Facilitating consumer involvement in design for additive manufacturing / 3D printing products

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Facilitating Consumer Involvement in Design for Additive Manufacturing / 3D Printing Products

by

YUDHI ARIADI

Doctoral thesis submitted in part fulfilment of the requirement for the award of
Doctor of Philosophy of Loughborough University

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Abstract

This research investigates the potential of the general public to actively design their own products and let consumers either manufacture by themselves or send the files to manufacturers to be produced.

This approach anticipates the rapid growth of fabrication technology, particularly in Additive Manufacturing (AM)/3D printing. Recent developments in the field of AM/3D printing have led to renewed interest in how to manufacture customised products and in a way that will allow consumers to create bespoke products more easily. These technologies can enhance the understanding of non-technology compliant consumers and bring the manufacturing process closer to them. Consequently, to make AM/3D printing more accessible and easier to employ by the general public, design aspects need to be developed to be as simple to operate in the same manner as AM/3D printing technologies. These technologies will then attract consumers who want to produce Do-It-Yourself (DIY) products.

This study suggests a Computer-aided Consumer Design (CaCODE) system as user-friendly design software to simplify the Computer Aided Design (CAD) stages that are required to produce 3D model data required by the AM/3D printing process. This software will be an easy-to-operate design system where consumers interact with parameters of designed forms easily instead of operating conventional CAD. In addition, this research investigates the current capabilities of AM/3D printing technologies in producing consumer products.

To uncover the potential of consumer-led design and manufacturing, CaCODE has been developed for consumer evaluation, which is needed to measure the appropriateness of the tool. In addition, a range of consumer product samples as pens has been built using a range of different materials, AM/3D printing technologies and additional post-processing methods. This was undertaken to evaluate consumer acceptance of the AM/3D printed product based on products’ perceived quality. Forty non-designer participants, 50% male and 50% female, from 5 to 64 years old, 6-7 participants per ten-year age groups in 6 groups, were recruited.
The results indicated that 75% of the participants would like to design their own product using consumer design software. The study compared how consumers interacted with the 3D model to manipulate the shape by using two methods: indirect manipulation (sliders) and direct manipulation (drag points). The majority of the participants would prefer to use the direct manipulation because they felt it was easy to use and enabled them to enjoy the design process. The study concluded that the direct manipulation was more acceptable because it enabled users to ‘touch’ the digital product and manipulate it, making it more intuitive and natural. The research finds that there is a potential for consumers to design a product using user-friendly design tools. Using these findings, a consumer design tool concept was created for future development.

The study indicated that 53% of participants would like to use products made by AM/3D printing although they still wanted the surface finish of injection moulded parts. However, the AM/3D printing has advantages that can fulfil the participants’ preference such as multi-materials from the material jetting method and it is proved that additional post-processing can increase participants’ acceptance level.
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Publications


Awards

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Highly commended Poster

Highly commended Poster

Best Poster
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CHAPTER 1 Introduction

In the past, companies developed consumer products without fully considering the needs of users, but then shifted to involving consumers in the early stages of product development to identify the key design based on the consumer's perspective (Leahy 2013). The degree of influence of consumer involvement in product development process is ranged from conception, specification, design to manufacture (Sinclair 2011). This means that the consumer’s involvement in products has gradually moved from being just a user to a designer, and has now progressed to becoming a manufacturer through the user-friendly design and manufacturing system.

1.1 Design and manufacturing by consumers

It is believed that the more users are involved in the product development process, the more they are satisfied with the manufactured products (Lagrosen 2005). Customers play a central role for companies and stakeholders in the process of creating new products or services (Hoyer et al. 2010). This means that the interaction between consumers and companies is one of the key factors to understand consumers’ needs. Many industries utilise social media as a foundation for interaction with users in value co-creation and/or co-design. For instance, Burberry fashion gathers customers’ preference trend all over the world using a social media program called Art of the Trench (Burberry 2009); Heineken Open Design Exploration
posted one question about the makings of a good lounge every week through Facebook to its 12 million fans (Heineken 2014); and Local Motors that allows its customers to build their own car together with manufacturer’s engineers in two 3-day weekends (Local Motors 2007). Social media is defined as interactive platforms such as websites or online communication applications that enable the individual user and/or communities to create, share, discuss and modify user-generated content (Kaplan and Haenlein 2010). These include text-based applications (blogs, wordpress, twitter), photographs (Flickr, Picasa, Instagram), videos (Youtube, Vimeo), game (Minecraft, Roblox) and social networking (Facebook, MySpace, LinkedIn, Google+).

