Once one layer is traced out with the deposited material, the build platform is lowered to enable successive layers to be built on top of one another. Objects built using photopolymer jetting require a support material in order to support part overhangs. The support material is typically different to the build material (e.g., wax) so that it can be removed easily. In addition to support material, some photopolymer jetting machines are capable of printing multiple build materials at the same time (Gibson et al., 2010; Warnier et al., 2014).

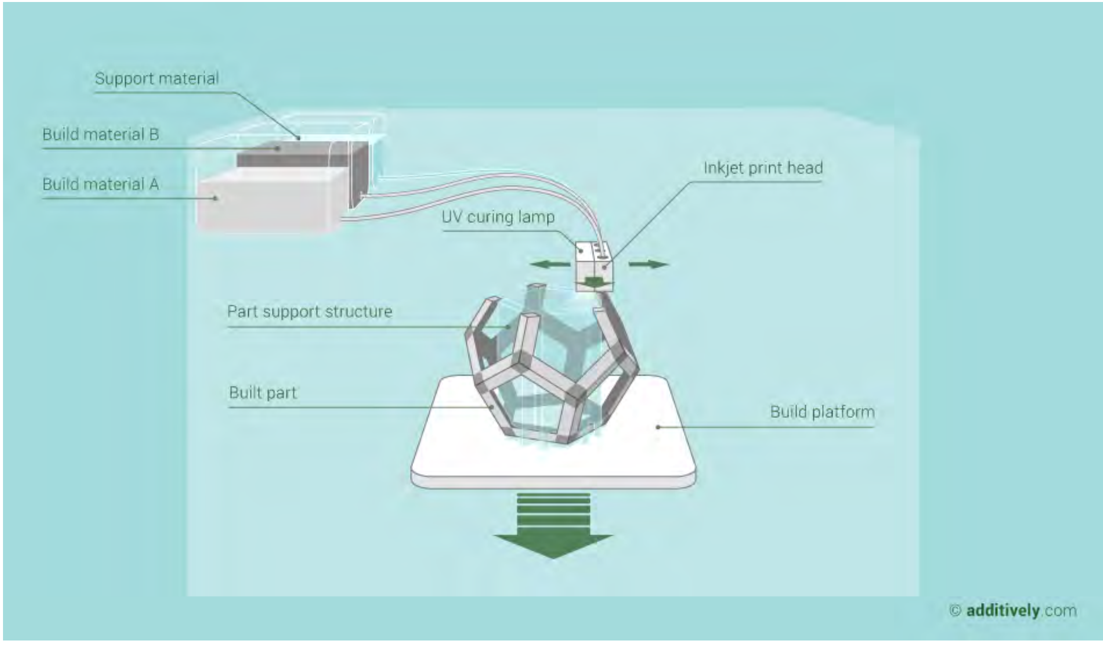


FIGURE 10. PHOTOPOLYMER JETTING (ADDITIVELY.COM, 2015)

MATURITY

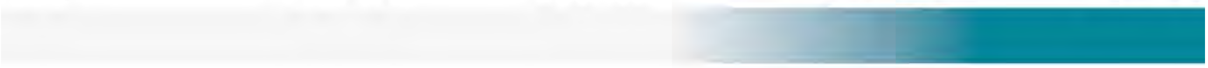
INNOVATION INTRODUCTION GROWTH MATURITY DECLINE

Photopolymer jetting systems are available in a number of desktop and professional class models. The most notable manufacturers are Stratasys and 3DSystems, and their systems start at $22,000 for desktop models and $100,000-$600,000+ for professional systems.

Recently, photopolymer Jetting technology has transformed into an area of innovation, with low-cost machines being produced that are capable of printing a variety of materials simultaneously. For instance, MIT's MultiFab (CSAIL, 2015) printer combines optical scanning, a 40-micron resolution and the ability to print up to 10 different materials on a single object. The 3D scanner is used to scan the part during printing to develop a print strategy and facilitate self-calibration and to fix print errors as they occur. It also improves the quality of printed assemblies comprised of multiple parts made from multiple materials (CSAIL, 2015).

APPLICATION

LIMITED EMERGING SPECIALISED EXPANDING WIDESPREAD



A key advantage of photopolymer jetting systems is the ability to print multi-material and multi-colour parts. This enables the creation of accurate and functional prototypes. A number of photopolymer jetting systems utilise a line array of print heads, which allows for significantly faster build times compared to point based systems (Gibson et al., 2010; Pham

& Gault, 1998). Photopolymer Jetting systems are capable of high part detail, accuracy and surface finish: minimum layer thickness of 0.016 mm, typical tolerance of +/-0.025mm and minimum feature size of 0.15 mm. A variety of photopolymer materials are available which allows parts to obtain a variety of mechanical properties (Additively.com, 2016e).

The main limitation of photopolymer systems is that they require UV-reactive photopolymers as the build material. Photopolymers can provide good initial mechanical properties, but they will deteriorate over time. Subsequently, this limits the end-use applications of parts. Applications include visual and form/fit prototypes, casting patterns and molds, and temporary mechanical parts (Bogue, 2013; Gibson et al., 2010).

INTEGRATION

Two candidate cotton-derived materials are identified for use with photopolymer jetting systems: cotton-derived photopolymer, and nanocellulose reinforced photopolymer. Researchers have documented the formulation of photopolymers from PLA, a naturally derived polymer (Miller & Soucek, 2012). Similarly, existing research documenting the use of Nano-SiO_2 reinforced photopolymers (Zhang, Cui, Li, & Jiang, 2015) suggests the feasibility of a nanocellulose reinforced photopolymer for 3D printing. While there is indicative potential to formulate photopolymers utilising cotton material, the specific requirements of this are unknown at this time. It is predicted that the ratio of cotton to other materials required might be quite low. Additionally, it is uncertain what the benefits of using cotton in such applications is. For these reasons, the feasibility of a cotton-derived feedstock for photopolymer jetting is determined to be low.

3.4.2 Liquid Metal Jetting

Liquid metal jet printing (LMJP) systems (Figure 11) deposit individual drops of molten metal to a specific location to build up objects layer-by-layer. This process is similar to photopolymer jetting, however, instead of depositing photopolymer material, metallic materials are used. As metal is used, high temperatures are required to keep the material in liquid form in order to print. Two forms of jetting are available in LMJP, on-demand and continuous. Continuous jetting is a rapid printing process where an almost continuous stream of material is deposited. This consumes less energy, however, creates material wastage. On-demand printing consists of larger droplets, which are deposited at a slower rate, and subsequently result in limited material wastage (Priest, Smith, & DuBois, 1997; Singh, 2013).

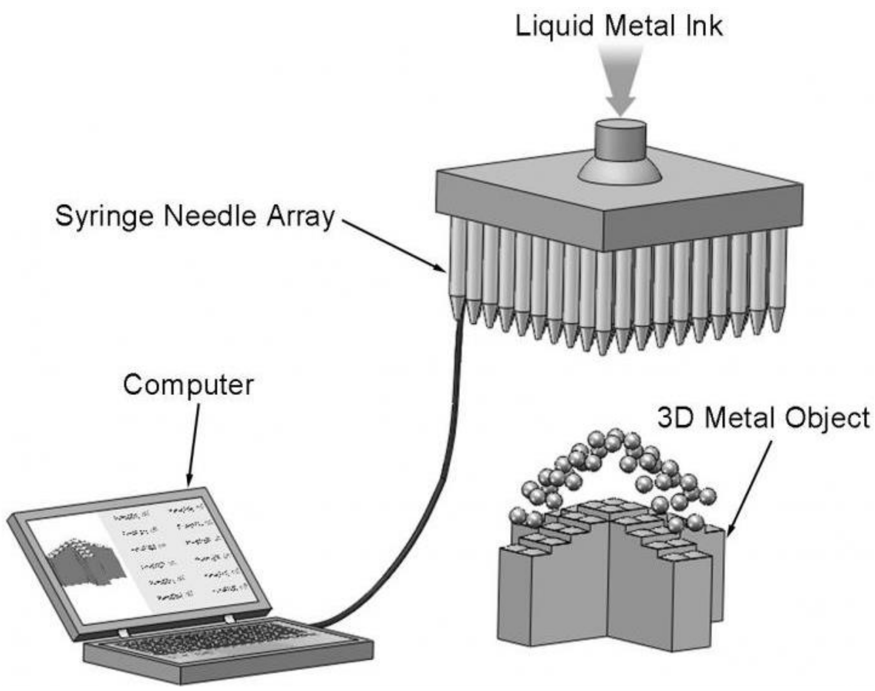


FIGURE 11. LIQUID METAL ARRAY OF 3D PRINTER (WANG & LIU, 2014A)

Maturity

INNOVATION INTRODUCTION GROWTH MATURITY DECLINE

IBM developed liquid metal jet printing in 1972, in the form of low temperature solder applications. The first patent was filed by Philips North America in 1989. Further research and development led to a patent filed in 1993 by IBM specifying an electrodynamic pump used to deposit molten metal material (Priest et al., 1997). Current technology development focusses on applications for LMJP with higher temperatures and different methods of material deposition. Although LMJP has existed since the 70's current research and application into electronics and mechanical printing has placed this technology in a stage of innovation and growth.

Application

LIMITED EMERGING SPECIALISED EXPANDING WIDESPREAD

LMJP at low temperature is widely used for electronic applications, such as conductive circuit boards and mechanical parts. Liquid metal inks are also being experimented with for printing circuits in flexible electronics (Wang & Liu, 2014a). Recent technology developed by Vader systems (vadersystems.com), a US start-up, has focused on low-cost solutions to 3D printing liquid metals. Most existing metal 3D printers (SLS, DMLS) require expensive components and are suitable only for large companies or manufacturers. Availability of inexpensive metal 3D printers with the ability to print free-form 3D structures may widen impact of LMJP. This will widen the specialist and limited nature of LMJP and potentially introduce a low-cost option for 3D printing of metal parts.

INTEGRATION

VERY LOW	LOW	MODERATE	HIGH	VERY HIGH

Liquid Metal Jet Printing systems are compatible with metallic materials. For this reason, this process is not suited to a cotton-derived feedstock.

3.5 SHEET LAMINATION

Sheet lamination techniques use a process in which layers of sheet material are cut to shape and then built up to form an object. While the general process of each sheet lamination process is the same, each process varies in terms of the material used, method of adhering each layer, and the extent of post-processing required.

3.5.1 Laminated Object Manufacturing

Laminated object manufacturing (LOM) machines construct 3D objects by layering thin cross sections of thermoplastic material together (Figure 12Error! Reference source not found.).

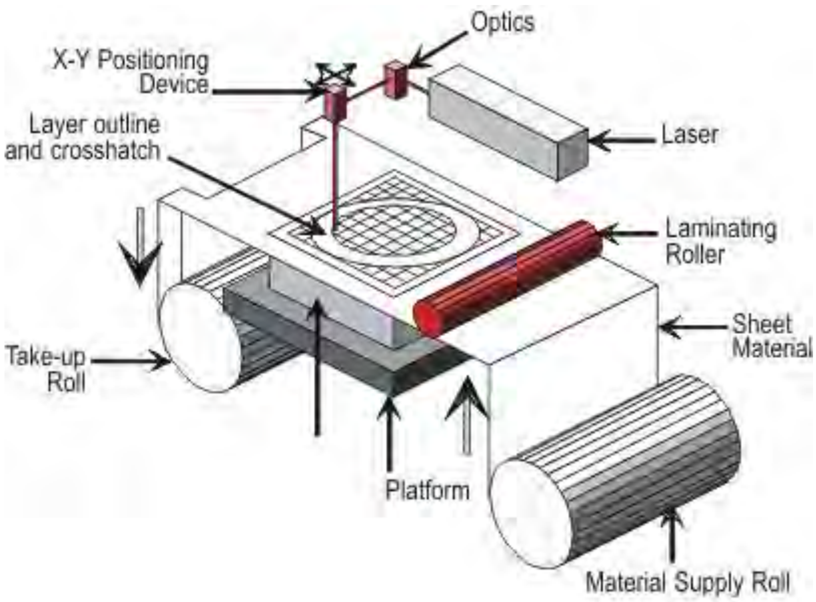
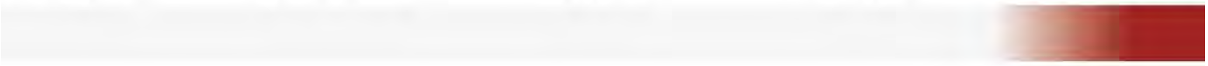


FIGURE 12. LAMINATED OBJECT MANUFACTURING (AZOM.COM)

Each layer of the object is cut from a roll of thermoplastic adhesive lined sheet material using a CO_2 laser. Successive layers are bound together through the application of heat and pressure. Once one layer of sheet material is cut and bound, the build platform is lowered to allow the plastic sheet to be rolled over, ready for the following layer. Areas of the sheets that do not form part of the solid object (for example, material outside of the objects volume, or inside cavities) act as the structure to support any part overhangs or undercuts. These sections are cut into small cube sections called 'tiles', and are removed from the object once all layers of the object have been completed (Chua, Chou, & Wong, 1998).

Maturity

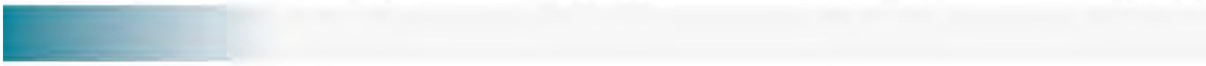
INNOVATION INTRODUCTION GROWTH MATURITY DECLINE



The laminated object manufacturing process has not been as successful as other commercial additive manufacturing technologies. A company known as Helisys developed LOM, however, they ceased production of LOM machines in 2000. Since then, Cubic Technologies has supported LOM, with their systems available for $15,000.

Application

LIMITED EMERGING SPECIALISED EXPANDING WIDESPREAD



A key limitation of LOM is high material wastage. As sheet material is used, the amount of material that is required for an object is fixed to the height of the object. Material that is outside the part volume is not reusable and thus creates a substantial amount of waste. This characteristic of LOM provides a significant limitation in comparison to other 3D printing techniques in which unused build material can be reused (Campbell & Parsons, 2005).

Beyond material wastage, the LOM process is characterised by a number of other limitations. Parts are characterised by a lower surface finish and detail than comparable AM technologies. The process requires substantial and often difficult post-processing to remove material surrounding complex geometries and enclosed volumes. Consequently, parts are limited by level of complexity that can be achieved (Gibson et al., 2010).

The main benefit of LOM is that a number of sheet materials can be used, including thermoplastics and paper. These materials are inexpensive compared to the expensive resins and powders required for other AM technologies.

Integration

VERY LOW | LOW | MODERATE | HIGH | VERY HIGH

As sheet material and adhesive is used in the LOM process, the feasibility of applying a cotton-derived feedstock is high. Five candidate cotton-derived feedstocks are identified: cotton-derived bioplastic sheet material, regenerated cellulose film (e.g., cellophane), cotton paper, cotton textile, and cotton-derived adhesive. Each of these candidate materials are known, and a number are ubiquitous and would require little alteration for use with LOM. Although these materials are widely available, the benefits of using these materials in the LOM process need consideration. Moreover, the parts created from these materials would be characterised by the same limitations as the existing materials used with the LOM process.

3.5.2 Selective Deposition Lamination

The selective deposition lamination (SDL) process creates 3D objects by bonding successive layers of standard copier paper together with an adhesive (Figure 13). Adhesive is selectively applied to each layer of paper as it is laid down onto the build platform. A higher density of adhesive is applied to sections of paper that will form the 3D object. A much lower density of adhesive is applied to sections of paper that do not form part of the 3D object. Once the adhesive is applied, the build platform is raised to a heat plate where heat and pressure is applied to ensure a strong bond between layers (Bhatia, 2015; Gibson et al., 2010). A blade is then used to cut the contour of the object, based on the layer information from the .STL file. The areas of the layer outside the object contours act as the structure to support any part overhangs or undercuts. These sections are cut into grid-like 'tiles' and are manually removed in small chunks (Bhatia, 2015).

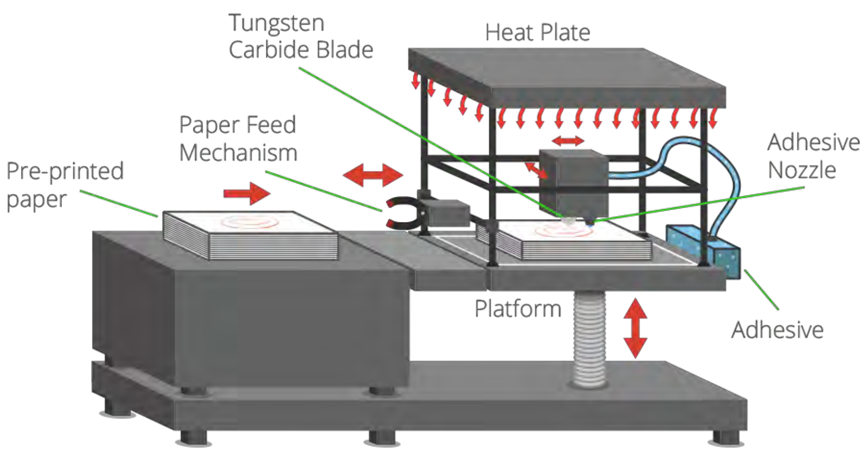


FIGURE 13. SELECTIVE DEPOSITION LAMINATION (3DPRINTINGINDUSTRY.COM, 2015)

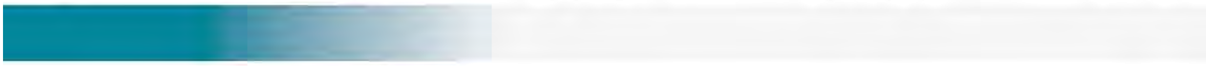
Maturity

INNOVATION | INTRODUCTION | GROWTH | MATURITY | DECLINE

SDL is a relatively new AM technology developed in 2005 by Mcor Technologies. Mcor Technologies released their most advanced machine in 2012, which is capable of printing full colour objects. Prices of Mcor machines range from $35,000-$50,000. Since their commercialisation, Mcor Technologies has reported consistent sales growth from 138 machines in 2012 to 600 machines in 2014 (Wohlers Associates, Inc, 2015b).

Application

LIMITED | EMERGING | SPECIALISED | EXPANDING | WIDESPREAD

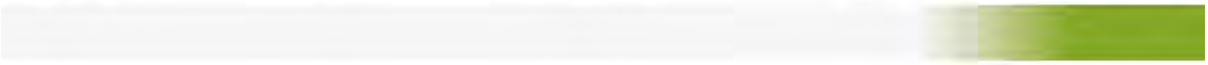


The greatest advantage of SDL is compatibility with standard photocopier paper. The use of this material is beneficial as it is widely available, inexpensive, renewable and recyclable. As parts are produced from paper and a water based adhesive, the objects can also be recycled using normal recycling processes. The Mcor Technologies IRIS 3D printer is equipped with a modified ink-jet printer, which allows for parts to be printed in full colour CMYK. This makes the Mcor Technologies printer an attractive option for visual prototyping (Krassenstein, 2014).

Despite these benefits, the SDL process is limited by the high amount of waste material that is produced. Furthermore, parts that are not treated with hardeners demonstrate limited part strength and application potential. Parts are particularly susceptible to heat and moisture damage (Wohlers Associates, Inc, 2015b).

Integration

VERY LOW | LOW | MODERATE | HIGH | VERY HIGH



The SDL process presents similar feedstock requirements as the LOM process described previously. For this reason, there is a high feasibility of using cotton-derived feedstock for the SDL process. Five candidate cotton-derived feedstocks are identified: cotton-derived bioplastic sheet material, regenerated cellulose film (e.g., cellophane), cotton paper, cotton textile, and cotton-derived adhesive.

3.5.3 Ultrasonic Additive Manufacturing

Other names: Ultrasonic Consolidation.

Ultrasonic additive manufacture (UAM) creates 3D objects by building up successive layers of thin sheet material. The material used is typically thin metal foils, which are bound together on a metallic substrate. To create the bonds between layers, foils are held together under pressure and then high frequency ultrasonic vibrations are locally applied to the metal foils using a rotating oscillating sonotrode (Figure 14). This process results in a solid-state weld between the foil materials, which subsequently create a rough part shape. 3-axis CNC contour milling is used to cut away the excess foil material to finish the part. This produces the required shape of the given layer and the geometric detail of the part. As with other additive manufacture methods, UAM enables the production of complex shapes with overhangs (Janaki Ram, Yang, & Stucker, 2006).

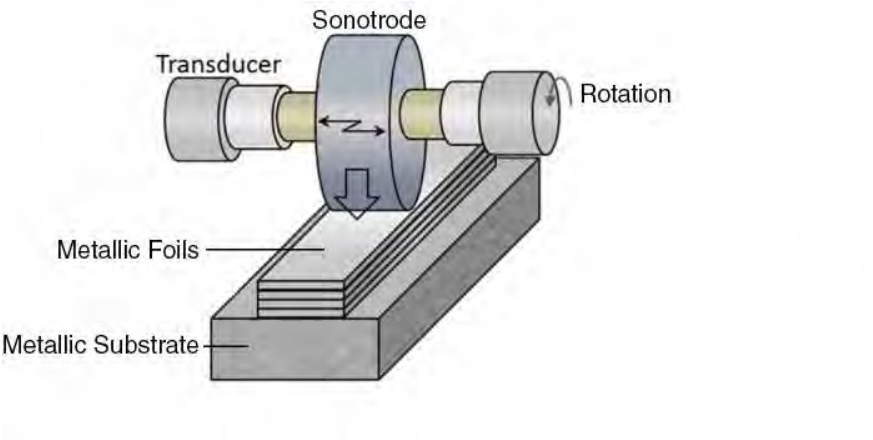


FIGURE 14. ULTRASONIC ADDITIVE MANUFACTURE (INSIDEMETALADDITIVEMANUFACTURING.COM, 2015)

The ability to machine away material during the layering process gives UAM significant advantages over traditional CNC machining. CNC machining processes do not allow for some complex geometries or parts with internal volumes as the cutting head is required to have direct access to the area being machined (Gibson et al., 2010; Lefteri, 2007). With UAM, internal structures or complex geometries can be created during the layering process.

MATURITY

Solidica Inc. patented (US 6519500 B1) and commercialised UAM technology in 2000. Subsequently, Fabrisonic was founded in 2011 through a joint venture between Solidica Inc. and EWI. Fabrisonic has continued the development of UAM equipment for research, development and manufacturing. Two UAM machines are available: The SonicLayerR200, (research platform) the SonicLayer 4000 and the SonicLayer 7200. Current research and development of UAM is exploring embedded electronics, and fibres for integrated optics and reinforcement (Gibson et al., 2010).

Application

The solid-state process used for UAM parts allows for true metallurgical bonds with full densities. Since the metals are heated only slightly (200°C) during the ultrasonic welding process, the process can be used in normal workshop environments, and the parts do not experience the same type of material changes experienced at high temperatures (e.g., phase changes, changes in grain size of precipitations). This also allows for electronic components, such as optical fibres to be embedded during processing (Gibson et al., 2010; Wohlers Associates, Inc, 2015b). A wide range of metals are suitable for UAM, including aluminum, titanium, copper, iron, magnesium, zirconium, beryllium, platinum, nickel, palladium, silver and stainless steel. Ultrasonic bonds are possible between dissimilar materials, allowing parts to take advantage of the properties of several materials simultaneously. UAM can also be used with a variety of common thermoplastics (Fabrisonic Inc., 2016).

The quality and strength of UAM parts are similar to those fabricated using CNC. UAM is capable of producing parts with excellent surface finish and tolerances of /+0.0127mm. The hybrid system of ultrasonic welding combined with CNC also produces some additional benefits to CNC. As CNC milling is used during the process of ultrasonic welding, complex geometries (honeycomb structures) and internal voids (pipes, channels) can be achieved which are not possible with traditional subtractive manufacturing. This also allows for the repair of parts. Damaged or worn sections can be machined off and new material can be deposited in a single process without having to move the part between different processes. The main downside of UAM is that it is much slower than traditional CNC and parts are susceptible to defects that compromise the strength of parts. Primary defects occur due to voids along the interface between two layers, or physical gaps between adjacent metal foils (Gibson et al., 2010).

Integration

The compatibility between UAM and thermoplastic material presents a high feasibility for use with cotton-derived feedstock. One candidate cotton-derived feedstock is identified: cotton-derived bioplastic sheet material. As discussed with previous technologies (e.g., FDM), cotton-derived bioplastic is a known material. However, for use with UAM, the material must possess relevant properties for use with ultrasonic welding. Additionally, consideration must be given to the benefits that a cotton-derived bioplastic provides over existing thermoplastics and bioplastics.

3.6 Vat Photopolymerisation

Vat photopolymerisation processes create 3D objects by building up successive layers of an object within a vat of radiation curable liquid resin. Individual layers of the liquid material are exposed to radiation, which causes the material to solidify and bond to the previous layer. Vat photopolymerisation processes vary in terms of radiation source, layer exposure method and build orientation.

3.6.1 Stereolithigraphy

Stereolithography (SLA) machines are comprised of five elements; a perforated build platform, material vat, laser and optics system, recoating system and control system (Figure 15).

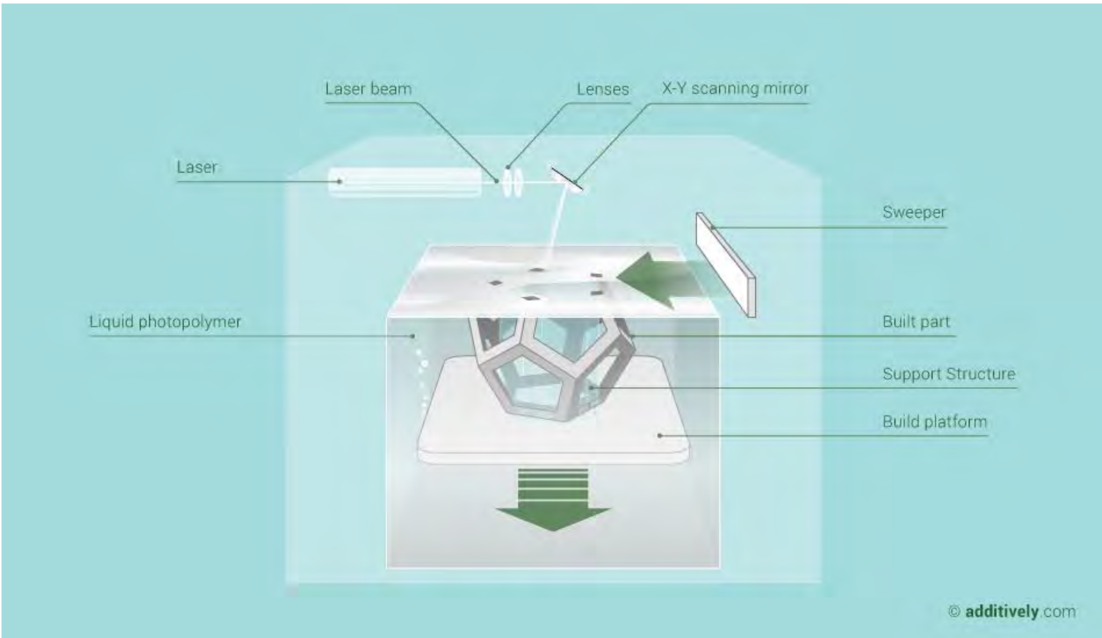


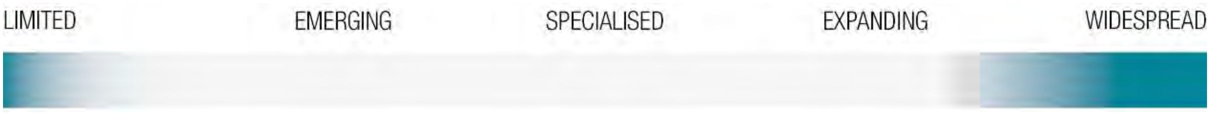
FIGURE 15. STEREOLITHOGRAPHY (ADDITIVELY.COM, 2015)

When building a part, the build platform is lowered into the resin to allow a thin layer of resin to form over the top of the build platform. The recoating mechanism (or sweeper), typically a hollow blade filled with resin, sweeps across the build platform to ensure a smooth surface of resin is on top of the build platform. The radiation and optics system, located above the vat and build platform, scans a laser beam across the surface of the vat within the contours of the objects layer. When the resin is exposed to the radiation it forms a polymer and hardens. UV and visible light radiation are most commonly used in SLA systems, however various types of radiation, including x-rays and gamma rays, can be used to cure photopolymers. Once a layer is completed the build platform is lowered to allow for another thin layer of resin to form on the surface (Gibson et al., 2010). As the laser traces over the next layer of resin, the resin is cured and bonds to the previous layer. This process is repeated for each successive layer to create an object. Upon completion, the part is removed from the vat and any excess resin is drained. The part is then post-cured in a UV oven to ensure that no partially cured resin remains and to improve the mechanical properties of the part (Bogue, 2013).