Co-creation is defined as a collaborative new product development (NPD) process where the system allows and encourages consumers to actively contribute/involve by constructing experiences, defining and solving problems or simply selecting various elements of a new product offering (O’Hern and Rindfleisc 2010; Prahalad and Ramaswamy 2004). Co-design refers to “the creativity of designers and non-designers or people not trained in design, working together in the design development process” (Sanders and Stappers 2008).

Sanders and Stappers (2008) use Figure 1-1 to compare the classical and co-design process. In the classical process, users (U) are placed as a passive object, observed and interviewed by market researchers (R). A survey report is then conveyed to designers (D) as an input for the product development process. Co-design uses a different approach, users are authorised to play a bigger role and an active part in knowledge, idea and concept development, working closely with researchers and designers.
Empirical studies have revealed that many consumers (10% ~ 40%) engage in modifying or even developing products (Hippel 2005). For instance, Do It Yourself (DIY), this activity is a more democratic product development process by the self-directed non-professional designer in which the manufacturing activity is driven more closely or even done by end users (Atkinson 2006). With regards to the development of design software, the notion that it can enable consumers to DIY their own product has become increasingly common (Sinclair 2012) as it helps companies to increase customer satisfaction by letting the consumer personalise their own product (Risdiyono and Koomsap 2011). Researchers have extended the concept of co-design by Sanders: instead of working together with consumers, designers can let users DIY their products by equipping them with the required tools.

Figure 1-2 shows if companies can provide a design tool that can be easily operated by the customer, the customer can directly send the design to a manufacturer to be produced. The designer’s role is to provide a basic design with all the features that can be selected by customers.
Hippel (2005) suggested that many consumers are innovative. According to his research 10%-30% of them have modified or made a product for their personal use. A recent survey conducted by Bain & Company indicated that less than 10% of 1,000 online shoppers had used customisation options before they bought products but 25% to 30% of them were interested in doing so (Spaulding and Perry 2013). Another study run by Deloitte, the business advisory firm, based-on 1,560 respondents, found that one in three consumers stated that they were interested in personalised products or services, but only one in six of had ever purchased any (Deloitte 2015b).

In general, consumers who want to personalise their product are younger, 43% of them are 16-24 year olds and 46% is 25-30 year olds (Deloitte 2015a), and have a sense of innovation (Hippel 2005; Cotte and Wood 2004; Vandecasteele and Geuens 2010). They want to have a sense of control over the product and/or sense of identity (Lee and Sundar 2014; Marathe and Sundar 2011). Although both reasons require an effort from consumers, the time and energy they spend to modify and self-express give positive value which strengthens their emotional bonding to the products (Bauer et al. 2007; Herd et al. 2010; Hernandez et al. 2010; Mugge et al. 2009). This can lead consumers to keeping the product longer to minimise disposal to landfill and may increase sustainability in product consumption (Chapman 2008; Ko et al. 2011; Lobos and Babbitt 2013; Page 2014).

For consumers who want to make a product, there are consumer manufacturing tools currently available on the market, at an affordable price, such as sewing machines for dressmakers and hand drills, handsaws and lathes for woodworking. However, those tools need significant skill in order to produce the product. AM/3D printing has a different approach to building a product by adding material layer by later. For that reason, this method is considered as a user-friendly fabrication technology that lowers the need for the hand-craft-skills in making a product. Hence, it has been suggested that in the near future this technology will give more opportunities for consumers to make their own products (Campbell 2013).

Compared to any other consumer manufacturing tools, many AM/3D printing machines are still relatively expensive. However, developments from the AM/3D
printing machine industries have indicated that the low-cost AM/3D printer (under $5,000 or £3,000) market segment has increased from 35,508 units in 2002 to 72,503 in 2013 and 139,584 in 2014 (Caffrey and Wohlers 2015). There are many options for consumers to have AM/3D printers, depending on the quality and whether it is a-ready-to-assemble kit or ready-to-use machine. There are more than 300 companies, mostly small start-up manufacturers, developing and selling AM/3D printers (Peels 2015). This means that consumers now have the capacity to manufacture their own products.