Maturity

3D systems patented the SLA process in 1984 and later commercialised it in 1986. Key patents protecting SLA processes have since expired which have allowed SL machines to be marketed by several other companies including Fockle & Schwarze, Denken Engineering, Mitsubishi and Sony. As well as professional machines, there are also some inexpensive SLA systems available to consumers, with the most well-known of these being Formlabs ‘Form’ series (Gibson et al., 2010; Wohlers Associates, Inc, 2015a). The price of SLA systems varies substantially, from $3000 for consumer models and over $300,000 for professional systems. With the continued development of AM technology, different vat polymerisation systems are in development that are more efficient than SLA systems.

Application



Material options are the weakest characteristic of SLA technology as photopolymer resins tend to be brittle. However, the variety of resins that are available is continually increasing. Polymer-ceramic composites with up to 53% powdered ceramic content are available and nanomaterial reinforcements have been explored (Zhang et al., 2015). In the case of reinforcing agents, the particles must be smaller than the layer thickness. Elastomer materials and other materials are available that demonstrate similar mechanical properties as some engineering materials. For example, form labs have a range of materials titled, ‘flexible, castable, standard, and tough’. While such developments allow SLA parts to be used for mechanical applications, their use is still limited as photopolymers are not stable and will deteriorate over time (Sorrel, 2015). In addition to limitations of material properties, SLA systems are limited to using one resin at a time (Gibson et al., 2010).

The key advantages of SLA over other AM technologies is part resolution and surface finish. SLA is capable of producing parts with 0.016mm minimum layer thickness, 0.1mm minimum feature size and +/-0.15mm typical tolerance. Due to the limitations in material properties and high part accuracy, SLA parts are often used for form/fit prototypes

(Additively.com, 2015). Parts are also used for biomedical engineering applications, including, fabrication of molds for the preparation of implants in cranial surgery and tissue engineering (Melchels, Feijen, & Grijpma, 2010).

INTEGRATION

VERY LOW | LOW | MODERATE | HIGH | VERY HIGH

Two candidate cotton-derived materials are identified for use with stereolithography systems: cotton-derived photopolymer, and nanocellulose reinforced photopolymer. As discussed with the photopolymer jetting process, both naturally derived photopolymers (Miller & Soucek, 2012), and the addition of reinforcing nanomaterial to photopolymers (Zhang et al., 2015) have been reported in existing research. While this suggests the potential feasibility of utilising a cotton-derived material for SLA processes, the specific requirements for formulating a cotton-derived photopolymer are unknown at this time. A consideration unique to vat photopolymerisation processes is that any reinforcing agent added to the liquid photopolymer must not exceed the thickness of the cured layer (Zhang et al., 2015).

3.6.2 Digital Light Processing

Other names: Mask Projection Stereolithography; Digital Light Projection.

Digital light processing (DLP) (Figure 16) is a photopolymerisation method that uses a similar process to stereolithography.

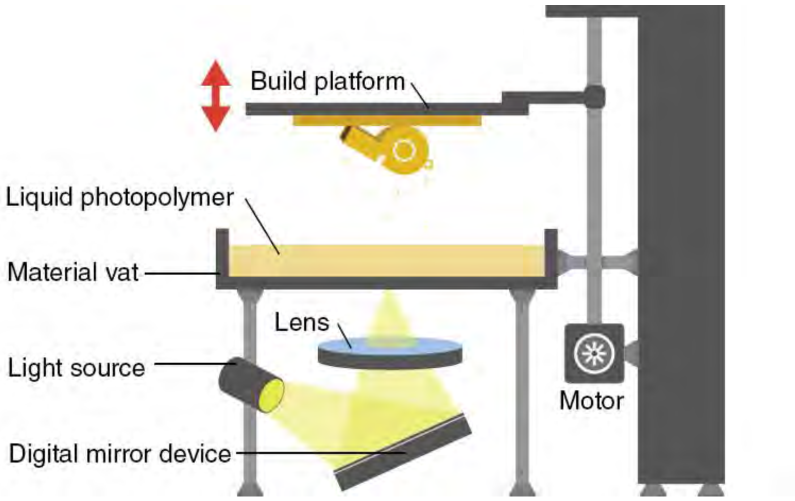


FIGURE 16. DIGITAL LIGHT PROCESSING (APAPTED FROM 3DPRINTINGINDUSTRY.COM, 2015)

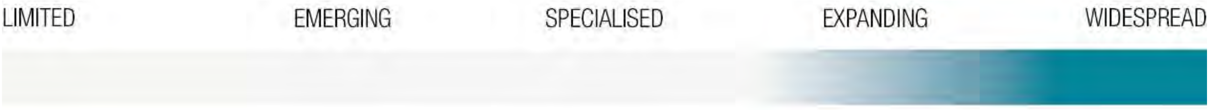
The differentiating characteristics of DLP is an alternative build orientation and method of illumination. The DLP method typically uses a bottom-up approach to build 3D structures. Using this approach, the build platform is located above the material vat and is dipped into the liquid resin. The UV source that cures the resin is located below the vat that holds the liquid resin. UV light is projected onto the bottom of the material vat, which is a transparent, non-adhering material. The liquid resin that is located between the build platform and material vat is cured upon exposure to the UV radiation. Once one layer of material is cured, the build platform is raised to allow for another layer of liquid resin to form between the material vat and the build platform. As this new layer of material is cured, it bonds to the previous layer of cured resin. This process is repeated for each successive layer of the object until it is completed (Gibson et al., 2010).

Unlike stereolithography, which uses a focused UV laser, DLP uses a UV lamp which is projected onto a digital mirror device to cure the resin. The digital mirror device is comprised of up to several million mirrors which can be controlled and rotated individually to an on and off state. Using the digital mirror device, a two-dimensional pattern can be projected onto the transparent plate and a whole layer of resin can be cured at once. This method of illumination is advantageous as it offers much higher build speeds than traditional stereolithography (Gibson et al., 2010).

Maturity

DLP was developed in the early 1990s. Commercial systems are available from EnvisionTEC, and are priced from $100,000 to over $250,000. There are a number of consumer grade DLP printers available including the Projet 1200, Autodesk Ember, B9 Creator, 3D Facture, Kudo 3D, and MoonRay. Consumer DLP machines range from $2,000 to $15,000. At present, DLP processes are being developed which allow for the continuous projection of layer masks (Wohlers Associates, Inc, 2015a). These developments allow for substantially faster creation of 3D objects. One such technology is ‘continuous printing’ from Gizmo 3D (gizmo3dprinters.com.au). Although a product is yet to be released, media releases have shown Gizmo 3D machines printing 150x80x26mm objects at 50um in 6 minutes, which is significantly faster than other AM technologies.

Application



Parts created from DLP machines share similar properties to those created by Stereolithography. DLP machines can achieve a high level of detail and surface finish, with a typical minimum layer thickness of 0.05mm on the z-axis and 0.035mm on the x- and y-axes. However, photopolymer parts are not stable and will deteriorate over time, and as such, they are commonly used for form/fit prototypes, casting patterns for jewellery, electronic components and dental molds (Additively.com, 2015). The improved speed of DLP over STL processes make this technology suitable for industries that require rapid part production. For this reason, DLP is an attractive option for the design industry and small design studios for the production of visual prototypes (Gibson et al., 2010).

Integration

VERY LOW | LOW | MODERATE | HIGH | VERY HIGH

Two candidate cotton-derived materials are identified for use with stereolithography systems: cotton-derived photopolymer, and nanocellulose reinforced photopolymer. The feasibility of formulating these materials for use with DLP is comparable to that discussed in relation to the Stereolithography process.

3.6.3 Continuous Liquid Interface Production

Continuous liquid interface production (CLIP) (Figure 17) is an emerging 3D printing technology that provides substantial benefits over other printing technologies in terms of speed and resolution.

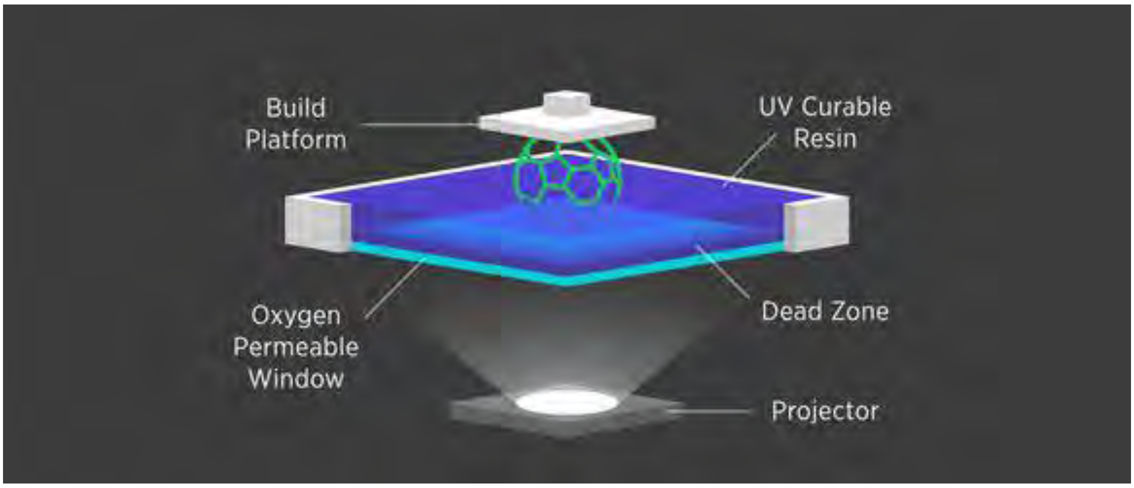


FIGURE 17. CONTINUOUS LIQUID INTERFACE PRODUCTION (CARBON3D.COM, 2015)

CLIP works in a similar way to DLP in that parts are created bottom-up, from photopolymer material that is exposed to UV radiation. However, where other methods create parts stepwise, layer-by-layer, CLIP is able to create parts continuously. This is achieved by "projecting a continuous sequence of UV images (generated by a digital light-processing imaging unit) through an oxygen-permeable, UV transparent window (Teflon AF-2400) below a liquid resin bath" (Tumbleston et al., 2015, p.1349). The ability to build layers continuously, without the need for a recoating mechanism and stepped process is enabled by the creation of an oxygen-containing 'dead-zone' - a thin uncured liquid layer between the UV transparent window and the cured part surface. "The deadzone created above the window maintains a liquid interface below the advancing part. Above the deadzone, the curing part is continuously drawn out of the resin bath, thereby creating suction forces that constantly renew reactive liquid resin. This non-stop process is fundamentally different from traditional bottom-up stereolithography printers, where UV exposure, resin renewal and part movement must be conducted in separate and discrete steps" (Tumbleston et al., 2015, p.1349). This continuous production enables parts with extremely fine resolutions below 100 microns, at between 25-100 times faster than other 3D printing methods. The speed of CLIP is only limited to the rate at which resin can cure and by the viscosity of the resin (Tumbleston et al., 2015).

Maturity

Carbon3D (cabon3d.com) patented CLIP in 2014. As of yet, CLIP systems are not available to the public and there has been no details on pricing. The technology has been limited to a few early access users, including Ford Motor Company and special effects company Legacy Effects. Carbon3D has received significant funding for the development of CLIP technology. This includes a combined $51 million from Sequoia Capital, Silver Lake and Autodesk. Adding to this, Google Ventures has invested a further $100 million.

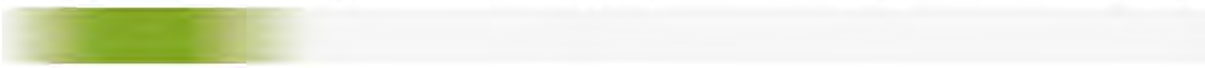
Application

The widespread applicability of CLIP processes is difficult to judge, as machines are not commercially available. Reports suggest that continuous printing is only effective for parts with thin walls. The developers or Gizmo 3D (gizmo3dprinters.com.au) describe that thin walled parts allow for the resin to quickly flow over the walls to allow for a continuous process. In contrast very thick walls or large flat surfaces do not allow resin to flow quickly enough to coat the surface and allow for continuous printing. It is possible that the suction forces created by CLIP printing will allow effective continuous printing of thick walled and solid objects, however, this cannot be determined until the technology is more widely available. If the capabilities described of CLIP are accurate, this will give it a distinct advantage in many industries. The continuous process utilised by CLIP means that the layer thickness can be reduced without altering print speed, ultimately allowing for smooth 3D objects with no model slicing artifacts (Tumbleston et al., 2015). This capability is highly desirable in many industries that rely on 3D printing for form/fit prototypes with excellent surface finish and detail.

Another uncertainty of CLIP is the material capabilities of finished parts. Carbon 3D (carbon3d.com) claim that CLIP printing is compatible with the entire polymer family including elastomers, which provide elasticity, strength and durability. However, the process utilises photopolymer materials, which are not stable over time and are limited in their use in long-term mechanical applications. It is likely that the material capabilities of parts made using CLIP will share the same limitations as stereolithography and digital light processing parts.

INTEGRATION

VERY LOW | LOW | MODERATE | HIGH | VERY HIGH



Two candidate cotton-derived materials are identified for use with CLIP systems: cotton-derived photopolymer, and nanocellulose reinforced photopolymer. The feasibility of formulating these materials for use with CLIP is comparable to that discussed in relation to the stereolithography and digital light processing processes. Considerations unique to the CLIP process include ensuring that the photopolymer material retains the appropriate viscosity to facilitate continuous liquid interface.

3.7 POWDER BED FUSION AND BINDING

Powder bed systems create 3D objects through selectively bonding successive layers of powdered material together. A roller spreads powdered material across a build volume to create the layers of the object. A print head then traces the contours of the object on the layer and either binds the material together using a liquid adhesive, or fuses the material together using thermal energy. The method utilised to bind the material is the main difference between the varying powder bed technologies. Subsequently, the binding method has a significant impact on the materials used.

3.7.1 Binder Jetting

Other names: Inkjet Powder Printing; 3DP.

The binder jetting (BJ) process builds 3D objects by selectively binding successive layers of a powdered material together with an adhesive (Figure 18). A thin layer of powdered material is first spread across the build platform by a levelling roller. An ink-jet style print head selectively applies an adhesive to the layer of powder to bind the material together. Subsequently, the build platform lowers and the levelling roller deposits another thin layer of powder on top of the previous layer. The print head then deposits the binding agent to the new layer. This process is repeated for each successive layer until the part is complete. Powder not exposed to the binding agent acts as the support structure for the part. This means that no additional supports are required for the part and powder not exposed to adhesive can be reused (Bogue, 2013; Warnier et al., 2014). Objects produced from the binder jetting process are required to be cured in a kiln then coated with additional adhesive in order to produce a robust object (Bogue, 2013).

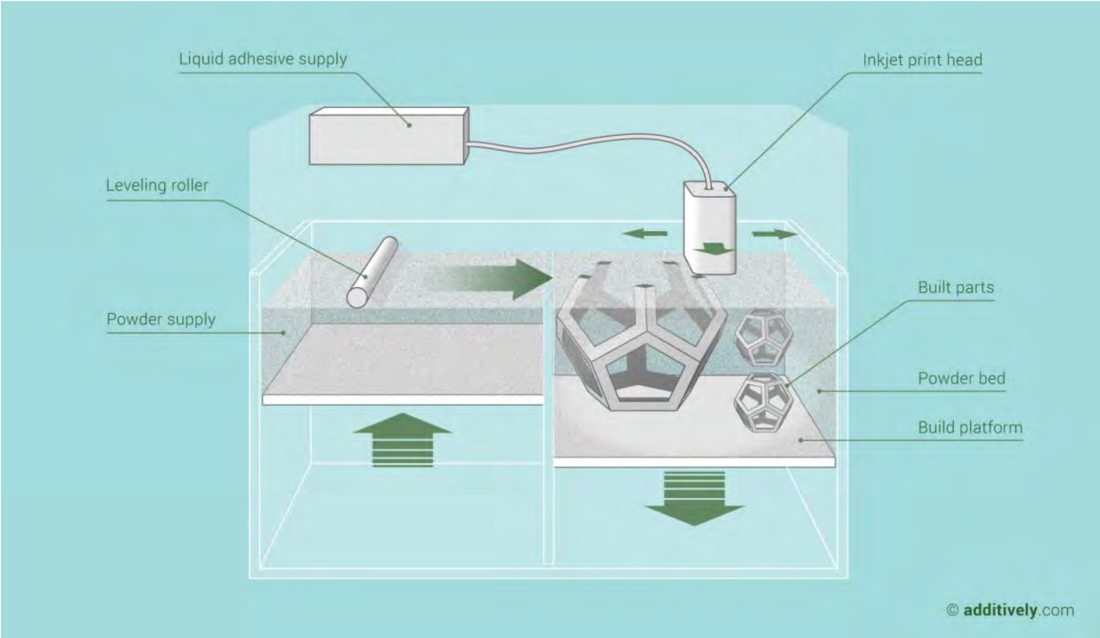


FIGURE 18. BINDER JETTING (ADDITIVELY.COM, 2015)

Maturity

INNOVATION | INTRODUCTION | GROWTH | MATURITY | DECLINE

MIT developed binder jetting technology in 1993 and licensed it to ExOne and ZCorp, which was later acquired by 3D systems. Gypsum based systems from Zcorp range in price from $13,000 - $100,000, however they have been superseded by superior technologies (e.g., multi jet fusion) and offer little benefit over other AM technologies. The technology has been rejuvenated by modern systems from Voxeljet and ExOne, which are compatible with a variety of materials (sand, metals, ceramics), have large build volumes and are valuable for creating metal cast parts (Gibson et al., 2010; Wohlers Associates, Inc, 2015a). These systems can be expensive, ranging from $100,000 to $2,300,000.

Application

LIMITED | EMERGING | SPECIALISED | EXPANDING | WIDESPREAD

Binder jetting processes typically use a gypsum based composite powder, however, other powdered materials such as metals, sand and plastics are also used. Regardless of the type of material, parts have limited mechanical properties owing to the use of adhesive. An advantage of the binder jetting processes is that some machines are able to print parts in full colour. Multi-colour printing works in the same way as inkjet printers; multiple print heads with a different coloured adhesives are used to generate full colour printed objects (Warnier et al., 2014).

The most promising applications for parts made from binder jetting result from the variety of compatible materials and the specific properties that they provide. Sand can be used to quickly create sand cast molds in which molten metal is poured in to create a metal part (Bogue, 2013). Parts created from ceramic, composite, metal (aluminium, silver, stainless steel) and plastic (ABS, PA, PC, Photopolymer, PMMA) materials can be post-processed in order to create more durable objects. Parts are fired in a kiln to ‘burn out’ the binding agent and sinter the part to form a solid part (Warnier et al., 2014).

Integration

Binder jetting requires a powdered material suitable for use with a binding agent. As no heat, or complex material changes are required in the process, there is a very high feasibility of formulating a suitable cotton-derived feedstock to be used with this process. Three candidate cotton-derived feedstocks are identified for use with the binder jetting process: cotton-derived bioplastic powder, nanocellulose powder and cotton-derived binding agent. Each of these materials are known; both bioplastics and adhesives have been formulated from cottonseed (Cotton Australia, n.d.) and cotton-derived nanocellulose exists in varying forms and is widely discussed in research literature (Moon et al., 2011). The main consideration for a cotton-derived material is tailoring the material to be compatible with binder jetting technology, and weighing up the benefits that a cotton-derived material provides over existing materials. A potential advantage that the candidate materials do present is the opportunity to produce entirely biodegradable parts with limited development of materials required.

3.7.2 Multi Jet Fusion

Multi jet fusion (MJF) (Figure 19) is a recent technology developed and patented by Hewlett-Packard. This technology uses layers of powdered thermoplastic material deposited on a print bed to create 3D objects. Thermal inkjet arrays scan the layers of powdered material and print fusing and detailing agents onto the thermoplastic powder. An energy source is then used to fuse the areas of material where the agents were deposited. Successive layers are built using this process until the entire part is complete (Wohlers, 2015).

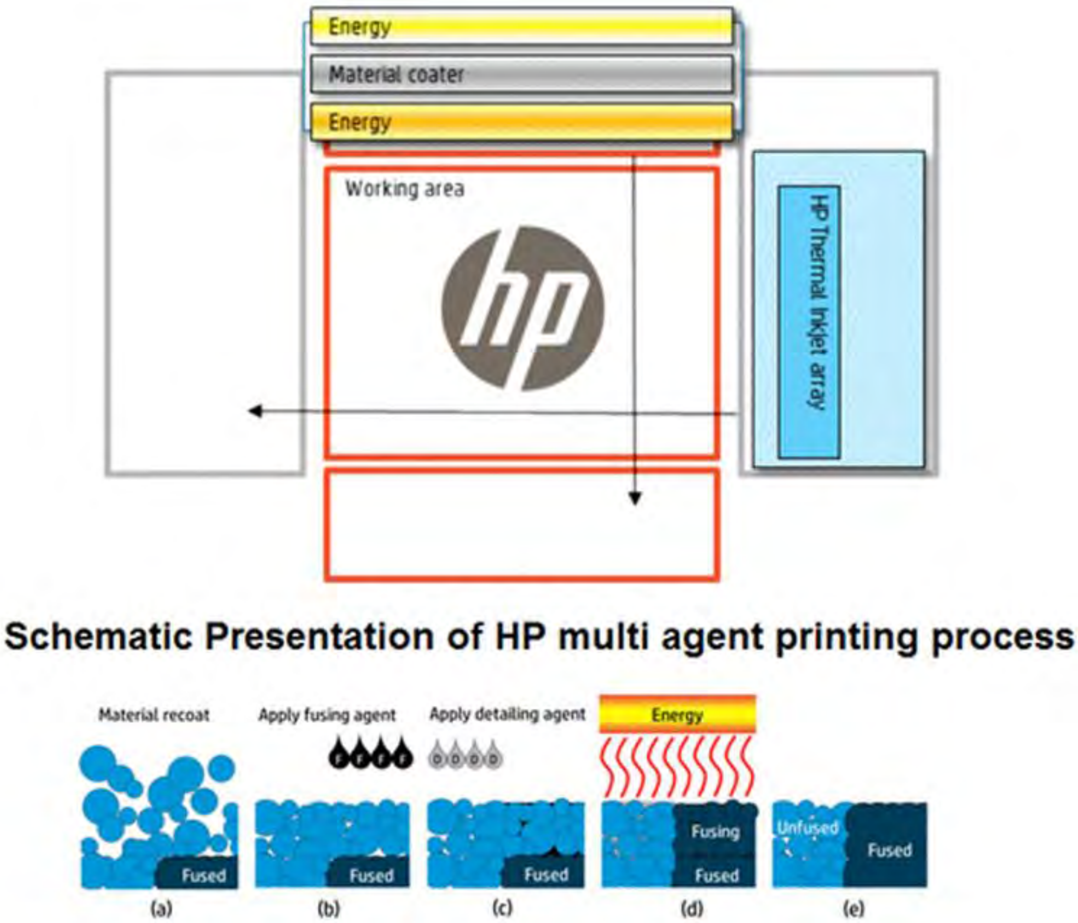


FIGURE 19. MULTI JET FUSION TECHNOLOGY (HP.COM, 2015)

Maturity

INNOVATION | INTRODUCTION | GROWTH | MATURITY | DECLINE

Hewlett-Packard developed and patented Multi Jet Fusion technology in 2014. At present, MJF is not available commercially and thus only provisional details are known about the technology. For this reason, MJF remains at a stage of innovation. However, it is considered to be a technology with immense potential and could be poised to change the additive manufacturing market if consumables and MJF printers are priced competitively (Wohlers Associates, Inc, 2015c).

Application

LIMITED | EMERGING | SPECIALISED | EXPANDING | WIDESPREAD

It is difficult to ascertain application potential of MJF, as the capabilities of the machines have not been tested in commercial applications. Initial impressions are very positive, however, with the machines promising fast production of detailed and strong parts. According to Hewlett-Packard (2016), 30 million droplets can be deposited per second across a 25mm area. A part that takes 38 hours using selective laser sintering and 83 hours using fused deposition modelling has been shown to take only 3 hours using MJF. Adding to the benefit of speed, MJF is able to print multi-colour parts - an ability that cannot be claimed for all 3D printers. At present, MJF is limited to nylon feedstock, however, this has been shown to result in parts with excellent strength. With good strength properties and part detail, MJF parts have the potential to be used in a wide range of applications. Successful implementation of MJF could create competition with existing plastic processing techniques such as injection moulding. This may disrupt the plastics and potentially the 3D printing market (Wohlers Associates, Inc, 2015c).

Integration

Evaluating the feasibility of using a cotton-derived feedstock for Multi Jet Fusion technology is problematic due to the limited information about MJF materials. One candidate cotton-derived feedstock is identified for use with Multi Jet Fusion: cotton-derived bioplastic powder. This material choice is indicative of MJFs compatibility with nylon thermoplastic powder. However, the compatibility of such a material depends on the ability to formulate a fine cotton-derived bioplastic powder that is compatible with the fusing agents used for MJF. Due to this inherent uncertainty, the feasibility of a cotton-derived feedstock for MJF is determined to be low.

3.7.3 Selective Laser Sintering

Selective laser sintering (SLS) creates 3D parts by building up and selectively sintering successive layers of powdered material (Figure 20). A levelling roller deposits a fine layer of powdered material (e.g., thermoplastic, sand, composite) onto the build platform. A focused CO_2 laser scans the layer of powder and selectively sinters material within the contours of the object. This process causes the material to fuse together and form a layer of solid material. After tracing an entire layer, the build platform lowers and another layer of powder is deposited. The laser then scans this new layer, sintering the material and causing it to bond to the previous layer of material. This process repeats for each successive layer until the part is complete (Gibson et al., 2010; Warnier et al., 2014; Wohlers Associates, Inc, 2015a).

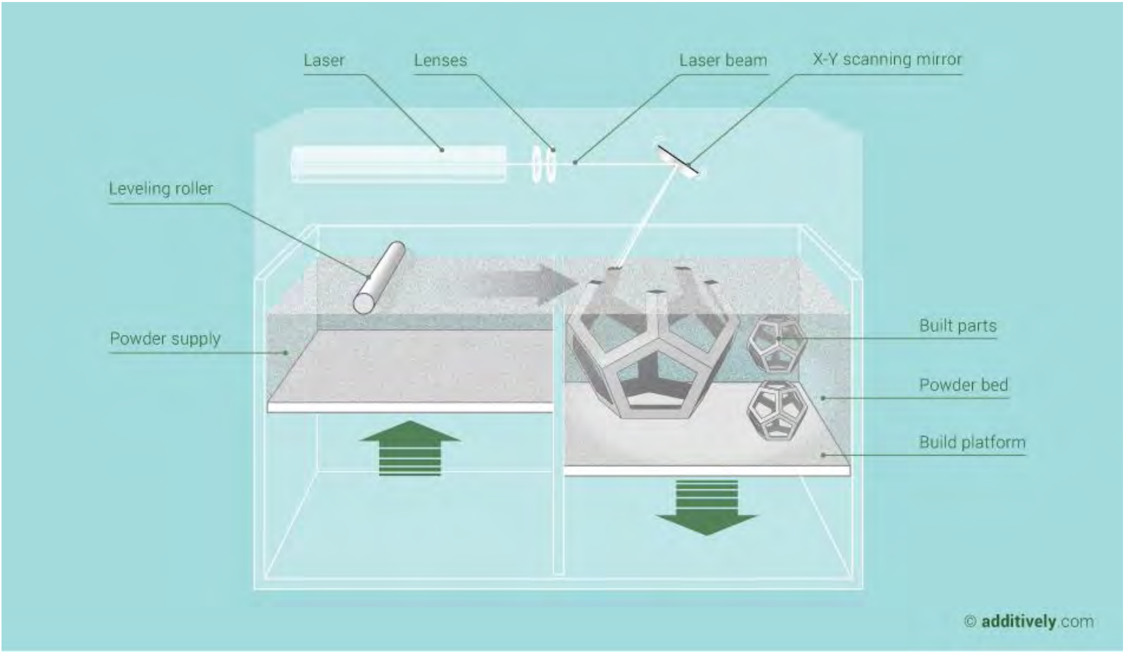


FIGURE 20. SELECTIVE LASER SINTERING (ADDITIVELY.COM, 2015)

SLS requires a certain level of environment control to ensure effective fusion of material. The powder bed is heated to just below its melting point to reduce the amount of thermal distortion required to sinter the material and fuse the layers. This heating process helps reduce part distortion, however this comes at the expense of long heating up and cooling down periods either side of printing (Baumers, Tuck, & Hague, 2015). Unlike other methods (e.g., FDM, SLA) which require the addition of support structures, SLS uses the un-sintered powder to support the part. Once the part is complete, the remaining powder can be re-used for future prints (Gibson et al., 2010).

Maturity

INNOVATION INTRODUCTION GROWTH MATURITY DECLINE

SLS was developed in the 1980s by DTM, which was acquired in 2001 by 3D systems. The patent (US 5597589) "Apparatus for producing parts by selective sintering" was filed in 1994 and was the most recent patent protecting SLS technology. With the recent expiration (January 28, 2014) of this patent, it was expected that selective laser sintering machines would become more affordable and widely available (Biggs, 2014). This projection has so far proved to be correct with several low-cost SLS printers entering the market. Norge (norgesystems.com) made the Ice1 and Ice9 SLS printers available on Kickstarter starting, at $13,000. Shortly after this, Sintratec (sintratec.com) released an SLS 3D printer kit within the $5000 range. A third company, ShareBot (sharebot.it) has also released an SLS printer for less than $20,000. Since these initial developments, other companies have also entered this space. Sinterit (sinterit.com) is releasing a SLS 3D printer for $8000, with units shipping at the start of 2016. The development and availability of such systems is significant as the cost of professional SLS printers from 3D Systems, EOS and others, range from $100,000 to $500,000.

Application

LIMITED EMERGING SPECIALISED EXPANDING WIDESPREAD

The SLS process is compatible with a range of powdered materials, however, is typically used with thermoplastics. Most thermoplastics that can be processed into a fine powder are suitable, including a variety of composite materials that contain, glass fibre, aluminium, mineral fibre or carbon fibre (Gibson et al., 2010). Thermoplastic parts created using SLS have good mechanical properties, although they do not achieve the same mechanical properties as injection molded parts. Parts have good surface finish and detail (0.1mm minimum layer thickness, +/-0.25mm typical tolerance, 0.15mm minimum feature size) and can be improved with CNC machining (Additively.com, 2016d). Because of the range of compatible thermoplastics and good mechanical properties, SLS parts have a range of applications. These include functional components, automotive parts, aerospace parts, research equipment (Daniel Eyers & Krassimir Dotchev, 2010), support parts (jigs, fixtures), small run parts and form/fit testing (Additively.com, 2016d).

Beyond thermoplastics, other compatible materials include sand, ceramics, wax and some metals. SLS technology is compatible with materials like sand and wax (e.g. SandMade LS ONE) and can be used to create metal parts through foundry and lost-wax casting techniques. Yttria-zirconia powders have been used to create ceramic parts on some SLS machines (e.g. Phenix Systems PM100). One of the primary difficulties of creating ceramic parts is that they require high melting temperatures which results in increased thermal stresses and lengthy cool-down periods. Very high powder bed particle density is required to avoid low density parts susceptible to cracking (Bertrand, Bayle, Combe, Goeuriot, & Smurov, 2007). Ceramic parts have the potential for use as bone tissue engineering scaffolds (Gibson et al., 2010).

Integration

VERY LOW LOW MODERATE HIGH VERY HIGH

SLS requires a powdered material that fuses together upon exposure to an energy source. One candidate cotton-derived feedstock is identified for this process: cotton-derived bioplastic powder. Cotton-derived bioplastic is a known material, however, the feasibility of processing this material into a powder suitable for SLS is unknown. The candidate material must be able to achieve a high particle density, and be tolerant to high temperatures produced by the heat source. The subsequent reaction to this heat source must produce the requisite bond between material layers. Due to this inherent uncertainty, the feasibility of a cotton-derived feedstock for SLS is determined to be very low.

3.7.4 Selective Laser Melting

Direct Metal Laser Sintering; Laser Melting; Selective Laser Powder Remelting; Laser Cusing.

Selective laser melting (SLM) uses a laser to melt successive layers of powdered metallic material to create metal parts (Figure 21). A recoating mechanism distributes a thin layer of fine grain (grain fraction 10-45um) metal powder onto the build platform. A laser beam scans the layer of powdered material and selectively melts the material together. Once a layer is scanned and melted, the build platform lowers by the thickness of one layer, and the recoating mechanism deposits the next layer of powder. The laser scans each successive layer, and the material fuses to the previous layer. This process repeats until the entire part is complete (Bogue, 2013; Gibson et al., 2010).

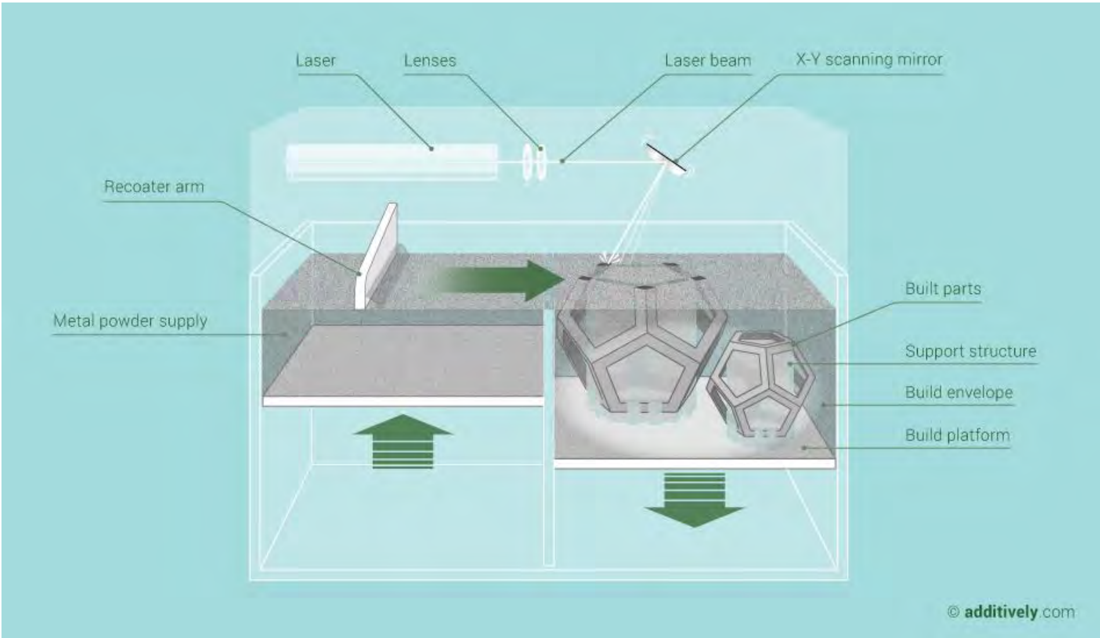


FIGURE 21. SELECTIVE LASER MELTING (ADDITIVELY, 2015)

To process metal powders, SLM requires a more powerful laser than other PBF methods. A ytterbium fibre (Yb-Fibre) laser is used, which requires a low oxygen, inert atmosphere. Parts made using Selective Laser Melting require support structures for overhangs. These supports also serve to anchor the parts to the build platform and facilitate heat transfer away from the area of the part. This is critical to reduce thermal stresses and prevent warping. Support structures are machined off during post-processing in order to produce a finished part (Bremen, Meiners, & Diatlov, 2012).

Maturity

Attempts at SLM technology in the 1980s and 1990s were largely unsuccessful due to the difficulty of processing metal powders. Although SLM technology was patented in 1995, it wasn't until 2002 that the Fraunhofer institute commercialised the technology and subsequently sold it to MTT technologies (now called SLM solutions). SLM machines are typically used with metallic and occasionally ceramic materials, however, it is possible to experiment with other materials. For instance, MTT machines provide substantial control over process parameters and include various safety features to minimise the risk associated with experimenting with new materials. SLM machines are sold by EOS GmbH, SLM Solutions, Concept Laser GmbH and Phenix Systems (Gibson et al., 2010). Prices vary substantially based on machine size and capability. Smaller systems can be prices around $225,000 with larger systems priced at >$1,000,000.

Application

Material compatibility depends on the features of the technology. Most SLM systems use standard metallic powders (stainless, aluminium alloys, titanium and nickel-based alloys). Machines with heated build volumes are capable of processing metals with higher melting points, and ceramic materials. Affordances have also been made which allow for custom materials to be experimented with (Bremen et al., 2012). Metallic parts can achieve a material density of up to 99.9%, resulting in high durability of parts. This is coupled with the production of parts with excellent detail and surface finish: 0.04-0.2 mm-minimum feature size; +/-0.1-0.2% accuracy; 0.02-0.06mm-minimum layer thickness; typical tolerance +/-0.1mm (Additively.com, 2016c). A limitation of SLM is that parts must be attached to the build platform and that any overhangs or complex geometries require support structures. This means that SLM parts do not share the same design flexibility as processes that sinter polymers, due to the need to remove supports by machining or cutting (Bremen et al., 2012).

Final parts created by SLM are comparable to cast or machined metal components and are used as functional parts. A common application of SLM parts is in the dental industry, where there is a requirement for small and intricate custom parts. Parts are used for creating tooling for injection molding and die casting, although for high quality surface finishes, molds must be machined and polished during post-processing. SLM parts are often used in medical domains with applications including titanium hip implants and surgical instruments, cobalt chromium dental restorations and special function implants with hollow structure, graded porosity, adapted rigidity or surface structure (Bremen et al., 2012). Other general uses include form/fit testing, tooling and molds, medical technology (implants), functional prototypes, support parts and small run/one off parts (Additively.com, 2016c).

INTEGRATION

VERY LOW | LOW | MODERATE | HIGH | VERY HIGH

Although SLM typically uses metallic powder material, this process is compatible with other powdered material. For use with thermoplastic material, SLM shares similar material requirements to SLS. Subsequently, one candidate cotton-derived feedstock is identified for this process: cotton-derived bioplastic powder. As discussed in relation to SLS, the feasibility of formulating a compatible cotton-derived bioplastic for SLM is determined to be very low due to the uncertainty associated with this material.

3.7.5 Electron Beam Melting

Electron beam melting (EBM) produces 3D metal parts through the fusion of layered metal powder using a high-energy electron beam (Figure 22).

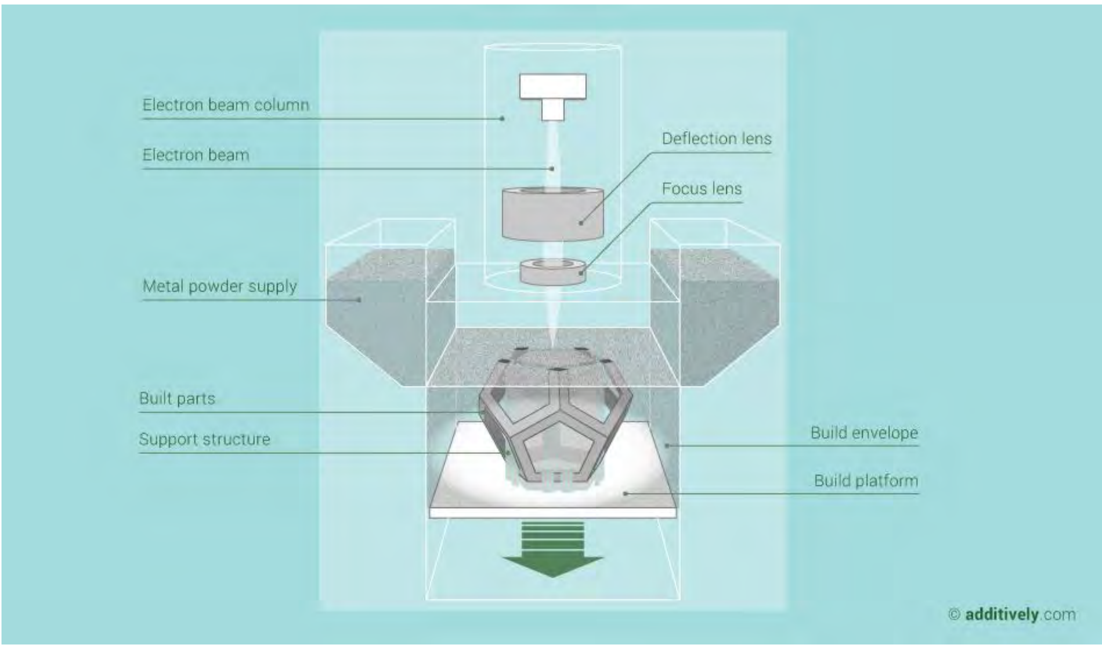


FIGURE 22. ELECTRON BEAM MELTING (ADDITIVELY, 2015)

A thin layer of metal powder is distributed onto the build platform. A focused electron beam then scans across the layer of powder, causing selective melting because of the transfer of kinetic energy from the electron beam to the powder material. In order to achieve this transfer, the material must be conductive, and as a result, the materials used in the EBM process are limited to metals. Following melting, the area resolidifies and bonds to the material on the previous layer. The build platform lowers and the next layer of metal powder is distributed and fused. The process is repeated until the part is complete. Although parts are created amongst powder, supports are required to anchor parts to the build platform, support overhangs and transfer heat away from the area of the part being melted. Heat transfer is required to reduce thermal stresses and prevent warping (Gibson et al., 2010).

The use of an electron beam differentiates EBM from the other powder bed fusion processes and places specific requirements on the system. First, EBM is performed in a low-partial-pressure vacuum environment to ensure that gasses at atmospheric pressure do not deflect the electrons. To maintain this required environment, an inert gas is swept through the chamber to remove gaseous by-products and oxygen (Gibson et al., 2010). Material fusion is performed at temperatures of 700 to 1000 degrees celsius (Bogue, 2013). Second, the properties of the electrons used in the process allow for faster scanning of powdered material in contrast to other powder bed fusion methods. Electrons have a magnetic charge and can be deflected and focused magnetically, rather than with mirrors. The magnetic coils used to focus the electron beam have an instantaneous response, which allows the beam to move very slowly, or very rapidly. In practice, this enables the electron beam to move instantaneously from one point to another without needing to traverse the area in between (Gibson et al., 2010).

Maturity

Chalmers University of Technology developed EBM and Arcam patented and commercialised the technology in 2001. Acram (arcam.com) holds 30 related patents for the technology. EBM has become a successful approach to powder bed fusion and further developments of material scanning strategies presents the greatest opportunity for the technology to improve (Gibson et al., 2010). At present, EBM machines are commercially available from Acram for between $640,000 to >$1,000,000.

Application

EBM requires reactive material in order to facilitate energy transfer and melting. As a result, compatible materials are limited to metals (e.g., cobalt-chromium alloys, nickel-based alloys, titanium) (Additively.com, 2016a; Gibson et al., 2010). EBM parts have poor surface finish and detail: 0.1mm minimum feature size, +/- 0.2mm typical tolerance, and 0.05mm minimum layer thickness. This is typically inferior to comparable methods such as selective laser melting. However, post-processing can improve surface finish and tolerances. Finished parts obtain a high material density (above 99%) and provide good mechanical properties. For this reason, they are used for functional testing, support parts (jigs and fixtures), small series and one off working parts. Titanium parts provide some specialised uses for the process, such as medical implants (Additively.com, 2016a).

INTEGRATION

VERY LOW LOW MODERATE HIGH VERY HIGH

The EBM process is compatible with conductive materials only. For this reason, this process is not suited to a cotton-derived feedstock.

3.7.6 Selective Heat Sintering

Selective Heat Sintering (SHS) (Figure 23) is comparable in many respects to the other powder bed fusion methods. The distinguishing feature of SHS is the use of a thermal print head to sinter layers of powdered material. This print head produces less thermal energy (115C) than the lasers (<175C) used in other processes, and as a result, SHS is restricted to thermoplastic powder material for part creation (Baumers et al., 2015). Consistent with other PBF methods, a recoating mechanism arm is used to deposit a fine layer of powdered thermoplastic material onto the print platform. The thermal print head concentrates a heat source and selectively melts the powdered material. Once an entire layer is traced out with the print head, the build platform lowers and the next layer of powder is deposited. The melting of successive layers causes each layer to bond to the previous layer and build up the complete object (Bogue, 2013). Unlike EBM and SLM solidified material support structures are not required for the part. Instead, the unmelted powder provides support for the 3D object (Blueprinter, 2016).

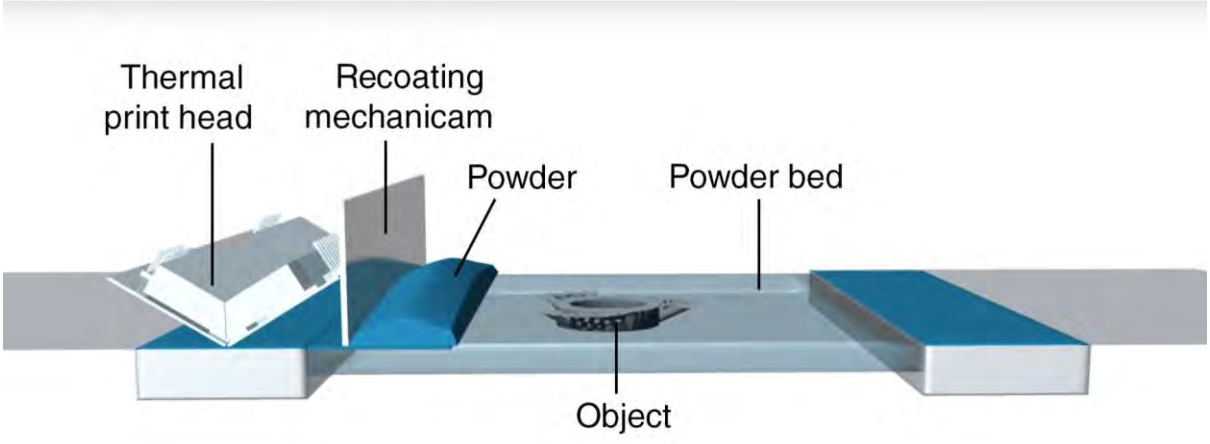


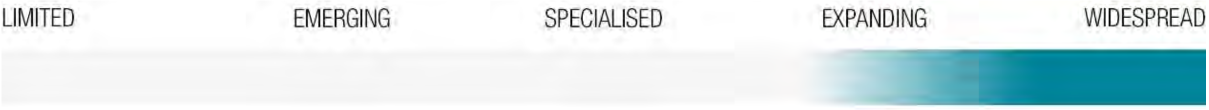
FIGURE 23. BLUEPRINTER SELECTIVE HEAT SINTERING (ADAPTED FROM BLUEPRINTER-POWDER-3DPRINTER.CO.UK, 2015)

MATURITY

INNOVATION INTRODUCTION GROWTH MATURITY DECLINE

Blueprinter (blueprinter-powder-3dprinter.co.uk) developed and patented SHS in 2008. The first-generation SHS machines became available in 2014. Blueprinter launched the second-generation Blueprinter M3 machine in 2015 at a price of $28,500. The thermal print head used in the SHS process is less expensive than the laser used in other powder bed fusion processes which provides it with good adoption potential and provides access at a consumer level.

Application



SHS is only compatible with thermoplastic materials, as the thermal print head does not produce the required energy to melt metallic materials. This lower energy source of SHS provides some advantages over other powder bed fusion technologies. For instance, SHS requires only short warm up times (~15 minutes) and no cool-down time at all. In contrast, warm-up and cool-down periods can be extensive for other powder bed fusion processes. For example, the EOSINT P100 SLS machine has been shown to require warm up times exceeding two hours and operator specified cool-down periods exceeding four hours (Baumers et al., 2015).

SHS is capable of producing parts with good detail and surface finish (0.1mm layer thickness; 1mm minimum wall thickness). This places it on par with other thermoplastic PBF technologies such as SLS. However, the Blueprinter M3 only has a build volume of 200x157x150mm, which is smaller than many of the available PBF technologies (Blueprinter, 2016).

Integration

SHS shares similar material requirements to selective laser sintering (SLS). Subsequently, one candidate cotton-derived feedstock is identified for the SHS process: cotton-derived bioplastic powder. The feasibility of formulating a cotton-derived bioplastic powder for SHS is comparable to that discussed in relation to SLS. Although SHS uses a much lower temperature than SLS, the uncertainty associated with material formulation results in a very low feasibility of producing an appropriate cotton-derived feedstock.

3.8 Electrospinning

Electrospinning is not considered a form of additive manufacturing, but rather is a fibre-production method that uses polymer solutions or melts. There are two categories of electrospinning: solution electrospinning and melt electrospinning. For both processes, an electric force is used to draw out polymer nanofibres to create meshes and shapes. The main difference between the two processes is the type of material used and the control of fibre deposition. Although not considered a form of additive manufacture, electrospinning presents a compelling opportunity for the manufacture of purpose built functional nonwoven textiles (Hochleitner et al., 2015; Stranger, Tucker, & Staiger, 2009).

3.8.1 Solution Electrospinning

Solution electrospinning (Figure 24) uses dissolved polymer solution to construct nanofiber meshes. The polymer solution is drawn out of a spinneret as threads using electric force. Drawn out threads undergo a period of evaporation and solidification before being deposited on a collector plate. A fibrous structure forms as the threads build up on the collector plate. The deposition of thread from this process is uncontrolled due to electrical instabilities.

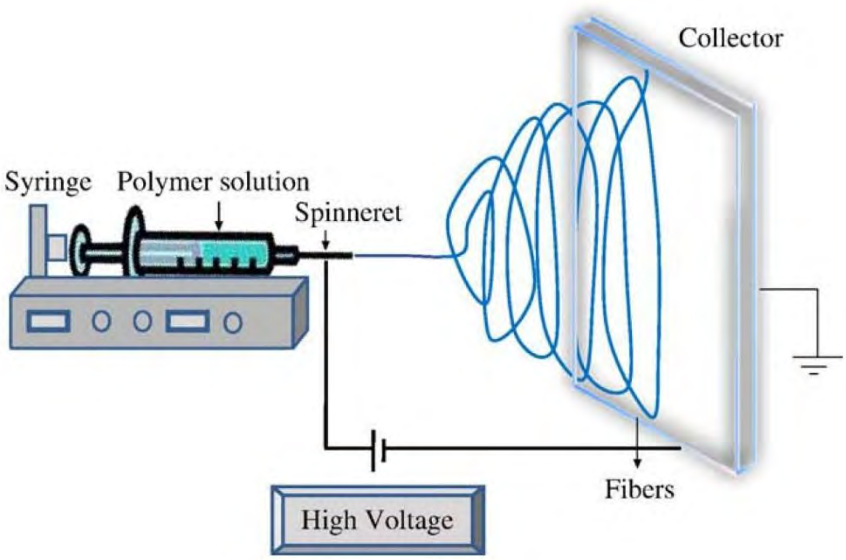


FIGURE 24. SOLUTION ELECTROSPINNING (ZHU & CHE, 2013)

MATURITY

INNOVATION | INTRODUCTION | GROWTH | MATURITY | DECLINE

A patent for electrospinning was first filed over a century ago in 1900. However, widespread interest in the technology did not occur until the early 1990s. Since then, electrospinning has seen broader use in development of nanofibre materials for a variety of industry applications (Reneker & Yarin, 2008). Electrospinning apparatuses can vary in complexity and cost, ranging from basic laboratory setups to larger scale industry equipment. In 2015, the process of electrospinning broke into the consumer market with the Electroloom – an electrospinning machine designed to make poly-cotton blend garments (White, Foley, & Rowley, 2015).

APPLICATION

LIMITED | EMERGING | SPECIALISED | EXPANDING | WIDESPREAD

Electrospinning has played a strong role in the development of nanomaterial membranes for a variety of applications. The ability to manipulate nanofibres with large, porous surface areas has resulted in the creation of high quality filtration materials, absorptive materials in clothing, drug delivery systems and biocompatible tissue scaffolding (Subbiah, Bhat, Tock, Parameswaran, & Ramkumar, 2005). Potential nanoparticle treatments added to polymer solutions may also enable the production of textile products that come pre-treated with unique properties, such as antibacterial, ultrahydrophobicity and antiviral properties (Mao & Russell, 2015).

Electrospinning has also emerged as a consumer technology with the success of the Kickstarter-funded Electroloom. The Electroloom uses clothing templates to catch electrospun cotton/polyester nanofibres. Continuous build-up of fibres on the template creates a seamless wearable piece of clothing (White et al., 2015). With ongoing research and development into composite polymers and electrospinning technology, electrospinning has the potential to be applied in many domains that make use of nanotechnology and nanofibre manipulation.

INTEGRATION

VERY LOW | LOW | MODERATE | HIGH | VERY HIGH

One candidate cotton-derived feedstock has been identified for use with solution electrospinning: cellulose polymer solution. The feasibility of formulating this material for use with solution electrospinning is determined to be high. This is based on Electroloom technology (White et al., 2015), which has demonstrated the successful use of electrospinning cotton-based polymer solution, though it should be noted that the durability of the garments produced with this device are yet to be proven.

3.8.2 Melt Electrospinning

Melt electrospinning (Figure 25) uses a viscous polymer melt in order to fabricate controlled nanofiber meshes. Polymer materials are heated electrically via the polymer deposition barrel, heated fluid circulation, or laser at the tip of the electrospinning jet. This heating process results in polymer fibre, which cools and solidifies on contact with the material collector. The deposition of this polymer fibre is controlled which allows for the production of defined structural meshes (Stranger et al., 2009).

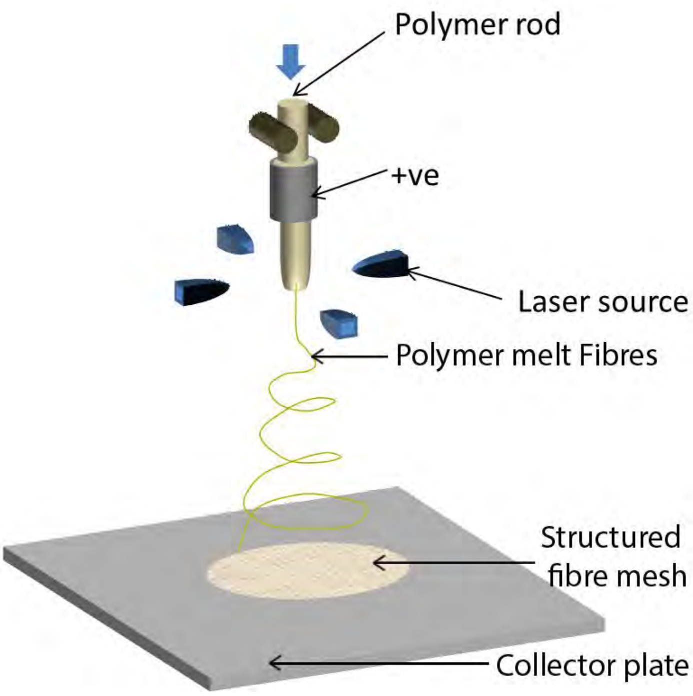


FIGURE 25. MELT ELECTROSPINNING, WITH LASER SOURCE FOR HEAT (ELECTROSPINTECH.COM 2013)

MATURITY

INNOVATION | INTRODUCTION | GROWTH | MATURITY | DECLINE

Melt electrospinning is still in its infancy when compared to solution electrospinning. Lesser development of melt electrospinning technology is partially attributed to the difficult nature of setting up melt electrospinning apparatuses, the high viscosity of polymer melts, challenges in electrical discharge as well as the need for a heating mechanism for polymer feedstock. With little scientific publication since 2001, there are comparatively fewer pieces of work on polymers in melt electrospinning (Nayak, Kyratzis, Truong, Padhye, & Arnold, 2012). Nevertheless, since 2011, melt electrospinning has seen an increase in research and development with emphasis on industry applications and material experimentation.

APPLICATION

LIMITED | EMERGING | SPECIALISED | EXPANDING | WIDESPREAD

Melt electrospinning has similar potential applications as solution electrospinning. It has the added benefits of a wider range of compatible polymers, and the ability to control material deposition. Melt electrospinning is compatible with a range of thermoplastics, including polyethylene and polypropylene, neither of which are compatible with solution electrospinning. The use of polymer melts also eliminates the need for volatile solvents, which increases their applicability in biomedical applications, such as tissue engineering (Nayak et al., 2012).

Integration

The formulation of a cotton-derived feedstock for melt electrospinning is a more difficult task than that presented by solution electrospinning. One candidate cotton-derived feedstock identified for use with melt electrospinning is cotton-derived bioplastic. Cotton-derived bioplastic is a known material and has been discussed in relation to several other additive manufacturing technologies throughout this section. The compatibility between this material and the melt electrospinning process has not been reported. However, other bioplastics (PLA) have been successfully electrospun for the development of drug delivery scaffolds (Santos et al., 2013). A cotton-derived bioplastic must be achievable with an appropriate glass transition temperature and melt viscosity to be used with melt electrospinning. Subsequently, the feasibility of formulating a cotton-derived bioplastic for use in the melt electrospinning process is determined to be moderate.

3.9 Additive Manufacturing Future Trends

Additive manufacturing is a dynamic area of innovation. The quality and capabilities of additive manufacturing technology is rapidly improving. In many cases, the quality of parts produced from additive manufacturing processes are nearing a standard comparable to those produced using traditional manufacturing processes. Alongside this technological development, additive manufacturing promises to have a significant social, economic and environmental impact. Current trends point to a change in how we produce, distribute and consume goods. This is underlined by a projected shift in focus from centralised business practices, to a decentralised collaborative economy. In the following sections, these technological and social trends will be further discussed.

3.9.1 Technology Trends

Due to the diversity of the additive manufacturing industry, it is difficult to present the full picture of technological development. At a high level, however, the enormous potential promised by 3D printing has resulted in a highly competitive market place where the number of 3D printing devices available is steadily increasing from a growing list of manufacturers, while costs continue to decrease (Chavez, Molitch-Hou, Horne, Park, Sher, & Taylor, 2014; Brooks, Kinsley, & Owens, 2014). Small manufacturers are flooding the market place with low-cost, capable and easy to use 3D printers. Meanwhile, larger manufacturers are continually pushing the limits of their technology and developing new technology to gain a competitive edge. These overall trends of improved technology and reduced costs can be summarised into two areas of the additive manufacturing market:

development trends in the low-end of the market, and development trends in the high-end of the market (Campbell, Williams, Ivanova, & Garrett, 2011).

Low-end Development

The development of additive manufacture in the low-end of the additive manufacturing market is focused on simplifying and reducing the cost of 3D printing technology so that it is accessible to a wide consumer audience. Where 3D printing was once reserved for design and manufacturing industries, it is now driving an emerging market of personal manufacturing (Lipson & Kurman, 2013). This has been enabled by the proliferation of 3D printers available to purchase with prices from as little as $700-$1,400 – around 0.1-10% of the cost of professional 3D printers (Stucker, 2011, p. 13). With consumers having easy access to 3D printing technology, the low-end of the market is showing explosive growth. According to the Wohlers report (Wohlers Associates, Inc., 2011 in Stucker, 2011), 5,978 personal 3D printers, and 6,164 professional 3D printers were sold in 2010. This number represents significant growth when compared to sales in 2007, where only 66 personal 3D printers were sold, while 4,938 other 3D printers were sold. The uptake of 3D printing has bolstered expectations of a personal manufacturing revolution, where ordinary people are able to download and print useful products on-demand in their own home. While theoretically, 3D printers do allow this, personal 3D printers have predominantly been used to print small trinkets that have not had significant impact, nor met the expectations of the personal manufacturing revolution. Despite this, the rapid growth of additive manufacturing in the low-end of the market has resulted in substantial attention from investors and innovators (Stucker, 2011, p. 13).

The emergence of 3D printing in the-low end of the market can be attributed to several factors. At a very broad level, personal 3D printing is facilitated by a general improvement of the technology (Gasparin, Micheli, & Campana, 2015) and steadily declining prices over the last 30 years (Brooks, Kinsley, & Owens, 2014, p. 273-274). Enabling these broad level factors has been the expiry of several key patents, and subsequently, increased development competition in the commercial additive manufacturing market. With the expiration of key patents came the emergence of open source 3D printer designs such as the RepRap (replicating rapid prototype) and Fab@Home printers (Brooks et al., 2014). These open source projects effectively reconfigured the 3D printing marketplace and provided a wide audience access to 3D printing technology (Gasparin et al., 2015). The success of these open source projects lead to the commercialisation of fun and easy to use 3D printing in the form of the MakerBot, which was developed with the idea of creating a consumer friendly FDM printer that anyone could use, regardless of experience. Since MakerBot, the market for personal 3D printing widened significantly as consumers are attracted to the ‘fun’ and ‘entrepreneurialism’ aspects of the technology (Gasparin et al., 2015). There are currently hundreds of low-cost personal FDM 3D printers available, with many more being introduced every week.

The competition and diversification that occurred with FDM technology is being repeated with other 3D printing technologies. For instance, a number of inexpensive ($3,000-$5,000) stereolithography 3D printers are available from high-profile manufacturers such as Formlabs and Autodesk. These printers have proven to be successful in a market where customers demand greater quality than what can be achieved with FDM. After stereolithography, the next trend in personal 3D printing is widely believed to be the emergence of low-cost selective laser sintering technology. This is based on the recent (January 28, 2014) expiry of patent (US 5597589 A) "Apparatus for producing parts by selective sintering". With the expiration of this patent it is expected that selective laser sintering 3D printers will become more widely available and the price of such systems will decrease substantially (Biggs, 2014). This projection has so far proved to be correct with the commercialisation of several low-cost SLS printers. Shortly after the expiration of Patent US 5597589 A, Norge (norgesystems.com) made the Ice1 and Ice9 SLS printers available on Kickstarter starting at $13,000. Shortly after this, Sintratec (sintratec.com) released an SLS 3D printer kit within the $5000 range. A third company, ShareBot (sharebot.it) has also released a SLS printer below $20,000. The development and availability of such systems is significant as the cost of SLS printers were previously within the $200,000 dollar range (Hipolite, 2014). Since these initial developments, other companies have also entered this space. Sinterit (sinterit.com) is releasing a SLS 3D printer for $8000, with units shipping at the start of 2016.

The availability of low-cost stereolithography and selective laser sintering technology is a significant step forward in personal manufacturing as they offer much higher resolutions and part accuracies compared to FDM printers. In many ways, this can be seen as the first access to 'professional' 3D printing technology for personal use. It is believed that the price of this technology and future technologies will continue to decrease as the technology matures and competition continues to diversify. In the low end of the market – targeted at small businesses and individuals - this will enable an affordable entry point and expand the prevalence of this technology for small-scale and personal manufacturing (Marcoux & Bonin, 2012, p. 274).

High-end Development

Development of additive manufacturing in the high-end of the market is focused on technological improvements that will enable 3D printing technology to move away from a prototyping medium and toward high applicability, end-use parts. "In 2009, Wohlers reported that 16% of AM process use was for direct part production, 21% for functional models, and 23% for tooling and metal casting patterns" (Wohlers Associates, Inc., 2009 in Campbell et al., 2011). In its present state, additive manufacturing technologies do not yet possess the capabilities to disrupt mass manufacturing systems. However it has been successful in industries that require one off or limited run parts, parts for specialised applications and fast turnarounds between prototyping and manufacture. Notable industries with these requirements include automotive and motor sports, aviation and aerospace, and medical and dentistry.

A key driver for the additive manufacture of end-use parts has been the improvement of the materials that can be processed. Of particular impact in this respect is the improvement to

3D printers capable of producing metal parts. Key technologies providing this capability have been discussed previously in this report and predominantly belong to the powder bed fusion category (Section 3.7). These technologies are able to “fabricate fully-functional parts using a wide range of metal materials including titanium and various steel alloys that have material properties that are equivalent to their traditionally manufactured counterparts” (Campbell et al., 2011). While we have reached the point where complex end-use parts can be created, there are still some limitations in part quality, with parts requiring extensive post-processing in order to remove build supports and to improve part accuracy, tolerances and surface finish. To address this, some systems have begun to integrate additive manufacturing processes with subtractive manufacturing. As a result, treatments typically required during post-processing can be performed concurrently with additive manufacturing. For instance, this technique is employed by ultrasonic additive manufacturing (Section 3.5.3) and a similar technique is also employed by the LUMEX Avance-25 by Matsuura Machinery Corporation, which combines selective laser sintering and milling (McLeod, 2014). Another limiting factor of metal 3D printing is that the technologies also often cost in excess of $1,000,000 making them prohibitive for many manufacturers. However, as discussed in regard to the low-end of the market, prices will continue to decrease as development and competition evolve. Already there are press releases reporting the development of a metal 3D printer costing only 10% of current metal systems (Krassenstein, 2014).

Beyond metal 3D printing, the longer term future for 3D printing technologies promises significant developments in the area of multiple material printing (Lipson & Kurman, 2013). Multi-material printing is currently a feature of several photopolymer jetting technologies (e.g., Objet Connex series) and emerging technologies (e.g., multi jet fusion). These may provide greater flexibility and efficiency when selecting materials and the production of full colour and functional prototypes. What makes multi-material potentially revolutionary, however, is the ability to create entirely new and complex meta-materials through co-printing materials simultaneously and patterning them together (Lipson & Kurman, 2013). For example, if hard and soft materials were printed in a random pattern, the part could achieve a combination of materials properties without having perfectly aligned weak links.

Another promise of multi-material printing is the eventual development of technology capable of printing entirely functional electronic devices in a single process. For this aspiration to be realised, it will involve the design and fabrication of products that incorporate active materials. With current technology the majority of objects created using 3D printers are comprised of passive materials. These are materials that “respond to their environments in a predictable mechanical way”. Active materials on the other hand are materials that “act and react, sense compute and respond to their environments” (Lipson & Kurman, 2013, p. 271). As active materials are rarely useful by themselves, advancements in multi-material printing are required in order to arrange a variety of active materials in meaningful configurations (Lipson & Kurman, 2013). We are already beginning to see the integration of passive and active materials to create usable products printed and assembled entirely within a 3D printer. One example of this is the Voxel8 3D, an FDM printer that is able to print conductive inks within non-conductive materials to create fully working circuits that are embedded in 3D objects. Alongside a standard FDM print process, a secondary print nozzle is used to lay down a conductive ink to connect electrical components that are inserted by the user during the print process. The conductive ink integrates these placed components within the object. The end result is a fully functioning electrical object produced in a seamless process (Voxel8, 2015).

Although this example provides some compelling opportunities for design, it also presents a process that is very much mimicking the capabilities of current manufacturing and product assembly. The most exciting opportunities lay where we breakaway from our previously held limitations about design. A good example of this is the research conducted at the Soft Active Materials Laboratory at MIT. Wang, Gossweiler, Craig, & Zhao (2014) covalently coupled a stretchable elastomer with a material (spiropyran mechanophores) that changes colour when subject to mechanical stresses to create an electro-mechano-chemically responsive polymer that emits strong fluorescent signals when subject to an electric field. By applying different voltages to the material, various patterns, including lines, circles and letters can be induced on-demand. While such an application of active materials is very experimental in nature, it is expected that such combinations of materials will present novel sensing applications such as biomedical devices, dynamic camouflage coatings and wearable technology. Other interesting possibilities being explored by research include printing of complex technology such as batteries, motors and actuators, transistors, sensors (Lipson & Kurman, 2013, p. 272), and even complex self-evolving objects that can adapt and transform when exposed to different environmental stimuli (Crawford, 2014; Raviv et al., 2014).

3.9.2 Social and Economic Trends

Concurrent with continued technological innovation, 3D printing presents a new paradigm for design and manufacturing which will have profound economic, demographic, environmental and social implications (Campbell et al., 2011). Of particular importance, it is expected that additive manufacturing has the potential to democratise the creation and distribution of physical goods similar to the way that the internet democratised the distribution of information. Over the next several decades, traditional industrial and economic systems relying on centralised business operations will make way for distributed business practices driven by adaptable manufacturing, collaboration and a boutique technical and professional workforce (Rifkin, 2011; Warnier et al., 2014).

An important concept behind this disruption to traditional industrial and economic systems is distributed manufacture. Distributed manufacture refers to the idea of decentralised manufacturing, to the point where people could manufacture items in their own businesses and even in their own homes. This has the potential to shift the production of products away from major manufacturing centres and closer to the customer where products are consumed (Campbell et al., 2011). With useable digital design tools and additive manufacturing, product conceptualisation and production can be performed by individuals, communities and small enterprises in any geographical region (Gibson et al., 2010). Rather than shipping physical goods around the world, digital files can be shared with the manufacturing locations where products can be produced on-demand, without the need for standing inventory (Campbell et al., 2011). The manufacture of goods on-site, using highly efficient manufacturing processes, has the potential to dramatically decrease logistical costs, reduce or eliminate supply chains, material usage, embodied energy, eliminate transportation costs and facilitate decentralised energy sources (Rifkin, 2011).

Beyond disrupting traditional manufacturing and distribution, additive manufacture has the potential to empower consumers and offer unprecedented choice. Without the need for expensive and time consuming tooling, additive manufacturing is capable of producing product ranges which can be customised to individual consumers or use-cases at no additional cost (Campbell et al., 2011; Gibson et al., 2010). Larger companies with standardised manufacturing and massive workforces cannot be as agile (Rifkin, 2011). The development of inexpensive and easy to use 3D design tools such as 3D scanning, Sketchup, Tinkercad, 123Design, Meshmixer, Mixee Labs and 123D Sculpt+ simplify the process of part creation and put the users in control of part creation and customisation. Using these types of tools, customers will be able to select various product options and apply their own functional, ergonomic, aesthetic, emotional and environmental requirements (Campbell, 2005). Not only does this functionality empower customers, companies can gain access to new sources of data on customer preferences and how products are used. Companies that adopt a customisation model could obtain a competitive advantage by offering customers more choice, as well as gain invaluable insights from customer data to predict customer and market trends, and inform the design of future products.

The platform for the trends discussed here are already firmly in place courtesy of a number of forward thinking entrepreneurs. There are a number of digital service platforms where designers can upload parts and get instant quotations for the production of objects. Many services also function as online marketplaces where designers can upload virtual products for customers to buy and print (Warnier et al., 2014). Maker communities are an emerging area which provide extensive repositories of 3D printable objects that can be freely downloaded and printed. Some of these communities also provide customisation by offering the ability to make alterations to objects directly from the website. Some of the most well-known maker communities include Thingiverse and Youimagine (Warnier et al., 2014). Printing services are also available in physical locations available to local customers and businesses. Physical print shops range from simple self-service systems to professional services. Self-service locations may provide several basic systems which people can directly use. Professional services use more complex technology and provide more specialised applications (Warnier et al., 2014). More recently, some online platforms (e.g. 3D Hubs, Makxyz) have emerged with the aim of connecting people to 3D printers in the local area. These services are open to anyone to advertise their services, including both individuals with 3D printers at home as well as businesses with large scale operations. Such enterprises are significant as they offer easy access to 3D printing at a range of different costs and qualities (Warnier et al., 2014).

3.10 SUMMARY

This section has detailed nineteen additive manufacturing technologies from six categories: material extrusion and deposition, material jetting, sheet lamination, vat photopolymerisation, powder bed fusion and binding, and electrospinning. A significant outcome of this survey is a criteria assessment which has evaluated each of the surveyed additive manufacturing technologies based on the maturity of the technology, application potential of the technology, and the technology's potential for integration with cotton-derived feedstocks. The outcomes of this criteria assessment demonstrate the most promising applications for each technology, and identify eleven candidate cotton-derived materials that may be compatible with additive manufacturing technologies. This provides a significant step for determining the feasibility of using cotton-derived materials with rapid customisation processes.

In addition to detailing individual technologies, this section outlined future trends that will affect the continued development of additive manufacturing technology and its broader impact on society and the economy. The main technology trends include the decreasing cost of technology at the low-end of the market, and the rapid improvements in feedstock variety and quality in the high-end of the market. Collectively, these trends result in greater access to additive manufacturing technology and their increasing use for the fabrication of end-use parts. Moreover, the dynamic and highly customizable nature of additive manufacturing technologies has the potential to disrupt current methods of product manufacturing and distribution. This is expected to result in consumer empowerment, the emergence of decentralised manufacturing and the development of new supply chains.

Having provided an overview of cotton materials and properties (Section 2) and now a survey of current additive manufacturing technologies (Section 3), the following section will assess the technical feasibility of using cotton-derived material with rapid customisation processes.

4

Technical Feasibility Assessment

This section consolidates the sections (specify the section numbers here) of this report with the aim of assessing the technical feasibility of utilising rapid customisation technologies in combination with cotton-derived feedstocks. A key outcome of this section is identification of the most promising rapid customisation processes and candidate cotton-derived feedstocks for future research.

4.1 Section Method

The technical feasibility assessment provided in this section is informed by two stages of activities:

Stage 1: Summary of rapid-customisation technologies and candidate-materials

Each surveyed rapid customisation technology is presented in a matrix and mapped to the applicable candidate cotton-derived materials. This is based on the information presented in the 'integration' criteria analysis sections in the literature survey, and is intended to provide an overview of candidate-materials and an indication of their applicability to rapid customisation.

Stage 2: Rapid customisation technology ranking

Rapid customisation technologies are ranked on a matrix based on the three criteria analysis categories outlined in the literature survey: maturity, application, and integration. Top ranked rapid customisation technologies are further discussed, providing brief reasoning for the ranking and outlining specific material requirements.

4.2 Technology and Candidate Material Matrix Mapping

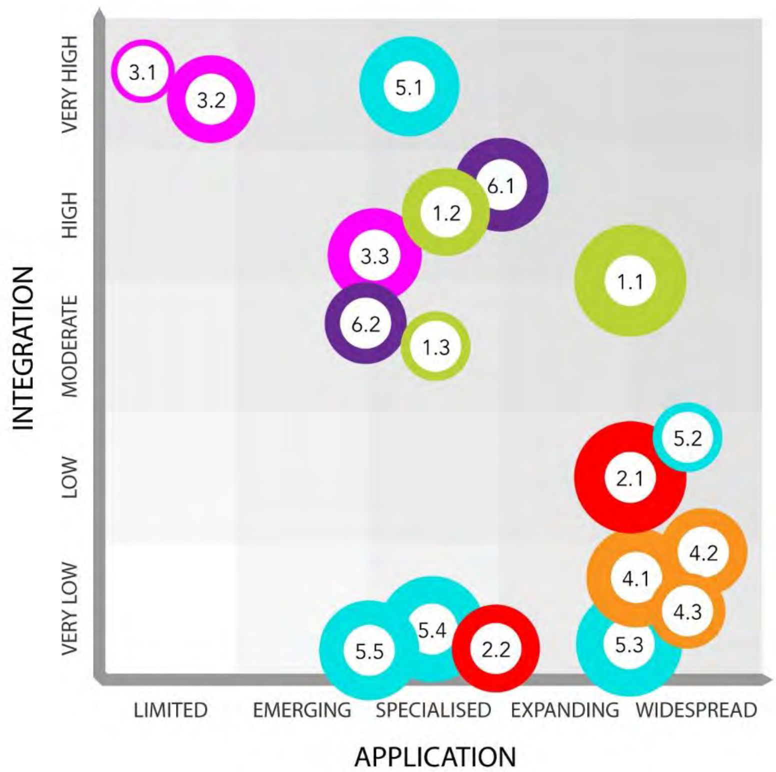
Nineteen rapid customisation technologies were surveyed in the previous section of this report. The criteria analysis presented for each these technologies aimed to provide an initial evaluation of the potential for integrating each technology with cotton-derived feedstocks. This resulted in the identification of eleven candidate cotton-derived materials. These candidate cotton-derived materials and the respective rapid customisation technologies are summarised in the following matrix (Table 4).

TABLE 4. RAPID CUSTOMISATION TECHNIQUES MAPPED TO CANDIDATE COTTON-DERIVED FEEDSTOCKS

	Cotton textile	Cotton paper	Cotton-derived bioplastic (filament, sheet, powder)	Cotton-derived photopolymer	Cotton-derived binding agent	Cellulose polymer solution	Regenerated cellulose	Nanocellulose reinforced polymer matrix composite	Nanocellulose reinforced photopolymer	Nanocellulose powder	Cotton-derived hydrogel / aerogel
Fused Deposition Modelling			■					■			
Robocasting											■
Beam Deposition			■								
Photopolymer Jetting				■					■		
Multi-jet Fusion			■								
Liquid Metal Jetting											
Laminated Object Manufacturing	■	■	■		■		■				
Selective Deposition Lamination	■	■	■		■		■				
Ultrasonic Additive Manufacture			■								
Stereolithography				■					■		
Digital Light Processing				■					■		
Continuous Liquid Interface Production				■					■		
Binder Jetting			■		■					■	
Selective Laser Sintering			■								
Electron Beam Melting											
Selective Laser Melting			■								
Selective Heat Sintering			■								
Solution Electrospinning						■					
Melt Electrospinning			■								

4.3 Technology Ranking

Based on the criteria of integration and application applied in the previous section, Figure 26 presents a mapping that positions each rapid customisation technology in terms of its compatibility with cotton-derived feedstocks and potential impact. Placement of rapid customisation technologies on the mapping was determined by the three criteria analysis categories outlined in the literature survey: maturity (size of coloured circle), application (x-axis), and integration (y-axis). Subsequently, the 5 most promising technologies for future research are identified and briefly discussed.



KEY:

1. MATERIAL EXTRUSION
1.1 Fused Deposition Modelling
1.2 Robocasting
1.3 Beam Deposition

2. MATERIAL JETTING
2.1 Photopolymer Jetting
2.2 Liquid Metal Jetting

3. SHEET LAMINATION
3.1 Laminated Object Manufacturing
3.2 Selective Deposition Lamination
3.3 Ultrasonic Additive Manufacturing

4. VAT PHOTOPOLYMERISATION
4.1 Stereolithography
4.2 Digital Light processing
4.3 Continuous Liquid Interface Production

5. POWDER BED
5.1 Binder Jetting
5.2 Multi Jet Fusion
5.3 Selective Laser Sintering
5.4 Selective laser Melting
5.5 Electron Beam Melting
5.6 Selective Heat Sintering

6. ELECTROSPINNING
6.1 Solution Electrospinning
6.2 Melt Electrospinning

FIGURE 26. TECHNOLOGY RANKING MATRIX

4.3.1 Fused Deposition Modelling (1.1)

The feasibility of developing cotton-derived feedstocks for use with fused deposition modelling (FDM) technology is determined to be high. This has many potential applications, particularly for the fabrication of eco-friendly products. Key factors underlying this assessment include:

- FDM is currently used in a wide range of industries and is growing in popularity as a domestic desktop 3D printing technology (Section 3.3.1). Developing cotton-derived feedstocks for FDM platforms offers the potential to target already established and growing markets.
- Current applications of FDM parts include form and fit prototypes, concept development prototypes, user testing, and novelties (Section 3.3.1). For these applications, in which parts have only a short lifespan, a cotton-derived feedstock is advantageous as it derived from a natural and renewable resource, and has the potential to be biodegradable and non-toxic.
- Current FDM machines are compatible with variety of thermoplastic filament materials. The use of cotton in the production of bioplastics and as a reinforcing agent in composite materials has been documented in the literature (Section 2.3.3).

4.3.2 Robocasting (1.2)

The use of robocasting technology to print cotton-derived materials is determined to be a feasible prospect, with potential impact in specialised domains, such as heavy industries, scientific research and medicine. Key factors underlying this assessment include:

- Robocasting technology is used to fabricate a range of components for specialised applications including: drug delivery, tissue scaffolding, chemical filtration, and water purification (Section 3.3.2).
- The use of robocasting technology to printing 3D Hydrogel matrices has been documented (Lewis, 2006). Consequently, robocasting technology may be used to print hydrogel matrices derived from cotton nanocellulose material. Due to the biocompatibility of nanocellulose, robocast nanocellulose hydrogels have the potential to be used in a variety of high-impact medical applications.
- Robocast hydrogel matrices may also be formulated into aerogel structures through various drying processes (Section 2.3.3). 3D printed nanocellulose aerogels have potential for a variety of filtration, absorption and insulation applications.

4.3.3 Electrospinning (6.1, 6.2)

Electrospinning technology has immediate potential for use with cotton-derived feedstocks for the fabrication of high-impact products in specialised domains. Key factors underlying this assessment include:

- Solution electrospinning technology has been successfully used to fabricate nanofibre membranes using cotton solution (Section 3.8.1).
- Bioplastics, such as PLA, have been used successfully with melt electrospinning technology (Santos et al., 2013). This presents the possibility of using cotton-derived bioplastics with melt electrospinning technology to fabricate nanofibre membranes with controlled fibre structure.
- Electrospinning technology is used to create nanofibre membranes used in specialised applications such as garment creation, tissue engineering, drug delivery and filtration (Section 3.8). Electrospun cotton nanofibre membranes may be particularly suited to biomedical applications due to their biodegradability and biocompatibility.

4.3.4 Photopolymer Systems (2.1, 4.1, 4.2, 4.3)

Photopolymer systems utilising cotton-derived materials have the potential to be applied in a broad range of common and specialised applications. However, there is uncertainty in regard to the feasibility of formulating functional cotton-derived photopolymer materials. Key factors underlying this assessment include:

- Photopolymers have been formulated using PLA bioplastic (Miller & Soucek, 2012), and with the addition of reinforcing material (Zhang et al., 2015). This indicates some potential for formulating cotton-derived photopolymer feedstocks for use with photopolymer systems.
- Photopolymer systems are used in a variety of professional industries, and are becoming increasingly accessible to small businesses and 3D printing enthusiasts (Section 3.6). Development of cotton-derived feedstocks for photopolymer systems offers the potential to target these already established and growing markets.
- Parts produced by photopolymer systems are of high quality, however they deteriorate over time. Consequently, they are often used in applications that require parts with limited lifespans, such as form and fit prototypes, design development prototypes and functional testing (Section 3.6). Biodegradable cotton-derived materials may be well suited to these applications.
- Parts produced by photopolymer systems are used for specialised applications such as implants for cranial surgery and tissue engineering (Section 3.6). The development of biocompatible cotton-derived photopolymer materials may be advantageous for such applications.

4.3.5 Sheet Lamination (3.1, 3.2, 3.3)

Sheet lamination processes are determined to have immediate potential for use with a variety of cotton-derived feedstocks. However, the impact of potential application is determined to be low, due to undifferentiated materials. Key factors underlying this assessment include:

- Cotton can be processed into a variety of sheet materials including paper, textiles, and transparent films. It is expected that current sheet lamination technologies (LOM and SDL) would require little alteration to work with these materials. Cotton-derived materials, however, may offer little differentiation to existing paper and thermoplastic sheet materials.
- Nonwoven textile sheet materials have been used in experimental sheet lamination processes to create soft interactive toys (Peng, Mankoff, Hudson, & McCann, 2015). While the objects created from this system exhibit poor surface finish and detail, refinement of this process using cotton-derived feedstocks may have potential for the development of novel toys.
- Ultrasonic additive manufacturing (UAM) is compatible with a variety of thermoplastic sheet materials (Section 3.5.3). This presents the opportunity to develop cotton-derived bioplastics for use with UAM. The potential of these UAM parts is that they can include integrated electronics. However, these parts would be expensive, and offer few benefits over FDM parts with integrated electronics.

4.4 Candidate Cotton-derived Material Considerations

This section has so far reported two outcomes that assist in assessing the feasibility of utilising cotton-derived feedstocks for rapid customisation technologies:

i. A summary of candidate cotton-derived materials and additive manufacturing technology combinations (Section 4.2).
ii. A ranking of each additive manufacturing technology, identifying the five that present the most promising opportunities for future research and development (Section 4.3).

The following subsections build on these two outcomes by providing key considerations for the candidate cotton-derived materials that are applicable to the top ranked additive manufacturing technologies. This information has been prepared by contributing CSIRO members with expertise in material science and chemistry. Key information presented includes material feasibility, development requirements and resources, technical challenges, limitations and recommendations if applicable.

4.4.1 Cotton-derived Bioplastic and Nanocellulose Composites

Additive Manufacturing Technologies

Fused deposition modelling; melt electrospinning.

Required Material Properties

Biodegradable, non-toxic, durable, glass transition point similar to PLA/ABS.

Material Feasibility Considerations

The material is technically feasible to produce, however, unlikely to be economically viable. There are no current materials specifically developed that incorporate cellulose at this point that are commercially available. To make the bioplastics will require breaking the cotton down to the monomer or oligomer state. This poses a problem as it is then a competing product against sugar. An alternative is to produce nanocellulose crystals, micro fibrillated cellulose, long cotton powder or short fibre, mix with a thermoplastic and then extrude. A multi-year funded project would be required to complete the research.

A feasible material appropriate for rapid customisation processes would require the development of 'inks', including trials to assess their suitability. A key stage of this assessment would include identifying the advantages and disadvantages of this new ink compared to current plastic inks. A technical challenge is making suitable material that can be printed and that has a superior performance against exiting inks. The expertise required to develop the candidate materials include polymer chemistry, and experience with composites in order to develop 3D prototypes for bench marking. The main concerns with this material for rapid customisation processes is whether it will have a suitable performance in the extrusion process, cost, and final product performance and properties.

4.4.2 Cellulose Polymer Solution

Additive Manufacturing Technologies

Solution electrospinning; melt electrospinning.

Required Material Properties

Ability to form fine meshes, durable, biodegradable, biocompatible, breathable, washable.

Material Feasibility Considerations

Current cellulose electrospinning is at low technology readiness level values (~3). For electrospinning, only high value end products should be considered. There are examples of derivatised cellulose (e.g., cellulose acetate electrospinning) in the literature. A trial project is recommended to ascertain the suitability of cellulose cotton and/or composite with nanocellulose for use with electrospinning techniques.

The main technical challenge to overcome is to establish if the cellulose can be spun directly or if it needs to be derivatised first and then spun. Consequently, processing cost would be a consideration. The main limitations with the material would be finding suitable applications that will take advantage of the cellulose nanofibre properties. The physical strength of nanofibre systems is low, so as a result they would need to be part of a composite system.

4.4.3 Cotton-feel Material

Additive Manufacturing Technologies

Fused deposition modelling; thermoplastic jetting.

Required Material Properties

Flexible, cotton-feel, soft, drape properties similar to woven or knitted textiles, washable, durable.

Material Feasibility Considerations

A cotton-feel material suitable for rapid customisation processes is technically feasible and cotton-like properties may be achievable. Further work is required to establish the materials, equipment, resources and indicative cost of materials required.

Limitations may be the lengthy and involved processing steps to combine and the dissolution of the carrier to leave the remaining cotton. This may in-turn result in a material that is not economically viable unless it is applied in a high value product.

4.4.4 Cellulose-derived Hydrogel

Additive Manufacturing Technologies

Robocasting.

Required Material Properties

Biocompatible, biodegradable, potential to be loaded with active material, healing agents and drugs.

Material Feasibility Considerations

The fabrication of cellulose-based hydrogels is technically feasible. The main challenge that this material presents is adding functionality through the incorporation of active material, sensors and drugs. These materials may be temperature or concentration dependent, and there is question as to whether or not they can be bound or contained within the structure. Cellulose type hydrogel materials do not rehydrate well, as the chains do not unfold. A challenge is to retain the product in the hydrated from. Much work would be required to determine release characteristics for drug loading. The hydrogel would also require a structure to contained or be attached to when maximum absorption capacity is required or reached.

4.4.5 Cellulose-derived Aerogel

Additive Manufacturing Technologies

Robocasting.

Required Material Properties

Ability to form a porous 3D structure, durable/flexible, biodegradable, insulation properties.

Material Feasibility Considerations

The fabrication of cellulose-based aerogels is technically feasible. Cellulose-based aerogels can be produced from either a hydrogel state or from cellulose solution. In either case, rapid freeze drying is an economical technique. More research is required to identify the materials, equipment and other resources required, however.

The main limitation of a cellulose-based aerogel is that it can only be used in combination with a hydrophilic material. Rehydration and unfolding of the chains is limited, so applications that may require rehydration of the aerogel may have the properties compromised.

4.4.6 Cotton-derived or Reinforced Liquid Photopolymer

Additive Manufacturing Technologies

Photopolymer systems.

Required Material Properties

Biodegradable, durable, non-toxic, similar properties to current liquid photopolymers used in photoplymer systems.

Material Feasibility Considerations

The fabrication of cotton-derived or reinforced liquid photopolymers is technically feasible. Cotton could be combined and polymerised to provide a high cotton component composite. The strength of the product, however, could be a limitation. The development of this candidate material would require trials to assess its suitability and the advantages and disadvantages it provides over current photopolymers. A key consideration for cellulose as a reinforcing material is whether it is an advantage to use cotton over other materials (i.e., glass fibre) which may be cheaper. Economics would have to be established.

4.4.7 Cotton Sheet Material

Additive Manufacturing Technologies

Sheet lamination processes.

Required Material Properties

Soft, flexible, non-toxic, potential compatibility with existing or modified sheet lamination processes.

Material Feasibility Considerations

Cotton sheet materials for use in sheet lamination rapid customisation processes are technically feasible. There currently exists a large variety of cotton-derived sheet materials including woven textiles, nonwovens, films and paper. These materials are widely available, can have a variety of properties and are inexpensive. The greatest challenge for cotton-derived sheet materials is developing or modifying compatible sheet lamination processes.

4.5 Summary

The first stage of this report presented literature surveys which outlined the potentials of cotton as a material, and detailed the available of additive manufacturing technologies and the future trends in this space. As the beginning of stage two of this report, this section has consolidated the information presented in the literature surveys and has assessed the technical feasibility of using cotton-derived feedstock as a material for rapid customisation technologies. A matrix mapping the available additive manufacturing technologies to the eleven identified candidate cotton-derived materials represents the diverse opportunities that cotton-derived materials may have for rapid customisation processes. These identified material and technology combinations have the potential to add value to existing technologies through the application of the unique properties of cotton-derived materials.

Having established potential material and technology combinations, each of the surveyed rapid customisation technologies were ranked based on the technology's maturity, application potential and potential integration with cotton-derived feedstocks. Subsequently, five additive manufacturing technologies were identified to have the greatest opportunities for future research: fused deposition modelling, robocasting, electrospinning, vat photopolymerisation processes and sheet lamination processes. While each of these technologies are differentiated by their unique characteristics, they share similarities in terms of the factors underlying their feasibility for use with cotton-derived feedstocks. These are summarised in Table 5.

TABLE 5. FACTORS SHARED BY TOP RANKED ADDITIVE MANUFACTURING TECHNOLOGIES

	Fused Deposition Modelling	Robocasting	Electrospinning	Photopolymer Systems	Sheet Lamination
Established consumer market	■			■	
Potential for developing sustainable products for existing applications	■			■	■
Potential for developing novel and high-impact applications		■	■	■	
High feasibility for use with cotton-derived materials	■	■	■		■

The outcomes of this section provide a vital step that informs the subsequent sections of this report which focus on detailing the potential applications facilitated by cotton-derived materials applied to rapid customisation.

5

APPLICATION ANALYSIS

Previous sections of this report have developed an understanding of the unique properties and potentials of cotton material, and provided a survey, assessment and ranking of additive manufacturing technologies. This section builds on this information by analysing the potential applications of cotton rapid customisation.

5.1 SECTION METHOD

The foundation of this section comes from the collaborative activities engaged during the joint QUT/CSIRO workshop. An application analysis activity was facilitated with the aim of developing initial application ideas made possible by cotton-derived feedstock and rapid customisation technologies. The application analysis activity comprised of two stages:

STAGE 1: APPLICATION BRAINSTORMING

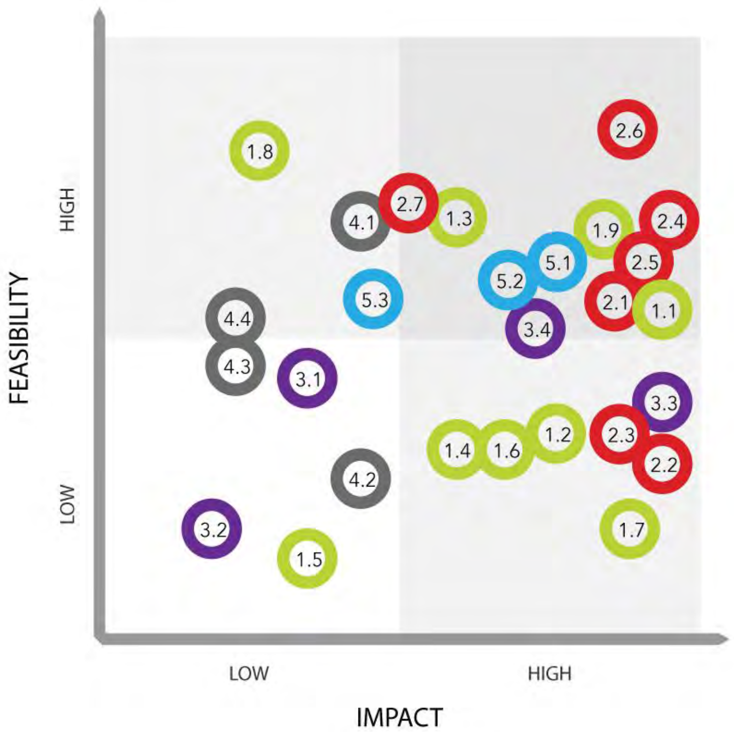
Brainstorming of potential applications was performed in small groups with the aim of developing a broad diversity of ideas to be further discussed and refined. Applications of particular interest were those that leverage the unique properties of cotton-derived materials and which gain added value through rapid customisation. Application ideas arising from this activity were recorded onto post-it notes and presented to all workshop attendees. Any comments and critique were encouraged during this stage to further clarify ideas.

STAGE 2: IMPACT/FEASIBILITY EVALUATION AND MAPPING

Immediately after presentation and discussion of application ideas, they were each evaluated in terms of feasibility and impact. Considerations for feasibility of an application included: the availability of a cotton-derived material suitable for the application, and ease of integrating the cotton-derived material with an existing rapid customisation process. Considerations for the impact of an application included: the added value that cotton brings to the application, differentiation from other products and materials, disruption potential, and generation of new markets and supply chains. After evaluating the impact and feasibility of each application, they were mapped on an impact/feasibility matrix.

5.2 Impact/Feasibility Evaluation and Mapping

Over fifty diverse applications were developed and evaluated during the brainstorming session. As there were similarities between some applications developed during the workshop, these have been refined to form twenty seven distinct applications from five broad application areas. These range from those with immediate application and impact, to those of greater speculation and requiring development of relevant materials and processes. Applications and the results of the impact/feasibility evaluation are presented in Figure 27.



KEY:

1. LIFESTYLE
1.1 Wearable technology
1.2 Footwear
1.3 Soft apparel & accessories
1.4 Hard goods & accessories
1.5 Food
1.6 Domestic products
1.7 Backpacks & travel goods
1.8 Toys & hobbies
1.9 Technical clothing

2. HEALTH
2.1 Drug delivery
2.2 Personal hygiene products
2.3 Disposable medical products
2.4 Prosthetics
2.5 Wound dressings
2.6 Tissue scaffolds
2.7 Disability aids

3. INDUSTRIAL
3.1 Repurposed cellulose waste
3.2 Barrier applications
3.3 Industrial filtration
3.4 Smart packaging

4. ARCHITECTURE & DESIGN
4.1 Soft furnishings
4.2 Non-structural components
4.3 Functional prototypes
4.4 Aesthetic prototypes

5. AUTOMOTIVE
5.1 Exterior modifications
5.2 Interior modifications
5.3 Custom seating

FIGURE 27. APPLICATION IMPACT/FEASIBILITY MATRIX

5.2.1 Lifestyle

Additive manufacturing technologies have received substantial interest in a variety of lifestyle product categories due to their ability to create complex and intricate objects. The fashion industry has experimented extensively with additive manufacturing, producing garments, shoes, and accessories. Fashion accessories have arguably been the most successful of these, with companies such as Nervous System (n-e-r-v-o-u-s.com) providing user-customised 3D printed accessories, and also a range of jewellery options available from platforms like Shapeways (shapeways.com). Progress toward commercialised 3D printed footwear has also been made with most major footwear brands developing a 3D printing presence within their companies. It is expected that the first generation of 3D printed footwear will be on sale by mid-2016 (Zaleski, 2015).

Despite the appeal and potential of additive manufacturing, commercially available garments created using additive manufacturing are limited (Yap & Yeong, 2014). This is due to the expense associated with additive manufacturing, and the difficulty of producing textile-like garments that are comfortable to wear. Current 3D printed garments are made from polymer materials and printed with FDM, SLS and Polyjet systems. The 'fabric' produced by these printers resembles a chainmail-like structure which allows for only limited flexibility and comfort (Yap & Yeong, 2014). However, recent research and development of soft 3D printed textile structures has been promising. For example, (Melnikova, Ehrmann, & Finsterbusch, 2014) soft and flexible 3D printed objects have been fabricated from novel composite materials and material treatments (Melnikova et al., 2014). Another example of textile-like 3D printed material is Cosiflex produced by the textile company, Tamicare. Cosiflex is a multistage 3D printed textile produced from a combination of liquid polymers and textile fibres (Yap & Yeong, 2014). Although there is still a great deal of development required for 3D printed textiles to be commercially viable, these recent developments are promising (Yap & Yeong, 2014).

For many domestic lifestyle products, in-home additive manufacturing has long been promised. This promise has been somewhat fulfilled due to the availability of inexpensive desktop 3D printers and access to large repositories of downloadable objects available from websites like Thingiverse (thingiverse.com). Toys, animated figures and 3D avatars from video games have become one of the most popular areas for home 3D printing. Recently, of the idea of home 3D printing has been specifically marketed toward children (Kelly, Drumm, & Baichtal, 2015). The most recent example of this is the 'Thingmaker' 3D printer released by Mattel. Another area of interest for home 3D printing is food. This is demonstrated by ChefJet Pro from 3D systems capable of printing decorative food items (3Dsystems, 2015). Researchers and various companies have been working to add further utility to 3D printed food, such as safer food shapes for consumption by the elderly (Lomas, 2015).

Lifestyle Applications for Cotton Rapid Customisation

Lifestyle applications of cotton feedstock in rapid customisation processes identified during the workshop included:

Soft-apparel and Accessories (1.3), Hard-goods and Accessories (1.4)

A range of fashion apparel applications with immediate application were discussed. Rapid customisation technologies may be used to customize the appearance and fit of apparel such as t-shirts, jeans, sweaters, shorts, socks, hats and gloves. Customisation may also be extended to fashion accessories, such as jewellery and hand bags.

Wearable Technology (1.1), Footwear (1.2), Backpacks and Travel Goods (1.7), and Technical Clothing (1.9)

Fashion apparel applications requiring greater development but enhanced with novel and functional cotton-derived materials were discussed. For example: performance rainwear and protective equipment customised for unique environmental conditions; backpacks and bags with customised storage design, moisture control and insulation; and footwear and innersoles that have custom fit, cushion and support structures. These applications also have the potential for integrated electronic functionality to create novel wearable devices.

Food (1.5)

The production of food using cotton-derived materials and rapid customisation was discussed in relation to two key areas. First, the use of rapid customisation to produce low-cost food with custom nutrient profiles, texture and diverse flavours. Second, rapid customisation and modified cotton feedstocks to produce edible food ornaments for fine dining experiences.

Domestic Products (1.6)

A number of domestic product categories were identified as having immediate potential for rapid customisation using biodegradable cotton-derived materials. One specific application presented was on-demand printing of eco-friendly disposable office products such as pens, pencils, clips, and other stationary items. This application has the potential to extend to extend to other domestic product categories that have short lifespans with similar manufacturing constraints, such as cleaning products.

Toys and Hobbies (1.8)

Rapid customisation of children's toys and hobbies was identified as another application area that can be implemented quickly with immediate impact. These applications would rely on cotton to be processed into alternative materials, such as bioplastics, to be suitable for existing rapid customisation processes. Expanding on this application, the possibility of 3D printing soft cotton-feel objects was discussed. Adding this functionality to toy customisation could increase the scope of products that can be printed and may have significant impact. A market of particular interest for this application is 3D printing of biodegradable and eco-friendly children's toys.

5.2.2 Health

Rapid customisation enabled by additive manufacturing is a driver of innovation in many medical fields. According to Toumi et al. (2014) the five major medical domains that additive manufacturing can be applied to are: i. Medical models for pre- and post-operative planning, education and training; ii. Medical aids, orthoses, splints and prosthesis; iii. Tools, instruments and parts for medical devices; iv. Inert implants; and v. Biomanufacturing.

Facilitating this diversity of applications is the capability of additive manufacturing to produce complex organic forms and difficult geometric shapes. This has had particular impact in the development of bone implants and assistive prosthetic devices (Tuomi et al., 2014). Additive manufacturing enables patient-specific implants to be created rapidly, which improve fit and biological implant acceptance (Douglas, 2014). In 2015, over twenty 3D printed implant products were approved by the FDA (Advantage Business Media, 2015). Of these, AM manufactured hip implants exceeded the 100,000 mark as of 2015, with dental products, hearing aids and custom cranial plates also entering the market with widespread use (Lipson & Kurman, 2013). The most common additive manufacturing processes for medical implants are powder bed fusion for metal and ceramic parts, and vat photoplymerisation and material jetting for polymer composites (Tuomi et al., 2014) Although the creation of most components can be achieved using these methods, more sophisticated levels of integration have been explored with a variety of hybrid technology platforms (Giannitelli, Mozetic, Trombetta, & Rainer, 2015).

A particularly exciting area of development for medical implants is bone tissue regeneration. Additive manufacturing has been used to create tissue scaffolds that are integrated with living cells to optimise cell migration for improved bone and tissue regeneration (Berner et al., 2014; Do, Khorsand, M. Geary, & K.Salem, 2015; Giannitelli et al., 2015). Another promising area of implantable medical devices is drug delivery. AM has recently gained media attention for the first printed pharmaceuticals, however, the technology also has significant potential for transdermal and implantable drug delivery systems. A strong area of research for these drug delivery systems is the formulation of hydrogels that are capable of controlled drug release, and even drug release that is activated by certain variables such as changes in blood PH (Hamidi, Azadi, & Rafiei, 2008).

Additive manufacturing has facilitated the design and manufacture of adaptive and rehabilitative products for people with disabilities and impairments, the elderly, and people recovering from injury. A notable application of AM for these user groups is custom fit prosthetics that are functional, attractive, and inexpensive (Warnier et al., 2014). Additive manufacturing has also been used to create specialised, lightweight tools for those in need of mechanical advantages for routine tasks (Halterman, 2015), and to provide access to leisure activities (Scott, 2015). Hearing aids are another high profile assistive application of rapid customisation technologies. Using 3D scanning, digital design tools and 3D printing, the manufacturing process of hearing aids has been shortened to just three steps: scanning, modelling and printing. Consequently, creating custom fitting hearing aids is no longer an issue and the lead times on device manufacturing have been shortened significantly (Rakesh, 2013).

Health Applications for Cotton Rapid Customisation

Health applications of cotton feedstock in rapid customisation processes identified during the workshop included:

Drug Delivery (2.1)

Cotton-derived cellulose hydrogels have the potential to be used in a variety of drug delivery systems due to their biocompatibility and biodegradability. Potential applications discussed included oral drug delivery, and transdermal and implantable drug delivery systems. Designed and manufactured with rapid customisation technologies, such drug delivery systems may be tailored to each patient and their unique requirements. In addition to pharmaceutical drug systems, cotton-derived cellulose hydrogels could be used in the manufacture of custom nutritional supplements. Like drug delivery systems, these supplements could be custom designed and incorporate controlled release of nutrients and vitamins.

Personal Hygiene Products (2.2), and Disposable Medical Products (2.3)

Personal consumer hygiene products discussed were those predominantly sold in pharmacies and supermarkets to consumers. Example products include makeup applicators, sanitary pads and shaving products. Disposable medical products discussed were those typically used in hospitals, surgeries and medical practices. Example products include swabs, gloves, facemasks, and other protective equipment. Cotton-derived materials are advantageous for these applications as they may be non-allergenic and biodegradable.

Prosthetics (2.4), and Disability Aids (2.7)

Disability aids discussed included simple tools to improve quality of life, as well as other aids such as prosthetics and protective equipment used for people susceptible to falls or those with degenerative diseases such as osteoporosis. Of these areas, prosthetics was identified as having the greatest potential as they may benefit greatly from rapid customisation technologies. This is validated by the already strong presence of additive manufacturing technologies used for the manufacture of prosthetics. In this area, cotton is advantageous for the creation of prosthetics that have a short lifespan, such as those for small children, or for producing fashionable prosthetic coverings.

Wound Dressings (2.5), and Tissue Scaffolds (2.6)

Cotton-derived cellulose is advantageous for wound dressings, and tissue scaffolds due to its biocompatibility. By incorporating 3D scanning technology it may be possible to develop wound dressings that match the match the shape of a patients wound. Moreover, wound analysis technology may be integrated into the customisation process to inform the inclusion of tailored healing agents, sensing agents and antibacterial treatments. Tissue implants could implement a similar 3D scan process to capture 3D geometry of soft and hard tissue damage. Printed soft and hard tissue implants using cellulose material have the potential to function as tissue scaffolds with the integration of living cells.

5.2.3 Industrial

Rapid customisation processes, and additive manufacturing technologies present opportunities for the manufacture of products for specialised industrial applications. An area of interest is packaging, where 3D printing has been used to print food packaging, personalised labelling on packaging, custom medication containers (Anon, 2015), and packaging for low-volume high-cost products such as high-end optic and electronic equipment (Gibson et al., 2010). Sustainability is a key consideration in packaging manufacturing, and is an area in which additive manufacturing technologies offer significant advantage. Additive manufacturing offers superior material efficiency and waste reduction in comparison to traditional techniques, which can result in substantial material wastage. The portable and customisable nature of many additive manufacturing methods also allows a transfer of capabilities to smaller scale businesses, which are now able to prototype and manufacture their own packaging products (Rowntree, 2014). Perhaps one of the strongest areas for packaging innovation facilitated by additive manufacturing is 'smart packaging'. Smart packaging is being developed to alert consumers and organisations to food spoilage (Pacquit et al., 2007). 3D printed smart packaging products capable of identifying evidence of tampering, contamination, exposure to heat or cold, and other environmental variables could be particularly valuable in industries such as health and nutrition, hospitality, and pharmaceuticals.

Beyond packaging, additive manufacturing technologies have been used for a variety of high performance industrial products such as filtration membranes, scientific labware and analysis tools. One of the driving technologies in this area is robocasting using ceramic materials. Robocast ceramics offer high strength parts with thermal shock resistance that are suitable for filtration of molten metals and chemical compounds. The unique lattice structure of robocast parts is particularly well suited to filtration applications as the consistent pore size results in a consistent flow rate and maximises the removal of impurities (Lewis et al., 2006).

Industrial Applications for Cotton Rapid Customisation

Industrial applications of cotton feedstock in rapid customisation processes identified during the workshop included:

Repurposed Cellulose Waste (3.1)

Waste cotton cellulose is an abundant material with very few current uses. Regenerated of cotton cellulose from waste textile has the potential to be used for the manufacture of a range of items, including, household cleaning products, filtration membranes, dust masks, packaging, and other single-use or disposable items. The ability to print small-scale, high turnover products on-demand may eliminate the need for manufacturers and businesses to create and hold onto a high volume of stock.

Barrier applications (3.2)

Barrier applications include films and coatings that protect from water vapour, oxygen, and other contaminants such as oil and grease. Microfibrilated cellulose has the potential to be used for these applications as it provides barrier properties that are competitive with many synthetic polymer barriers (Lavoine et al., 2012). Specific applications discussed at the workshop included antifouling coatings, food safety and preservation. Rapid customisation technologies could be used to tailor the properties of different barrier products to suit specific applications and environmental conditions.

Industrial Filtration (3.3)

Cotton nonwovens are widely used for filtration purposes. Products range from those used for domestic applications, such as coffee and tea filtration, to industrial applications, such as gasoline and air filtration. Due to the diversity of filtration applications there is the potential for the fabrication of customised filtration products using additive manufacturing. Such products could be particularly valuable for applications characterised by variable environmental conditions or where specific performance standards are required. Rapid customisation technologies capable of producing high performance nanofibre materials, such as electrospinning, may be suitable for this application.

Smart Packaging (3.4)

Cotton is a compelling material for a variety of packaging applications due to being a renewable resource and biodegradable. In addition to these properties, the variety of potential cotton-derived materials may facilitate the development of innovative biopackaging solutions. Cotton-derived bioplastics are a good candidate material for use in food packaging and other general packaging applications. High performance cotton materials, such as aerogels and hydrogels have the potential to be used for packaging requiring moisture control and insulation. Such applications could be further enhanced by the addition of sensors that monitor variables such as bacteria contamination and heat exposure.

5.2.4 Architecture and Design

Additive manufacturing has a long history in architecture and other design disciplines as a rapid prototyping tool. While it was once confined to the production of prototypes and visual models, the potential applications of additive manufacturing in the design disciplines is expanding. In architecture and construction, additive manufacturing is used to manufacture full-scale architectural components, such as facades and walls, acoustic panelling, furniture, sculptural elements, and garden features (Lim et al., 2012). Over the past several years, additive manufacturing has also been explored as a method of manufacturing entire houses from extruded cement and other materials (Warnier et al., 2014). Additive manufacturing is advantageous for such applications as it produces minimal waste, reduces labour costs and is capable of delivering custom building parts (Lim et al., 2012).

This is an area likely to receive continued interest due the demand for low-cost housing, particularly in emerging markets (Warnier et al., 2014).

Additive manufacturing has become an invaluable tool in other design disciplines such as industrial design, animation, film, and games design. Additive manufacturing is deeply integrated in the design process used in these industries, facilitating rapid feedback and fast design iterations. High-speed 3D printing technologies, such as continuous liquid interface production from carbon3D (carbon3d.com), are being used as design tools in the automotive and animation design industries where they have received positive reviews. Craft industries are also making use of additive manufacturing to offer differentiated products to their customers. Popular products include furniture, lighting, ceramics, ornaments and fixtures (Warnier et al., 2014).

Architecture and Design Applications for Cotton Rapid Customisation

Architecture and design applications of cotton-derived feedstock in rapid customisation processes identified during the workshop included:

Soft furnishings (4.1)

Soft furnishings include cushions, towels, blankets, wall hangings, rugs and other textile items. Leveraging existing materials and processes, value can be added to these products through providing simple customisation options. Novel cotton-derived materials such as expanded biofoams and bioplastics present an opportunity to produce high-value products such as mattresses, office seating and sofas. Applying additive manufacture to these products has the potential to disrupt traditional supply chains and manufacturing processes.

Non-structural components (4.2)

The ability to process cotton into a variety of different materials with insulation, barrier and strength properties lends it to a number of non-structural applications. Potential non-structural applications include insulation, vapour barriers, moldings and fixtures.

Functional (4.3) and Aesthetic (4.4) prototypes

Additive manufacturing is currently used for both functional and aesthetic prototypes in many design industries. For this application, a naturally biodegradable cotton-derived feedstock may be an attractive material option for prototypes that require only a short lifespan. Moreover, such a material could be advantageous for applications in which object recovery is difficult or not possible. For such applications, a cotton-derived material could be left to naturally biodegrade.

5.2.5 Automotive and Aerospace

The automotive and aerospace industries have embraced additive manufacturing for the production of specialised parts that are required in limited quantity or that are unachievable using other manufacturing processes. According to Wohlers Associates, Inc (Wohlers

Associates, Inc, 2015c), "nearly all major aerospace OEMs including Airbus, Bell Helicopter, GKN Aerospace, Honeywell, Lockheed, Martin, MTU Aero Engines, Northgroup Grumman, Pratt and Whitney, Raytheon, and Rolls Royce have built infrastructure within their corporations to evaluate and implement additive manufacturing". A key driver of the aerospace and automotive industry's interest in additive manufacturing is the improvement of technologies capable of producing end-use metal parts, and metal casting molds and tooling. These capabilities have been shown to increase the speed of part design cycles and overall part manufacturing (Black, 2015). For the production of tooling, additive manufacturing provides substantial benefits over traditional tooling made using CNC machining. Additive manufacturing allows for tools to be produced with integrated cooling channels that improve part accuracy and reduce molding cycle times (Wohlers Associates, Inc, 2015c). Sandcast molds created using selective laser sintering technology expand further on these benefits by allowing highly complex parts to be cast that are not possible using traditional tool molds (Gibson et al., 2010). For these reasons, many tool manufacturers are investing in additive manufacturing capabilities (Wohlers Associates, Inc, 2015c).

Additive manufacturing has also been integrated with advanced optimisation tools to significantly reduce the material and weight in parts (Wohlers Associates, Inc, 2015c). This provides significant potential for fuel economisation and the subsequent benefit of decreasing CO^2 emissions and total primary energy supply (Joshi & Sheikh, 2015). In addition to part production, additive manufacturing has had an effect on employee performance and workplace human factors. At the German Regensburg BMW plant, which has begun FDM printing of specially designed hand-held tools which have enhanced productivity, comfort and process repeatability (Bogue, 2013).

Automotive and Aerospace Applications for Cotton Rapid Customisation

Automotive and aerospace applications of cotton feedstock in rapid customisation processes identified during the workshop included:

Exterior modifications (5.1)

Exterior modifications included aesthetic components not integral to a vehicle's structure such as: roof racks, decals and protective covers. Such products could be customised by consumers to fit their individual aesthetic preferences and practical requirements.

Interior Modifications (5.2)

Interior modifications included aesthetic components for the interior of vehicles. Discussed products included seat covers, dash panels, control modifications, seat adjustment levers, arm rests, steering wheel covers, air fresheners, and other decorative features.

Custom Seating (5.3)

Rapid customisation technology combined with personal 3D scan data was discussed for the application of manufacturing custom automotive seating. This application would depend on developing a variety of cotton-derived materials, such as those with structural performance as well as adequate cushion properties. Combing these materials in different arrangements and structures could be used to print seating with cushion and support structure tailored to an individual user.

5.3 Summary

This section has mapped out the diverse application potential of cotton-derived feedstocks utilised in rapid customisation processes. The catalyst for this was an application brainstorming activity conducted at the QUT-CSIRO joint workshop. This resulted in the development of twenty-seven unique application ideas from five broad categories: lifestyle; health; industrial; architecture and design; and automotive and aerospace. Subsequent to their development, each application idea was evaluated based on its potential impact, and its perceived feasibility given the availability of compatible cotton-derived feedstocks. Represented on a visual matrix, this evaluation illustrates the application areas and ideas with the greatest potential for further development.

In the interest of gaining a greater understanding of the application areas with most potential, the current implementation of rapid customisation and additive manufacturing technology was discussed within the five application categories identified. This has showcased the breadth and versatility of rapid customisation processes in a broad application space, and signposted the most appropriate areas for the development of applications. This outcome has provided the foundation for the development of the design visions that are presented in the following section.

6

Design Visions

This section presents the five most feasible design visions that demonstrate the potential capabilities of cotton-derived feedstocks applied to rapid customisation processes and technologies. Development and selection of design visions was intended to represent the findings of this report, showcasing the versatility of cotton-derived materials and their applicability to rapid customisation applications.

6.1 Section Method

The catalyst for design vision development was the application ideas identified at the QUT-CSIRO workshop (Section 5). Further development of these applications was performed collaboratively among QUT members. Conceptual sketches and scenarios were developed to visualise the main aspects of each application, with particular importance given to outlining the potential for rapid customisation and the advantages of utilising cotton-derived feedstocks. Evaluation of these scenarios occurred throughout the design process, allowing some ideas to be discarded, while others were further refined. Key criteria for the design visions included:

- The application context and target-user group must benefit from rapid customisation.
- Candidate cotton-derived feedstocks must enhance the application.
- The diverse potentials of cotton-derived materials must be evident.
- The application should address rapid customisation and cotton future trends.
- The application should have disruptive potential in terms of supply chain innovation, and the development of new business models and new markets.
- The application should present future areas of research.

Where appropriate, expertise internal to QUT was sought to further validate and expand the potential of developed applications. Through this process, five design visions were selected and are presented in the following sub-sections. Each design vision is comprised of an outline of the context, the design vision scenario, discussion of the applicability of rapid customisation and cotton-derived materials, an overview of the potential impact including other areas of application, and identification of areas that offer potential for future research.

6.2 Design Vision 1: On-site Fabrication

Current Context

Cotton is a common material found in many commercial filtration products. Current filtration products are mass manufactured for specific equipment and machinery. These filters are typically inexpensive and are available from online and brick-and-mortar retail locations, or at locations where machines and vehicles undergo repair. While suitable for many applications, this general supply chain is not easily applied in certain industries. For instance, in primary industries, defence and construction industries, operations and equipment maintenance is often performed remotely, and in some cases, offshore. In such cases, filtration products must be transported and stored until they are required. Moreover, a variety of product types are required for use with diverse applications which demand high performance. They are required for the maintenance and smooth running of plant and equipment, are used to protect against environment contamination, and are essential for protecting workers against contaminants such as air pollution. Consequently, a vast number of filtration products are required to be on hand to maintain productivity and avoid any costly production shutdowns or health risks.

Design Vision Scenario

On-site Fabrication proposes customised on-site and on-demand manufacture of cotton-based filtration products, as well as other disposable maintenance products used for absorption and barrier applications. It is envisaged that maintenance engineers could access a virtual inventory of products to manage inventory levels and part manufacture to correspond to routine vehicle maintenance schedules (Figure 28). Moreover, there is the potential to employ automated scheduling of part manufacture. This may be achieved through integrating inventory management and manufacture scheduling with the systems that remotely monitor the performance of assets such as vehicles, boilers and smelters. Monitoring sensors collect data about these assets and feed it back to the operations centre where it is used to predict potential problems and maintenance needs (Latimer, 2015). For On-site Fabrication, this type of data may be used to identify when specific items require replacement, and schedule on-demand printing and replacement of these parts. Not only does this system have the potential to disrupt current supply chain logistics, but it also has the potential to improve efficiency and reduce costs resulting from disruptions to operations.

FIGURE 28. CONTROLLED AND AUTOMATED SCHEDULING OF PART MANUFACTURE

Most filtration products are comprised of specific mountings, housings and casings, in addition to filtration membranes (Jandos, Lebrun, Brzezinski, & Canizares, 2007). Consequently, the use of hybrid rapid customisation technologies is envisaged that are capable of manufacturing structural components as well as permeable membranes suitable for diverse filtration applications. Potential candidate technologies are fused deposition modelling (FDM) for structural casings, and electrospinning for membrane material. Hybrid systems utilising these technologies have the potential to create parts with precisely controlled part structures integrated with filtration membranes tailored to specific applications and the environmental conditions encountered (Figure 29).

FIGURE 29. CUSTOM PART STRUCTURE AND FILTRATION MEMBRANES

By leveraging the adaptability of rapid customisation technologies such as FDM and Electrospinning, it may be possible to manufacture a diverse range of industrial filtration products. While vehicular maintenance applications have been used as the primary example in this design vision, it is expected that other filtration applications can be catered for. This includes, but is not limited to vehicular and indoor HVAC systems, personal filtration systems (Figure 30), chemical filtration and water purification.

FIGURE 30. DIVERSE APPLICATIONS

Applicability of Cotton and Rapid Customisation Technologies

The applicability of a cotton-derived feedstock in this design vision is justified by the already widespread use of cotton in a variety of air filtration membranes (Chuang, Hong, & Chang, 2014; Jandos et al., 2007; Seyffer, 2012). Cotton membranes are used extensively in vehicular engine air cleaners owing to their cost effectiveness and ease of manufacture. Similar filter types are used for domestic water purification, air filters for HVAC systems and in appliances such as vacuum cleaners. The continued use of cotton-derived feedstocks has the additional benefits of being inexpensive and biodegradable. This is an important consideration in industries that often have poor reputations when it comes to environmentally sensitive practices.

Employing rapid customisation technologies for filtration applications has the potential to drive the development of next generation filtration products that are tailored for specialised applications. The driving technology behind this design vision is electrospinning. Electrospinning apparatuses are typically low in cost and are already compatible with cotton-derived feedstocks (Sambaer, Zatloukal, & Kimmer, 2011). Current solution electrospinning systems compatible with dissolved cotton solution have been used to successfully fabricate cotton nanofibre webs. Moreover, the use of cotton-derived bioplastics may be to be a feasible candidate cotton-derived feedstock for use with melt electrospinning systems. Nanofibre filtration membranes fabricated by melt and solution electrospinning have proven to be superior in performance and operation when compared with traditional nonwoven filtration membranes (Chuang et al., 2014; Dalton et al., 2013; Nayak, Padhye, Kyratzis, Truong, & Arnold, 2011; Stranger et al., 2009; Wendorff, Agarwal, & Greiner, 2012). Nanofibre webs, with their large surface areas and porosity, allow for efficient absorption of harmful particles, including microorganisms, dust, bacteria and other molecules (Reneker & Yarin, 2008). Nanofibre webs used in filtration can also act as a carrier material for a variety of substances. Filters loaded with SiO^2 or other hybrid materials with oxide nanoparticles may act as air pollution controllers, while cationic polymers with silver components and act as contamination reducers (Jandos et al., 2007). These various filters, if spun as a nonwoven material, can be made smaller in size and have a longer lifetime than conventional filtration materials. With the development of hybrid electrospinning processes that integrate the functionality of FDM, it may be possible to create a variety of housings and mounts for filtration membranes, making them compatible with an enormous variety of machinery, equipment and applications.

Impact

Potential areas of impact for this design vision are diverse due to the wide range of sectors in which nanofiltration membranes are used. These include "water and wastewater treatment, food and beverage, chemical and petrochemical, pharmaceutical and biomedical, metalworking, agriculture, textiles and solid waste management" (BCC Research, 2014). According to BCC Research (BCC Research, 2014), the "global market for nanofiltration membranes increased from $172.8 million in 2012 to $190.2 million in 2013". At the time of the market analysis, the market value was estimated to reach $215.6 million by the end of 2014, corresponding to a CAGR of 11.7% during the two-year period. Projected growth over a five year period starting in 2015 is expected to be at an even greater rate due to a variety of factors. These include the increasing need for potable water access, the need to reclaim materials from industrial processes, improving global economic conditions and a rising number of research and development activities. "As a result, the total market for nanofiltration membranes is forecast to grow at a compound annual growth rate (CAGR) of 15.6% from 2014 to 2019, reaching global revenues of $445.1 million by 2019" (BCC Research, 2014).

Of the potential application areas, water and wastewater treatment represent the greatest market share, with an estimated 74.6% share of the total market in 2014. While this segment of the market is likely to be serviced by mass manufacturing of filtration products, certain industries may benefit from on-site and on-demand manufacturing of water and wastewater treatment filtration products. As discussed previously, this includes primary industries, defence, and other commercial applications in which traditional supply chain logistics may not be suitable.

Future Research Areas

- Cotton-derived feedstocks for use with electrospinning and FDM technologies
- Biodegradable cotton-derived nanofibre membranes and FDM printed structures
- Filtration performance of electrospun cotton nanofibre membranes
- Development of hybrid FDM and electrospinning technologies
- New service models and supply chains for disposable industrial parts
- Market and consumer acceptance.
- Integrating 3D printing with automated monitoring and inventory systems

6.3 Design Vision 2: Rapid Bespoke

Current Context

Consumers looking for high-end homewares and furnishings have diverse needs and wants. Practical needs may be driven by variables such as the size and style of their home, number of family members, and anthropometrics. Their wants may extend to a host of variables such as style and colour preference, type of material, softness and firmness, social habits, and many other unique personal characteristics. The purchasing experience of these customers looking to buy home furnishings is currently limited. They must either visit brick-and-mortar retail locations to inspect a limited range of furniture, or they can navigate a multitude of online retail locations for a greater range of choice. In order to cater to a broad range of customers, retailers must have showrooms for floor stock and adequate warehouse capacity to maintain standing inventory – both of which create financial risk for the retailer. Oftentimes consumers must settle with products that are close to meeting their needs, but not exactly what they want. If customers want goods customised to meet their exact desires, they are subject to high costs and long lead times associated with bespoke furniture.

Design Vision Scenario

Rapid Bespoke is the on-demand manufacture and delivery of bespoke furniture utilising cotton-derived feedstock and rapid customisation processes. This design vision is not intended to supplant current methods of furniture manufacture and retailing. Instead, it aims to expand customer choice by providing designs not possible with existing manufacturing methods. Moreover, Rapid Bespoke looks to facilitate alternative purchasing methods and provide sustainable furniture options that will become more attractive to consumers in a growing market.

It is intended that consumers will access modern retail locations, where they will use digital design tools in collaboration with design assistants to design unique furniture pieces (Figure 31). Customers can input information about their size requirements, colour and texture preferences, and even 3D scan data that contains information about anthropometrics, posture and seating preferences. Using this information, furniture can be designed to exact consumer preferences.

FIGURE 31. INTEGRATION WITH DIGITAL DESIGN TOOLS

The designed furniture item is fabricated using additive manufacturing techniques and cotton-derived materials. As cotton can be processed into diverse material types and composites, furniture items can potentially be manufactured with soft textile-like outer layers (1), cushion layers with user defined levels of softness (2), and rigid support structures (3) (Figure 32). In addition to facilitating functional material properties, additive manufacturing technologies enable unique material structures and aesthetics to be created that are not possible with traditional manufacturing. This has the potential to drive new style trends in furnishings and homewares.

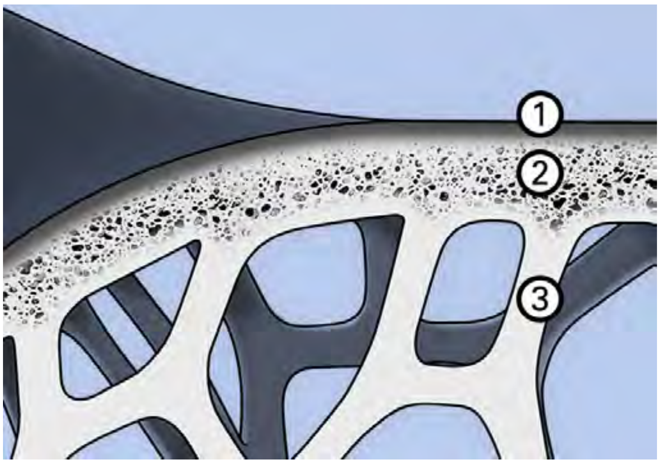


FIGURE 32. DIVERSE MATERIAL STRUCTURES

Using these methods, an extensive range of existing and entirely new homewares and furnishings can be created. Potential products include, office chairs, sofas, lampshades, cushions, beanbags, blankets, curtains, towels, and decorative items (Figure 33).

FIGURE 33. FABRICATION OF A WIDE RANGE OF CUSTOM HOMEWARES AND FURNISHINGS

Applicability of Cotton and Rapid Customisation Technologies

Cotton-derived materials are highly suited to custom homewares and furnishings fabricated using rapid customisation technologies. Cotton is already widely used in the manufacture of homewares and furnishings as it is breathable, soft, non-allergenic, derived from natural sources, and can be easily maintained by standard laundering or dry cleaning. For cotton-derived materials used in this design vision, it is desirable to maintain these properties of cotton.

An additional advantage of cotton for this design vision is that it has the potential to be processed into a diverse palette of materials, each with unique properties. For instance, cotton-derived bioplastics and composites have the potential to provide structural materials, while cotton-derived cellulose can be used to produce insulating aerogels, threads for soft textiles, and nonwoven sheet materials. Moreover, many of these materials have the potential to be formulated from sustainable sources such as waste cotton-products. The application of these materials with rapid customisation processes offers the consumer customisable, on-demand printing of their desired product. Rapid customisation allows the customer to vary the size, shape and other attributes relevant to the customer's specific needs for their domestic environment. This is something that current modes of purchase do not permit as shops need to have specific quantities of a limited range of products that may not suit everyone's needs. Moreover, the on-site manufacturing capabilities facilitated by rapid customisation processes have the potential to limit stock requirements to generic raw materials.

At present, there are a range of rapid customisation technologies that can facilitate the manufacturing of bespoke homewares and furnishings. Rapid customisation of textile products such as blankets, cushion covers, quilts and towels can be easily facilitated by current computerised weaving looms and whole garment knitting machines. Computerised knitting processes have particular potential for the manufacture of custom three-dimensional textile products. Such an application is already being explored with JS shoes (jsshoe.com). While rapid customisation could add value to these products, the greatest potential is in high-value furnishings such as chairs and sofas. There are no rapid customisation technologies dedicated to the manufacture of these items, however, current technologies have demonstrate the feasibility of printing furniture items. For structural components, large scale material extrusion processes have been used to manufacture furniture such as chairs and tables (Warnier et al., 2014). Soft deformable structures have also been created using sheet lamination style processes, where layers of soft fabric material are deposited, cut and bonded together (Peng et al., 2015). In order to fully realise the proposed design vision, however, the development of hybrid additive manufacturing processes capable of printing both structural and cushion materials is required. This may be facilitated by combining material deposition processes, and developing novel materials, such as expanded biofoams.

The feasibility of a low density cotton-derived biofoam is dependent on the feasibility of a cotton-derived bioplastic/nanocellulose reinforced bioplastic (Section 4.4.1). For a cotton-derived biofoam, low area density forms of cotton cellulose would need to be considered. Due to the novelty of this material, further work is required to establish the materials, equipment, resources and indicative cost of materials required. The main challenges to overcome surround this candidate cotton-derived material is that cotton fibre would have to be incorporated into a melt of solution (incorporating starch) of suitable viscosity. The cotton fibres themselves would remain intact and act as a reinforcing system. The main limitation with the material is likely to be cost compared to other cellulose based materials. Alternative materials that might be more suitable are starch from other sources of cellulose.

Impact

In 2013, the Asia-Pacific regions retail market for furniture and floor coverings was valued at $97.5 billion in total revenues. Between 2009 and 2013, the market experienced a compound annual growth rate of 7.9%. This market includes the sale of furniture items for bedrooms, offices, living rooms and kitchens, as well as floor coverings such as rugs, tiles, laminates and hardwoods. The most lucrative segment in this market was hard coverings, which accounted for 38.3% of total revenues. This was followed by living room furniture and bedroom furniture, which accounted for 29% and 14.3% of revenues, respectively. In the period from 2013 to 2018, the total market is expected to increase 53.9% to a forecast $150.2 billion. This growth is largely attributed to the emerging markets of China and India, which both experienced double digit growth in 2013 (MarketLine, 2014).

The characteristics of this market are favourable for new and differentiated entrants. According to MarketLine analysts (2014), “a focus on material quality and design increases the power of manufacturers”. Additionally, brand power is considered to be relatively unimportant to end-consumers. This makes it difficult for existing brands to dominate the market which means that there is greater opportunity for new entrants to the market. As stated, this particular vision is not intended to supersede existing modes of purchasing these types of products. Instead the idea is intended to augment the existing market and provide consumers with a unique, attractive and distinctive mode of purchasing homewares and furnishing products with advantages that existing methods do not permit.

Future Research Areas

- Market and consumer acceptance of rapid customisation
- Market potential of generative furniture design and manufacture
- 3D printing machine capable of printing variable cushion materials in one print
- 3D printing machine with various colours and patterns in one print
- Printing speed and accuracy of soft materials
- Online interface for consumers to design own products

6.4 Design Vision 3: Senseable Style

Current Context

An area of development in the lifestyle fashion industry is performance sportswear and activewear. Innovation in this space has typically been driven by new fashion trends and added functionality provided by performance textiles. Recently, new spaces within the lifestyle and activewear market have been developing with the introduction of “smart” fabrics and wearable technology (Grand View Research, 2014). In terms of textile products, the majority of ‘smart’ garments and wearables has focused on sport and fitness applications. There currently exists a plethora of wearables that are equipped with sensors to capture biometric and biomechanic data such as heart rate, muscle activation, breathing rate, workout intensity, and range of movement. This data allows the wearer to monitor their activity to track progress and enhance performance (Charara, 2015; Kosir, 2015). In addition to sport and fitness applications, wearable devices for lifestyle applications have increased in popularity. MisFit fitness trackers (misfit.com) are positioned primarily as a lifestyle product rather than a fitness product. This is strongly reflected in the aesthetic styling and marketing of the products. Other notable lifestyle wearables include the Apple Watch (apple.com/watch), and a vast number of other smart watches that use the Android Wear operating system. These products are often positioned as fashion items with functionality to make life easier, rather than enhance performance. Despite the backing of massive media campaigns, many lifestyle wearables have failed to gain traction in the market, and are criticised for being overly complex and lacking a focused application (Bohn, 2016).

Design Vision Scenario

'Senseable style' is a range of intelligent fashion garments and accessories that utilise cotton-derived material, smart sensing material and rapid customisation technologies. As lifestyle products, they will provide a variety of different functionality to users that are applicable to everyday environmental and personal health monitoring. It is important that this functionality is unobtrusive to a person's lifestyle, but provides valuable information and assistance in common circumstances. For the purpose of outlining this design vision, the specific garment functionality presented is air-quality monitoring.

Air quality is a major concern in both developing and developed nations. The population of developing nations is at greatest risk, with more than 3.2 million people suffering premature deaths in 2010 from air pollution. While not faced with the same level of risk, residents in developed nations also need to be vigilant in protecting against air pollution. Recent studies show evidence that there is no safe level of air pollution, and that health problems in the population rise in line with increases in average pollution levels. A European study has found that long-term exposure to particulate air pollution boosts the risk of lung cancer, and heart failure, even at concentrations below the legal maximum.

The Senseable Style design vision facilitates the custom design and manufacture of garments to assist in this scenario. Using personal 3D scan data and web-based design tools, users can design fashionable garments (Figure 34). Garments can be customised in terms of type, colour, shape, size, style and detailing.

FIGURE 34. CUSTOMISATION THROUGH WEB-BASED DIGITAL DESIGN TOOLS

In addition to custom styling, users are able to incorporate active materials and nanobiosensors that provide the garment with added functionality. Embedded in the material structure (Figure 35), these active materials are selected based on the garment functionality a user desires.

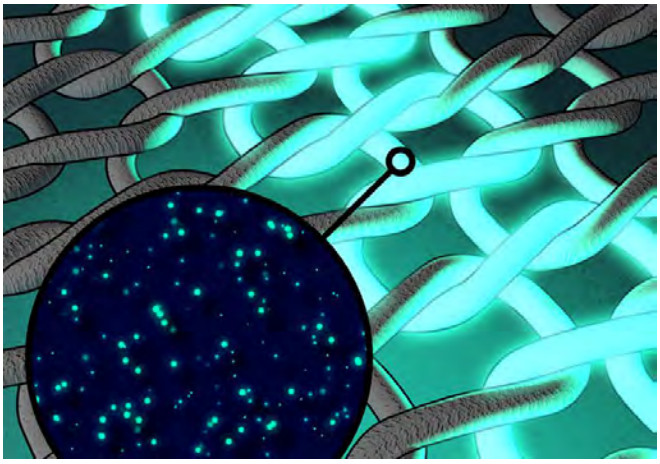


FIGURE 35. ACTIVE MATERIALS EMBEDDED INTO MATERIAL STRUCTURE

For the proposed scenario of air quality monitoring, active materials in the garments structure react to contaminants and pollutants in the atmosphere (Figure 36). Where there is negligible risk to the user, the garment remains static (left). In cases where harmful pollution levels increase, the active material in the garment reacts and illuminates (right). The concentrations and arrangement of active materials can be controlled by the user to suit their preferences. For example, different active materials may be restricted to certain locations so that they form patterns and features on the garment as they react to different stimuli. This type of functionality can be applied to any type of fashion garment, including scarves, jackets, hoodies, sweaters, pants and masks.

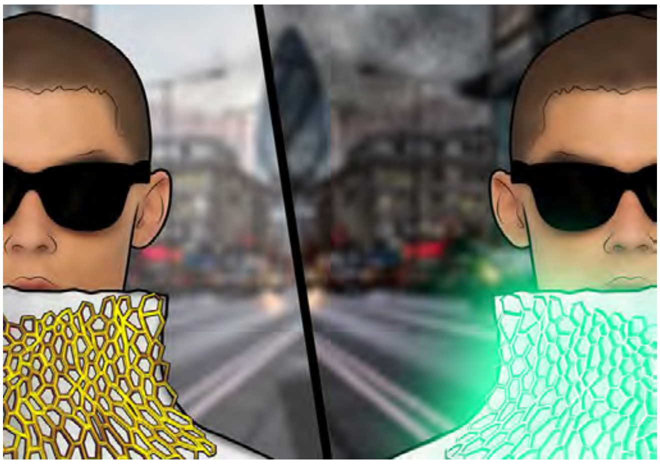


FIGURE 36. INACTIVE WHEN HARMFUL AIR POLLUTION IS NOT DETECTED (LEFT), ACTIVATED WHEN HARMFUL AIR POLLUTION IS DETECTED (RIGHT)

Applicability of Cotton and Rapid Customisation Technologies

Cotton-derived materials are widely used in fashion apparel and accessories. For close to the skin applications, cotton is highly suited as it is breathable, non-allergenic, and comfortable. For Senseable Style, the potential of cotton material is its ability to be dissolved and regenerated as a variety of different materials. In order to provide functionality to garments, active materials, such as quantum dots and nanobiosensors, may be integrated into dissolved cotton solution. Biosensors are analytic devices that are modified to detect and react to specific agents, such as electricity, skin conductance, moisture, pH, chemicals, and many others (Edwards et al., 2013). The addition of active material to regenerated cellulose is technically feasible. Through different processing techniques, the cotton solution containing such active material is able to be regenerated into a variety of material types, including rayon, transparent films, and aerogels. The key challenges of developing this material include identifying and incorporating the biosensor and sensor, and determining if it is to be combined with the cotton or incorporated into the structure. Thermoplastic techniques and knowledge could be directly applied for cotton in this area.

These cotton-derived materials integrated with active materials are proposed to be used with computerised complete garment knitting systems. Development of these systems have investigated the use of 3D scanning to facilitate rapid customisation and on-demand manufacture of garments (Peterson et al., 2011; Power, 2015). Such capabilities, combined with regenerated cotton thread with integrated active material, may allow for the development of garments with user-determined placement of active material containing threats to form unique user defined patterns and styles. This process has the potential to be further enhanced with the use of integral knitting to allow for the addition of features that may be required to fabricate the sensor system in the 'smart' garments. To function correctly, the signal produced by biosensors must be transmitted to a transducer that converts the signal to be passed onto the reader device. These additional components could be fabricated into the garment using integral knitting.

Impact

The global market for smart textiles was USD$350.3 million in 2013, and is expected to have strong growth over the period from 2012 to 2020, reaching over USD$500 million. Key drivers in this market are expected to be the decreasing cost and miniaturisation of electronic components, and the rising popularity of sophisticated gadgets. End-use applications of smart textiles with greatest potential are in sectors such as defence, automotive, medical, fashion, sports and fitness, architecture and entertainment. Of these, military accounted for 25% of revenue in 2013. The capabilities presented in the Senseable Style design vision have the potential to adapt to these alternative market segments. Functionality identified to have strong potential in these sectors include the ability to react to stimuli from electrical, thermal, chemical, mechanical and magnetic sources (Grand View Research, 2014).

Future Research Areas

- Regenerating cotton with biosensors and other active materials
- Consumer acceptance of wearable technology for lifestyle applications
- Smart materials
- Rapid customisation processes for the fashion retail market
- Customisation interfaces for intelligent garments

6.5 Design Vision 4: My Toy Lab

Current Context

3D printing for children has gained interest recently, with a number of manufacturers entering the children's toy market with simple form deposition technologies capable of printing solid objects (Bhatia, 2015; Bogue, 2013; Lipson & Kurman, 2013). The most recent entrant to this market is Mattel, with the release of their Thingmaker 3D printer. One of the greatest barriers for 3D printers entering the mainstream has been the complexity of the equipment, knowledge required of software, and file set-up and print settings. Thingmaker addresses many of these concerns through a partnership with Autodesk. They provide an app that takes care of many of the complexities associated with 3D printing. Children and their parents are able to work from existing templates or build their own creations through a simple drag-and-drop style app (Barrett, 2016). In addition to this, there are a number of online object repositories, such as Thingiverse, that allow for a huge diversity of designs to be downloaded and printed for free (Warnier et al., 2014).

While the decreasing cost of 3D printing technology, availability of easy to use design tools and expansive object repositories have increased the value of desktop 3D printers, they are still limited in the material choices available. Most 3D printers aimed at the general consumer are capable of only printing solid objects using thermoplastic materials. Although 3D printed textiles are in development (Robinson, 2014), they require specialised technologies in order to achieve the mechanical and strength properties of current soft fabrics (Melnikova, Ehrmann, & Finsterbusch, 2014). The opportunity to providing a 3D printing of both hard and soft materials has the potential to disrupt the toy industry and offer children and their parents entirely new opportunities.

Design Vision Scenario

My Toy Lab is a children's 3D printing system that is capable of printing soft objects from novel cotton-derived feedstocks. The first element of this design vision is the provision of a system that enables access to and design of soft objects (Figure 37). Taking cues from current services, this system would include a number of avenues to make objects available to users. This includes and online repository of objects that users share with each other, as well as specially designed software that allows users to create their own design from scratch or from templates. In addition to these services, this design vision has the potential to develop new retail service models for current toy manufacturers. For example, it would be possible for manufacturers to offer licenced products on a pay-per-print sales model.

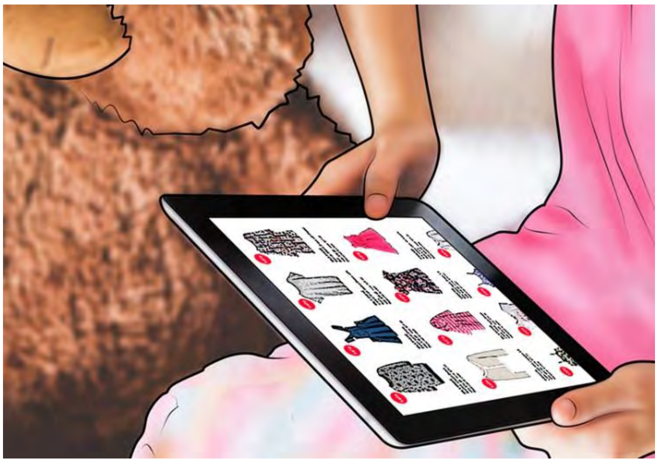


FIGURE 37. OBJECTS CREATED FROM ONLINE REPOSITORIES AND EASY TO USE DESIGN TOOLS

Upon obtaining a desired object, children can then send the object directly to their My Toy Lab 3D printer and watch it come to life (Figure 38). With the provision of novel cotton-derived feedstocks, material treatments and 3D printing processes, children will be able to print hard and soft objects simultaneously.

FIGURE 38.PRINT HARD AND SOFT TOYS

The ability to print objects with soft surface finishes and drape qualities is envisaged to provide new possibilities for toy creation. Potential objects include clothes for dolls (Figure 39) and figurines, plush toys, teddy bears, doll house furnishings and dress-up accessories. This has the potential to widen the scope of 3D printing beyond traditional solid plastic objects.

FIGURE 39. NEW POSSIBILITIES FOR 3D PRINTED TOYS

Applicability of Cotton and Rapid Customisation Technologies

Cotton is used extensively in children's soft-goods, such as plush novelties, dolls clothes, and teddy bears. Cotton is ideally suited to these applications as it is inexpensive, easy to source, non-toxic, non-allergenic, biodegradable, and easy to care for (Barnett, 2014; Cotton Incorporated, 2016). Cotton is a compelling material for use with rapid customisation technologies and has the potential to provide numerous benefits to users. Rapid customisation of toys and entertainment goods for children may be transformative to the process and distribution of goods to users. It can facilitate greater flexibility of products and designs available to children, as well as allow users to build custom creations. The use of cotton-derived material in this process has the potential to facilitate the fabrication of biodegradabe toys, which will help address the ecological impact of current toys fabricated with non-biodegradable plastics.

The greatest challenge for this design vision is developing materials that provide tactile properties comparable to traditional cotton products and soft toys, while also interfacing with existing or new rapid customisation technologies. An ideal 3D printing machine in this space would combine soft textile fabrication with existing plastic printing, thereby creating greater variability in what can be manufactured. Some research has explored this to some extent, by investigating 3D printing of polymers onto textiles (Eujin Pei, Jinsong Shen, & Jennifer Watling, 2015; Richter, Schmuelling, Ehrmann, & Finsterbusch, 2016). However, this research does not directly investigate 3D printing of soft-textile structures. For this purpose, there are three candidate processes that may be applicable.

First, is a process similar to sheet lamination technologies developed by Disney Research. Instead of paper or thermoplastic sheets, this process uses sheets of felt material that are laid down, cut and then bonded together. Layers are built up to form a deformable object. As well as creating soft toys, these objects can incorporate electronics to provide additional functionality. The main limitation of this technique, however, is the poor object resolution and rough surface finish (Peng et al., 2015).

Second, electrospinning is capable of producing soft textile-like structures from cotton-derived material. This technology is limited in that it is predominantly used to create thin sheet material, rather than 3D volumes. However, electrospinning could be combined with a diversity of templates to create garments for children and toys. This capability has been demonstrated by the Electroloom which is able to fabricate a variety of custom fashion items (Foley, Rowley, & White, 2015). It may also be possible to combine electrospinning with other 3D printing processes for the purpose of fabricating 3D objects with cotton exteriors.

Third, composite materials compatible with FDM technology have been developed that can be transformed into soft and flexible structures. These materials are comprised of a mix of soluble and insoluble materials. When soaked in water, the soluble materials dissolve, subsequently leaving the insoluble materials with cavities where the soluble material was. This results in a flexible material with a felt-like texture (Melnikova, et al., 2014). Cotton-derived composite materials could be developed with similar structure and functionality to facilitate hard and soft object printing.

Impact

The retail market for toys and games in the Asia-Pacific region was valued at 28.2 billion in 2014. This market is forecast to grow 34.5% to reach a value of $37.9 billion in 2019. The growth in this market is attributed to the expansion of toy industries and increasing disposable income in China and India. The largest segment of this market is activity toys (21.9%), followed by infant toys (16.9%), dolls (15.1%), games and puzzles (14.2%), plush toys (12.8%), and sports (12.1%) (MarketLine, 2015). The development of 3D printers compatible with novel feedstocks for printing flexible and solid objects has the potential to derive value from each of these segments. An area of particular opportunity for My Toy Lab, is in facilitating new supply chains and retail models. According to MarketLine (MarketLine, 2015), licenced brands (e.g., Star Wars, Transformers, and Marvel) create particularly strong consumer demand. New online retail models that give consumers access to on-demand 3D printable toys and games from major brands is a potential area of development.

Future Research Areas

- Flexible, soft-feel cotton-derived materials for 3D printing
- 3D printing of complex 3D textile structures
- Hybrid 3D printing technology for printing cotton exteriors onto 3D structures
- Consumer acceptance of children's 3D printing
- Usability of 3D design software for children
- Retail sales models for online 3D printing platforms

6.6 Design Vision 5: Regenerative Skin

Current Context

Dressings are required for a range of wound types including, burns, lacerations and incisions. Depending on the type and severity of the wound, dressings may contain a range of additives such as healing agents, hydrogels, silver films, antimicrobials, and splinting (Landriscina, Rosen, & Friedman, 2015; Watson & Dabell, 2006). For severe wounds, consistent monitoring and specialised treatment is required. For example, wounds over joints that are not appropriately splinted and ranged will develop contactures (Procter, 2010).

Though current methods of wound treatment are employed successfully, an area of research and development is smart bandages. Smart bandages provide the existing functionality of bandages for wound treatment, with added functionality for enhanced healing and monitoring of wounds. This is still an emerging area of research, however, the manufacture of wound dressings using additive manufacture have been successfully demonstrated (McLister et al., 2014; Moein & Menon, 2014; Mostafalu et al., 2015; Phair et al., 2013; Whelan, 2002). For example, polyjet technology has been used to print bandages that contain sensors to monitor oxygen (Mostafalu et al., 2015). Researchers have reported success with techniques such as carbon meshing and auxetic fibres to enhance mobility, as well as active drug delivery agents in bandages (Phair et al., 2013, 2013; Ravirala, Alderson, Alderson, & Davies, 2005; Whelan, 2002). A critical area of innovation moving forward is providing diagnostics of the biomolecular structure of wounds, a functionality that few bandages are capable of at present (McLister et al., 2014).

Design Vision Scenario

Regenerative Skin proposes the use of cotton-derived materials with rapid customisation technologies to fabricate smart bandages that are customisable to a specific user and wound type. Patient and wound data is obtained from 3D scanning technology and wound diagnostic technology (Figure 40). 3D scanning data allows the wound dressing to be fabricated to fit the contours of the patient's body and be tailored to the wound topology. The incorporation of wound diagnostic technology may enable additional data to be gained about variables including wound depth and severity, the presence of any contaminants, and likelihood of infection.

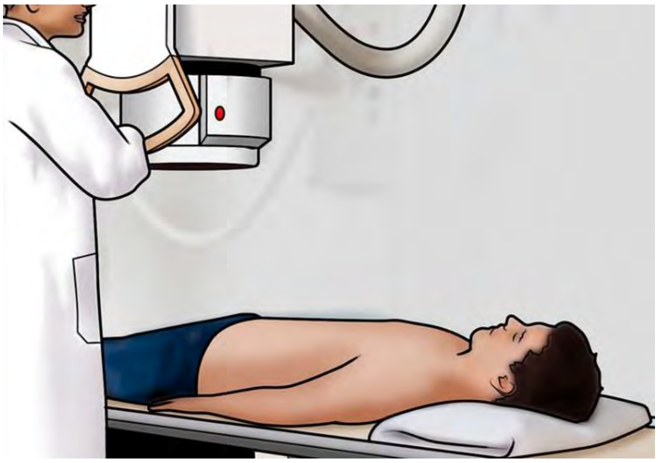


FIGURE 40. WOUND DATA COLLECTED BY 3D SCANNING AND WOUND DIAGNOSTIC TECHNOLOGY

Each component and layer of the wound dressing can be tailored to the patient based on the data collected (Figure 41). For example, wound dressings can be tailored in terms of the moisture, absorption and porosity at the point of skin contact (3); Structure may be required to restrict or allow certain movement (2); and, various barrier layers may be required to protect from contaminants or enhance breathability (1).

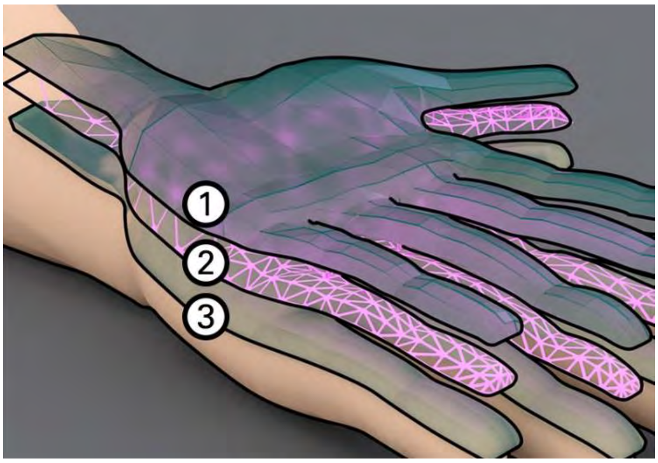


FIGURE 41. CUSTOM WOUND DRESSING STRUCTURE: BARRIER LAYER (1), STRUCTURAL LAYER (2), AND ABSORPTION/MOISTURE LAYER (3)

Incorporation of nanobiosensors and pharmaceuticals to the wound dressings offers the potential for additional functionality (Figure 42). Nanobiosensors can be used to detect infection or inform a patient when a dressing needs to be changed. The addition of pharmaceutical agents has numerous applications, such as including healing agents to speed up recovery, antibiotics to protect against infection, and pain-management medication to enhance patient comfort.

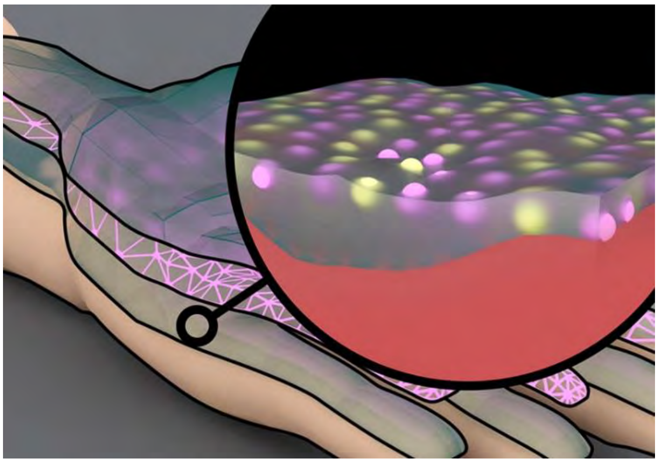


FIGURE 42. INTEGRATION OF DRUG DELIVERY AND BIOSENSORS TO ENHANCE WOUND MONITORING AND HEALING

Applicability of Cotton and Rapid Customisation Technologies

Cotton-derived materials are well suited to biomedical applications due to their biocompatibility. Of particular potential is the use of cotton-derived nanocellulose as it is compatible with a number of rapid customisation technologies already in use for high performance applications. For instance, nanocellulose membranes can be produced using electrospinning technology. Nanofibre membranes produced using electrospinning have a number of potential biomedical applications due to their strength, low cost, compatibility with elastic gels, and biosresponsive characteristics (Rees et al., 2014). Another valuable cotton-derived material for this design vision is nanocellulose hydrogels, which have enormous potential for use in drug delivery systems and tissue engineering (Chang & Zhang, 2011). This potential is predominantly driven by their biocompatibility, as well as their ability to be incorporated with functional agents that can be made responsive to specific stimuli, such as changes in skin pH. For wound dressings, nanocellulose materials are ideal as they can provide a moist wound healing environment (Rees et al., 2014). Moreover, hydrogels can be processed into highly porous and absorbent aerogels (Moon et al., 2011). Used in conjunction with one another, these hydrogel and electrospun membrane materials are well suited to the fabrication of smart bandages.

The applicability of rapid customisation technologies for this design vision is demonstrated by the current interest in rapid customisation technologies for biomedical applications (McLister et al., 2014; Moein & Menon, 2014; Mostafalu et al., 2015; Phair et al., 2013; Whelan, 2002). As discussed in the previous paragraph, electrospinning technology provides one potential technology for the fabrication of nanofibre web materials to be used in smart bandages. In combination with this, robocasting technology offers the greatest potential for the fabrication of hydrogel matrices for the Regenerative Skin design vision. This potential is driven by the capability of printing hydrogels using robocasting assemblies (Lewis, 2006). Similar capabilities have been described with bioplotting, a hybrid material extrusion technology which works by depositing gels, polymer melts and fluids through a nozzle, creating complex shapes via 'bioink' feedstock (Do et al., 2015; Rees et al., 2014).

Impact

The potential areas of impact for Regenerative Skin has potential impact in the advanced drug delivery market. This market includes "technologies used to present a drug for release and absorption to a desired body site" (BCC Research, 2016). According to BCC Research, the value of this market in 2015 was approximately $178.8 billion. This value is expected to increase to nearly $227.3 billion in 2020, a compound annual growth rate of 4.9%. The market is segmented into advanced immediate drug release and modified drug release. "Modified drug release is further categorised as targeted, extended, delayed and pulsatile release. Of these, targeted- and controlled-release dominate the market" with 36% and 25%, respectively. As a transdermal method of wound treatment and drug delivery, Regenerative Skin is situated in the modified drug release segment and has the potential to impact both categories of targeted- and controlled-release.

In addition to transdermal wound treatment, Regenerative Skin has the potential to expand to other treatment categories due to the biocompatible nature of cotton-derived materials. The most easily achieved of these is the fabrication of implantable drug delivery systems. These have been created using drug integrated hydrogel matrices capable of controlled release drug administration (Hamidi et al., 2008). A further area of expansion is soft-tissue scaffolding. This would involve iterating on the Regenerative Skin vision to incorporate hydrogel matrices and living cells to encourage tissue regeneration. Additive manufacturing has already had a strong impact in tissue scaffolding with a variety of custom-tailored structures successfully implemented in biomedicine (Giannitelli, Mozetic, Trombetta, & Rainer, 2015).

Future Research Areas

- Nanocellulose hydrogel wound dressings
- Electrospinning and nanocellulose fibres for wound dressings
- Integration of nanocellulose hydrogels with nanobiosensors
- 3D printing of bandages with custom compression and structural functionality
- Utilisation of 3D scan data for the design of 3D printed wound dressings
- Nanocellulose hydrogel tissue scaffolds
- Nanocellulose biocompatibility

6.7 SUMMARY

The five design visions detailed in this section represent the main findings of this study, showcasing the diverse potential of cotton-derived feedstocks utilised in rapid customisation processes. Each design vision is summarised in Table 6.

TABLE 6. SUMMARY OF DESIGN VISIONS

	Description	Candidate Materials	Candidate Technology
1. On-Site Fabrication	Rapid of industrial filtration devices and other disposable industrial products for remote industries	Cotton polymer solution; Cotton-derived bioplastics and composites	Fused deposition modelling; Robocasting
2. Rapid Bespoke	Rapid manufacture of homewares and soft furnishings using rapid customization technologies	Cotton-derived bioplastics and composites; Cotton sheet material;	Robocasting; Fused deposition modelling; Sheet lamination
3. Senseable Style	Rapid customization and fabrication of intelligent garments using cotton-derived material with embedded active material	Regenerated cotton thread; Cellulose aerogels	Computerised knitting; Robocasting
4. My Toy Lab	Rapid customization and manufacture of cotton-feel soft toys	Cotton-derived bioplastics; Cotton-derived sheet material	Fused deposition modelling; Sheet lamination
5. Regenerative Skin	Rapid customization and manufacture of cotton-based smart bandages	Cellulose-derived hydrogels; Cotton polymer solution	Robocasting; Electrospinning

While the design visions have been represented for specific contexts and applications, each offers strong potential to be transferred to other contexts and address alternative market segments. Identification of this capability is indicative of the diverse application potential of rapid customisation technologies utilising cotton-derived feedstock, and the potential impact that the resulting end-use may have

Looking beyond the scope of this study, an important outcome of the design visions is not only to provide an indicative assessment of the potential impact of cotton rapid customisation, but also to provide directions for future research and development. With this in mind, design visions were developed to provide diverse applications with potential impact over both the short-term and long-term, and provide rich opportunities for future research. These opportunities are summarised in Figure 43 on the following page.

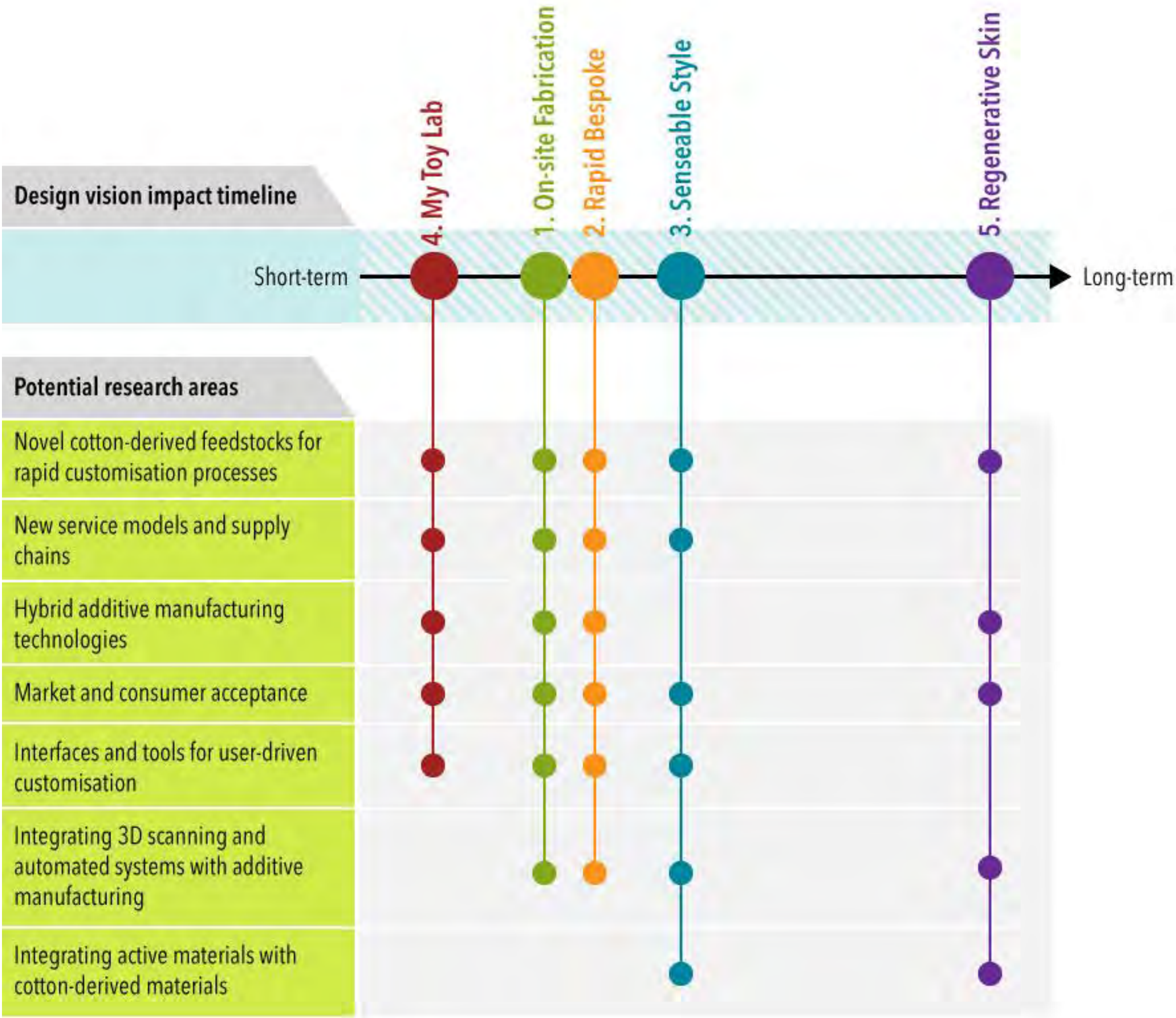


FIGURE 43. SUMMARY OF DESIGN VISION IMPACT AND POTENTIAL RESEARCH AREAS

7

CONCLUSION

This report forms a vital first step in outlining specific rapid customisation technologies as potential market opportunity for the Australian cotton industry. It aimed to establish the technical and economic feasibility of cotton-derived feedstock in rapid customisation processes; specifically identifying application areas where cotton has a clear advantage over other synthetic and non-synthetic materials due to its inherent material qualities and characteristics.

The report surveyed in detail two key areas. The first relates to cotton materials and processing technologies including a survey of the most common techniques as well as three key future trends relevant for rapid customisation processes. The second relates to a detailed survey of additive manufacturing technologies in order to evaluate their potential for use with cotton-derived feedstocks. Relevant future trends in this area were also identified. Following from this a technical feasibility evaluating the surveyed additive manufacturing technologies is outlined, resulting in the five most promising rapid customisation technologies identified.

Building on the technical feasibility assessment the most promising potential application areas for cotton rapid customisation were identified. Twenty-seven application ideas were outlined from five broad application areas including lifestyle, health, industrial, architecture and design, and automotive and aerospace. Further development of these application ideas informed design visions for cotton rapid customisation.

The five design visions proposed encapsulate the results of the overall analysis conducted through the study. Design visions are presented as product and system concepts that emphasise the versatility of cotton-derived materials and their potential impact as rapid customisation applications. Although focused on specific application contexts, the diversification of these design visions to other applications and markets is emphasised. This is facilitated by an outline of the design visions broader impact and potential areas for future research.

The report has identified significant opportunities for cotton-derived rapid customisation that would significantly impact the Australian cotton industry. It has identified this through a detailed and thorough feasibility of cotton material and processing technologies in combination with relevant rapid customisation technologies and its application to potential market areas. For the cotton industry to capitalise on these opportunities, further investment into specific research areas relating to the proposed design visions needs to be made. With appropriate research projects underway, the Australian cotton industry has the potential to become a world-leader in cotton-derived rapid customisation technologies; thus guaranteeing its future competitiveness in this growing market potential.

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ON-SITE FABRICATION

MARKET:
Global nanofiltration market forcecast revenues of $445.1 million by 2019.

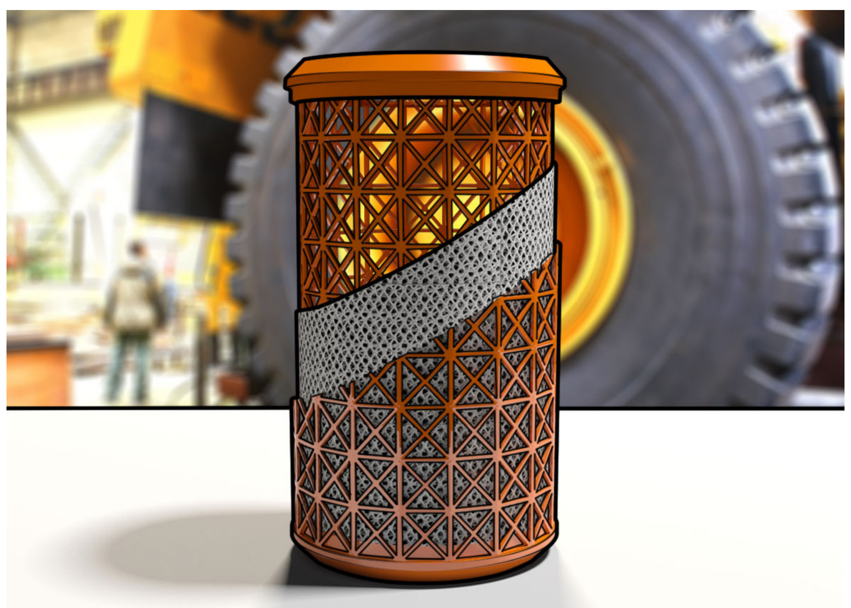
PROCESSES/MATERIALS:
Electrospinning/nanofibre meshes, fused deposition modelling/bioplastics.

FUTURE RESEARCH:
Hybrid rapid customisation technologies, new supply chains and service models, market and consumer acceptance, integrating additive manufacturing with automated systems.

Cotton is a common material in many filtration, absorption, and barrier products used in the industrial sector. In primary industries, such as mining, these product categories are required to ensure the effective maintenance of plant and equipment, and the safety of workers. While these products are generally inexpensive, the variety required, the need for transportation and storage, their short lifespan, and the potentially large costs to firms due to stoppages, presents a compelling opportunity for rapid customisation.

On-Site Fabrication combines electrospinning and fused deposition modelling (FDM) technologies for the rapid customisation of disposable industrial products. Electrospun nanofibre membranes have demonstrated superior qualities to traditional nonwoven products and are considered a driver for the next generation of performance nonwovens. By combining electrospun nanofibres with FDM-produced structural components, such as housings and mounting brackets, a range of functional products for use in the industrial sector can be achieved.

ON-DEMAND: Print pre-existing and custom equipment parts on-demand from a catalogue or schedule recurring part printing.



CUSTOMISATION: Precise control over part layers to customise products for specific machinery, job type and unique environmental conditions.

DIVERSIFY: Other disposable industrial products include chemical filtration, personal air filtration, cleaning products and protective equipment.

QUT Queensland University of Technology
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Cotton Rapid Customisation Feasibility Study

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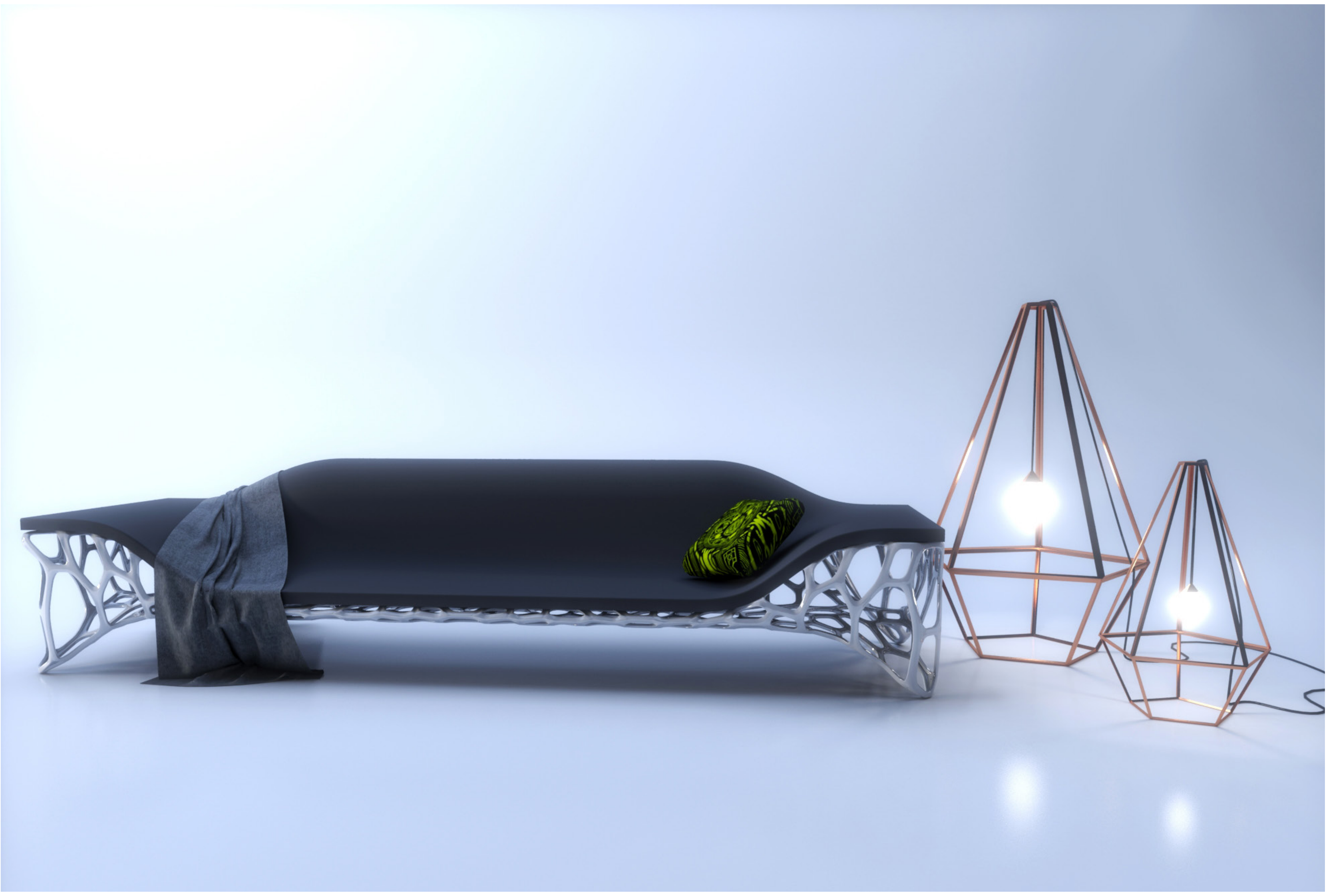


RAPID BESPOKE

MARKET:
Asia-Pacific furniture retail market forecast revenues of $150.2 billion by 2018.

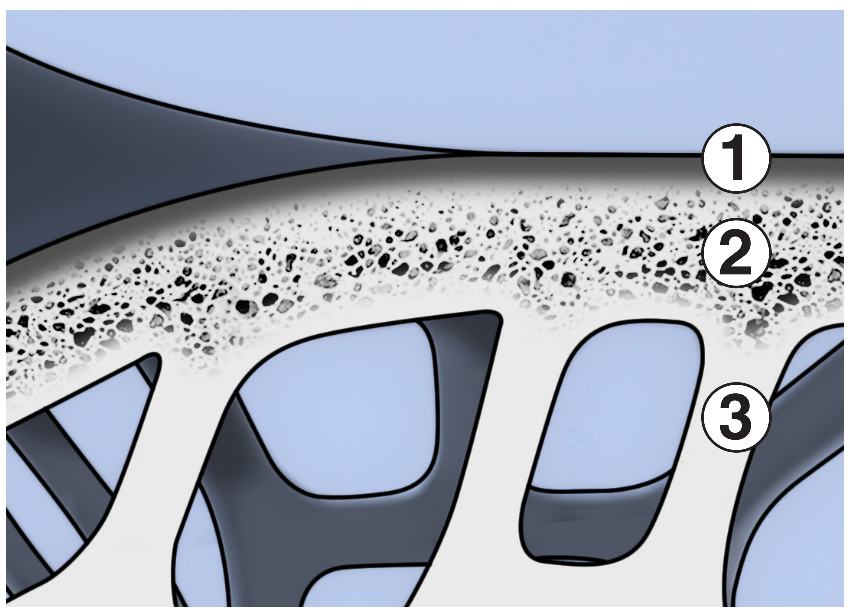
PROCESSES/MATERIALS:
Robocasting/biofoams, fused deposition modelling/ bioplastics, sheet lamination/cotton sheet material.

FUTURE RESEARCH:
Hybrid rapid customisation technologies, new supply chains and service models, market and consumer acceptance, design interfaces, novel cotton materials.

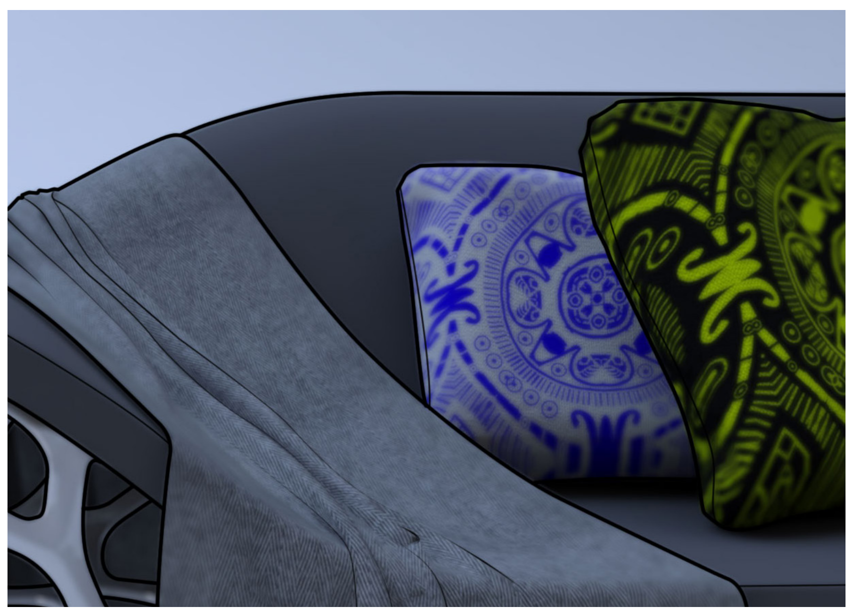
Homewares and furniture retailers must meet a variety of consumer needs such as diverse tastes, material preferences and size requirements. To cater for these needs, retailers must have large showrooms for floor-stock and adequate warehouse capacity to maintain standing inventory - all of which create financial risk for the retailer. If customers desire unique or custom goods, they are often subject to high prices and long lead times.

Cotton is already used extensively in home furnishings and decorations. Consequently, it offers a familiar and versatile material for the manufacture of bespoke furnishings using rapid customisation technologies. Rapid customisation in this context is not intended to supplant existing retail models, but rather enhance them through offering customers greater product choice and purchasing methods. Customers are empowered to tailor their products to their unique tastes, while retailers can be more competitive as a result of an efficient supply chain.

CUSTOMISATION: Digital design tools allow customers to customise the shape, size, colour and texture of homewares and soft furnishings.



MATERIALS: Cotton-derived barrier layers (1), expanded biofoams (2) and bioplastics (3) can be combined to create a range of soft and durable products.



VERSATILITY: The range of 3D printed cotton furnishings can extend to blankets, curtains, cushions, rugs, sofas, chairs and towels.

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Cotton Rapid Customisation Feasibility Study

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SENSEABLE STYLE

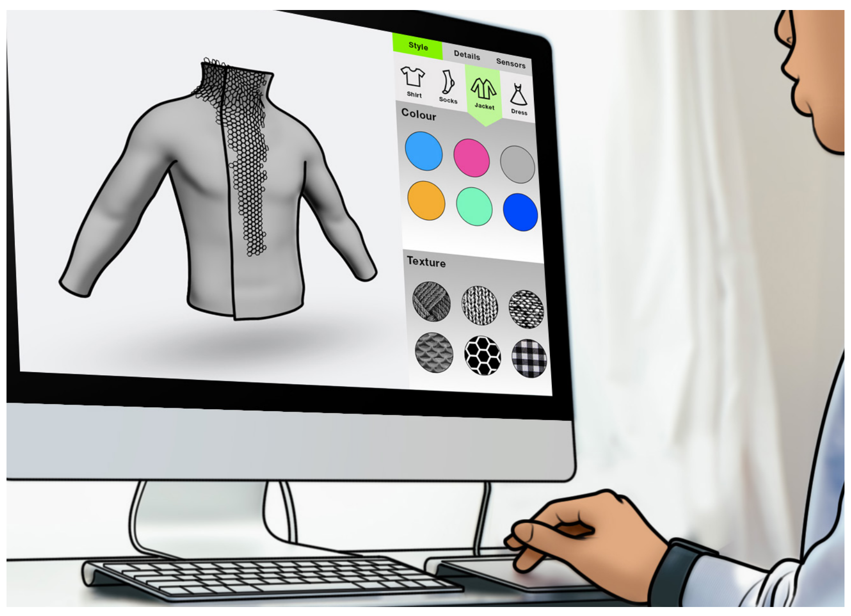
MARKET:
Global smart textiles market forecast revenues of over $500 million by 2020.

PROCESSES/MATERIALS:
Computer controlled knitting/regenerated cellulose thread with active material.

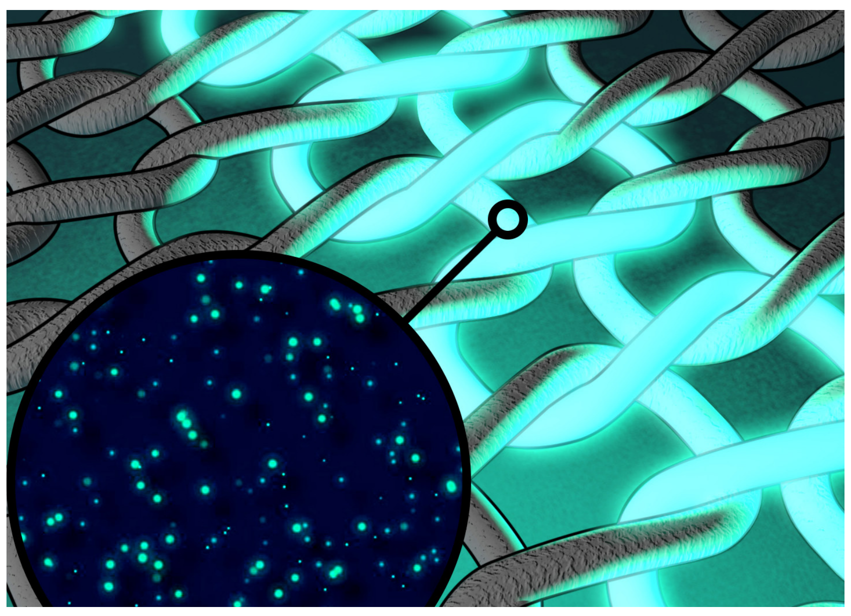
FUTURE RESEARCH:
Hybrid rapid customisation technologies, new supply chains and service models, market and consumer acceptance, design interfaces, smart materials.

Performance active wear and wearables is an area of growth in the fashion industry. Driving innovation in this space is the development of 'smart' materials with sensing capabilities. This technology is used in a number of recently commercialised products that are able to collect extensive data about a person's activities. As this technology develops it presents an opportunity for the development of lifestyle garments and accessories with novel functionality.

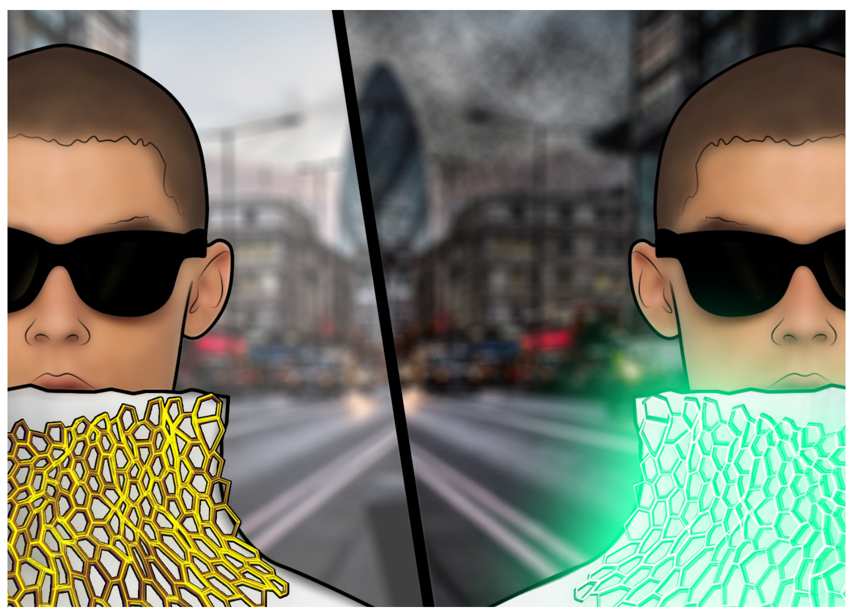
Senseable Style proposes next generation lifestyle garments and accessories that utilise cotton-derived material, smart sensing material and rapid customisation. By incorporating these elements, custom garments can be created that provide functionality for everyday environmental and personal health monitoring. Style and functionality can be determined by the user, resulting in garments that are unobtrusive to a person's lifestyle, and provide information and assistance in common circumstances.



CUSTOMISATION: Combining 3D scan data and digital design tools, customers can customise the style, colour, texture and details of their garments.



SMART MATERIALS: Regenerated cotton material with embedded smart materials enable garments to sense and react to the surrounding environment.



FUNCTIONALITY: Rapid customisation allows for the manufacture of garments with user defined functionality, e.g., sensing air contaminants and health monitoring.

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MY TOY LAB

MARKET:
Asia-Pacific toys and games retail market forecast revenues of $37.9 billion by 2019.

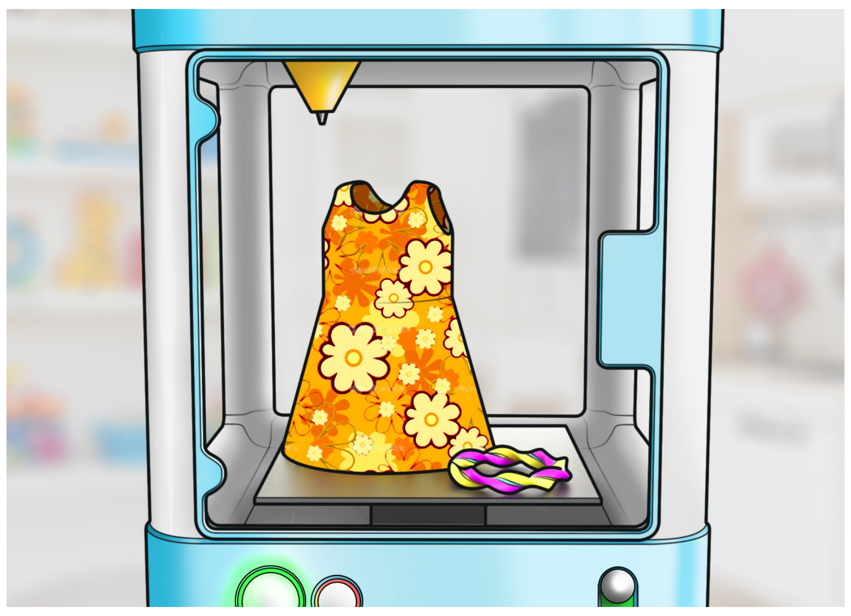
PROCESSES/MATERIALS:
Fused deposition modelling/bioplastics, sheet lamination/ cotton sheet material, novel treatment or process for soft-feel material.

FUTURE RESEARCH:
Hybrid rapid customisation technologies, new supply chains and service models, market and consumer acceptance, design interfaces, soft-feel materials.

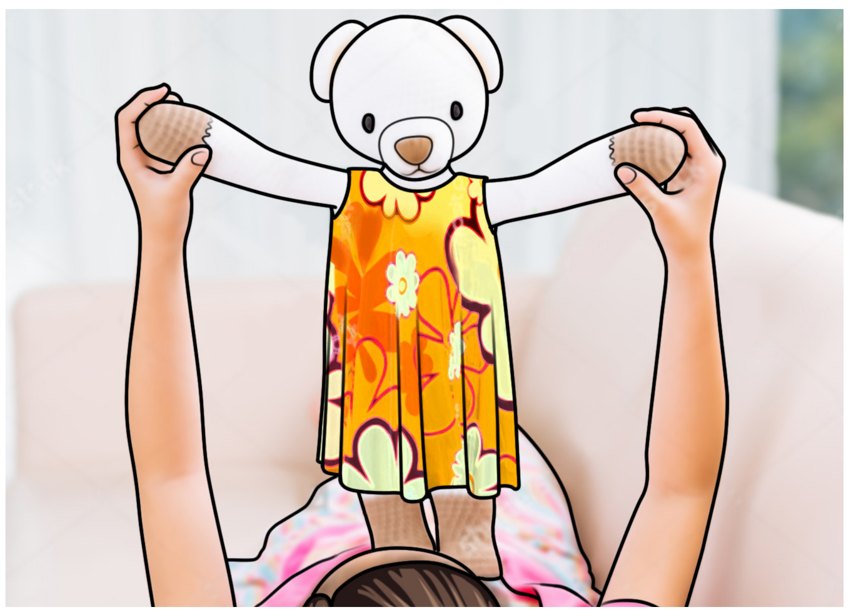
3D printing for children has received increased interest recently with a number of manufacturers releasing simple and safe 3D printers marketed at children. The ability to print children's toys on demand and engage children in the process of designing their own toys is an attractive idea and has the potential to disrupt the toy industry.

One of the biggest concerns in this context is providing materials that have flexible uses and are safe for children. Cotton is an attractive material for this purpose as it is non-toxic and can be processed into a number of forms. Through different processing and treatment methods, cotton offers the ability to produce both hard and soft toys. This presents a significant advantage over many other materials and gives children great freedom to bring their imaginations to life. Moreover, cotton is a renewable and biodegradable resource. This presents the opportunity to create toys that are less harmful to the environment than those made from non-renewable and non-biodegradable polymers.

DIVERSITY: Kids can browse catalogues of user-created and licensed toys, or they can design their own using easy to use software.



KID SAFE: Cotton-derived materials combined with 3D printing enable children to print custom toys that are non-toxic and biodegradable.



SOFT FEEL: Objects with soft surface finishes and drape qualities provide new possibilities for toy creation in the home.

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REGENERATIVE SKIN

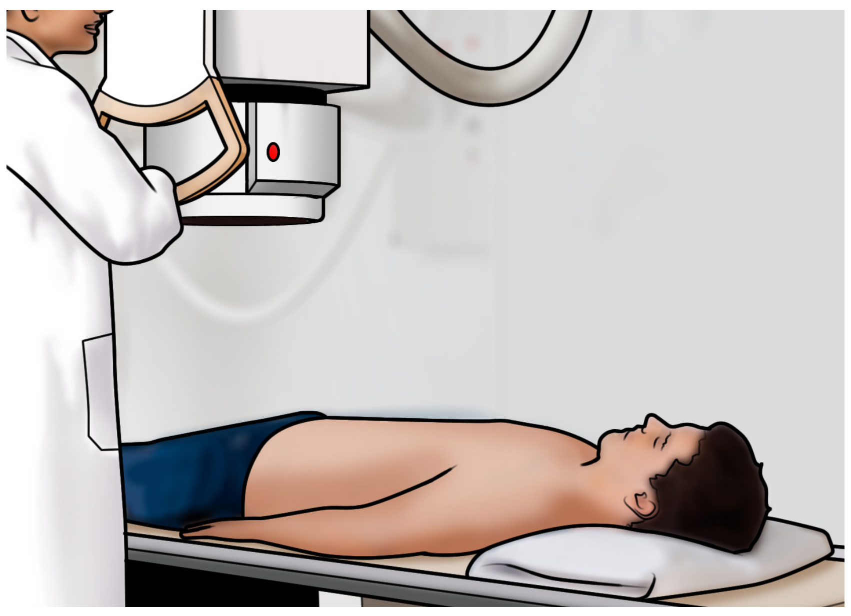
MARKET:
Global advanced drug delivery market forecast revenues of $227.3 billion in 2020.

PROCESSES/MATERIALS:
Electrospinning/nanofibre meshes, robocasting/hydrogels.

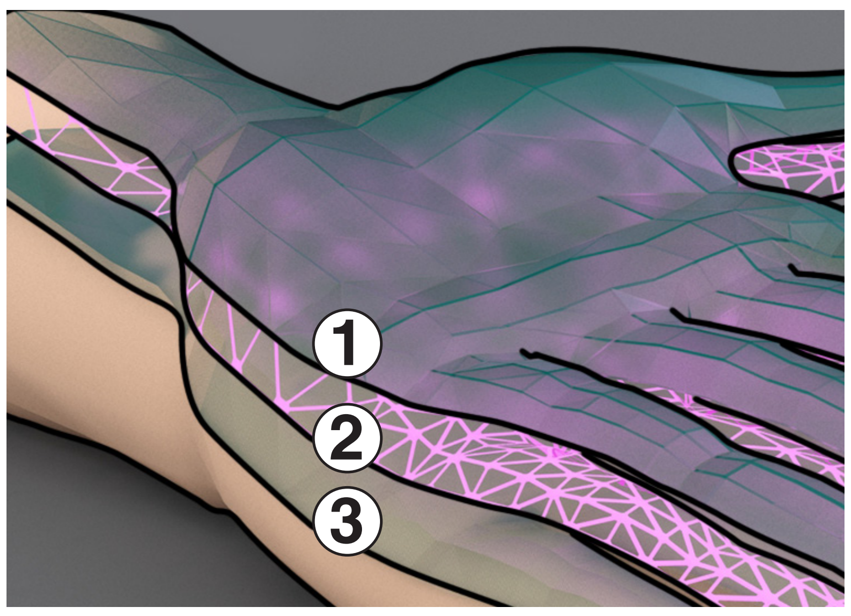
FUTURE RESEARCH:
Hybrid rapid customisation technologies, integrating 3D scanning with additive manufacturing, smart materials, market and consumer acceptance.

Dressings are required for a range of wound types including burns, lacerations and incisions. Depending on the type and severity of the wound, dressings may contain a range of additives, healing agents, hydrogels, silver films, antimicrobials, and splinting. For severe wounds, consistent monitoring and specialised treatment is required. For example, wounds over joints that are not appropriately splinted and ranged will develop contractures.

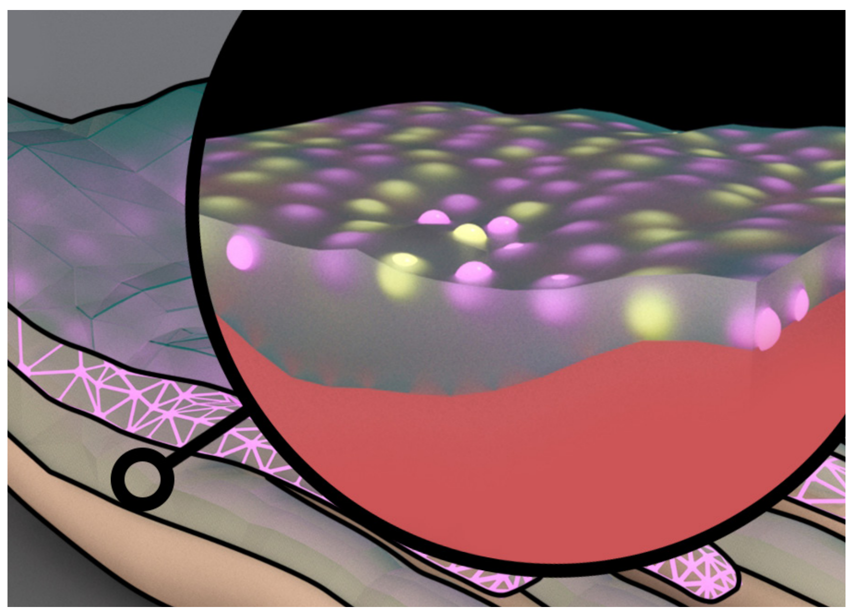
Regenerative Skin proposes the use of cotton-derived cellulose and rapid customisation for the production of patient specific smart wound dressings. It is possible for tailored drug delivery, sensing material and structural elements to be integrated with the wound dressing to assist healing and monitoring. Cotton is an ideal material for this application as it is biocompatible. Moreover, rapid customisation in this context enables medical staff to focus their attention on the patient and reduce the time required for the preparation of wound dressings.



3D SCAN: Patients are 3D scanned in order to capture wound topology data and other data about infection risk, wound severity and wound density.



CUSTOMISATION: Wound dressings are printed to custom specification containing barrier (1), structural (2) and hydrogel (3) layers.



FUNCTIONALITY: Incorporation of wound specific drug delivery and biosensing capabilities can assist wound monitoring, patient comfort and recovery.

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