Figure 1-3 shows an extension of the concept of consumer design, by providing a user-friendly manufacturing system. However, this system would rely on the digital model created by design software. Designers would provide a basic design together with the design modification software. AM/3D printer manufacturers would need to make machines available in which both software and hardware can be easily operated by the general public.

Figure 1-3: Facilitating users to design and manufacture products

This research suggests a user-friendly design system by developing easy to use design software to simplify the CAD stages before the manufacturing process; and also helps to understand what systems are suitable for consumers to get involved the design process.

Other benefits for letting consumers personalise their product are because the process requires an effort from users. Therefore, consumers may attach their personality to the product and it could improve the emotional value of the product. As a result, personalised products become more self-expressive and have personal
unique identity (Mugge et al. 2004). It is believed that the higher the consumers’ emotional attachment to a product is, the longer the product’s service life will be (Tseng and Ho 2012).

1.2 Aims and objectives

The aim of the research presented in this thesis is to investigate the potential of consumers to actively engage in product design and lead the product creation process to manufacture via AM/3D printing technologies.

Therefore, the objectives of this research are as follows:

1. To identify the state of the art in consumer design tool development software and AM/3D printing with capacity to facilitate this.
2. To determine the viability and parameters of 3D computer-modelling software for consumer uses.
3. To employ the findings from Objective 2 to explore how consumers would respond to a consumer design tool.
4. To examine AM/3D printing capabilities in terms of materials, colours and surface finish by creating a sample of consumer products.
5. To examine the level at which consumers will accept the material and production properties of AM/3D printing.

The reason for choosing AM/3D printing technology as a tool for consumers is because it needs low manual skills to create a product compared to other consumer manufacturing techniques. As AM/3D printing constructs the product, it is not dependent on the manual skills of consumers directly, but relies on 3D models. So to utilise the AM/3D printing, consumers rely only on CAD skills. Hence, this thesis will investigate available options to develop consumer design tools especially for AM/3D printing (objectives 1, 2 and 3).

Objectives 4 and 5 anticipated a time when consumers would be able to manufacture their own design, accepting the output of personal AM/3D printing machines based on their perceived quality. Since these machines are still low quality, this thesis evaluated the consumer acceptance of products manufactured by industrial AM/3D
printing machines assuming that this level of quality will eventually be offered by personal AM/3D printing machines.

1.3 Structure of Thesis and Research Phases

The research outline is as follows and the structure of the thesis is described in Figure 1-4.

Chapter 1 introduces the subject area and presents the research goals and project focus, establishing the research boundaries.

Chapter 2 presents the literature review in two domains to identify gaps. Firstly, consumer design includes mass customisation (MC) and supporting systems. CAD was also reviewed to observe the progression of the design system. Secondly, consumer manufacturing covers AM/3D printing technologies as systems to support consumer design. This phase also defines the terms: design, consumer design and consumer manufacturing.

Chapter 3 describes the research design and comprises a justification of the research methodology employed in terms of the five elements: paradigm, purpose, strategy, type and method.

Chapter 4 is a development phase of consumer design software and a description of the samples of AM/3D printed consumer products that were built.

Chapter 5 examines the ability of a non-designer to engage in designing a product using design software and the survey results of the consumers’ acceptance of the AM/3D printed products. In this phase an innovative design system was generated and a range of consumer product samples made by AM/3D printing.

Chapter 6 discusses the findings of the study as a whole. The outcome of this phase was feedback from research participants describing consumer appropriateness and acceptance to refine consumer design software and the future improvement of AM/3D printing technologies demanded by consumers.
Chapter 7 concludes the key findings of the thesis and recommendations for development of consumer design software and AM/3D printing, discusses the limitations of the study, reviews how the aims and objectives were met, and establishes the contribution to knowledge and future research.

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Figure 1-4: Thesis structure
CHAPTER 2 Literature Review: Consumer Design and Manufacturing

As a literature review, this chapter provides two key functions. Firstly, it offers an overview of the consumer design literature; defines terminology; outlines the emergence of the paradigm and the development of research themes; and explores the nature of consumer design and issues of designing by the consumer. Secondly, it reviews the literature surrounding consumer manufacturing: 3D printing; its development; the current state of the manufacturing technology for the consumer; and exploration of the potential for laypersons to do product design and product manufacturing by themselves.

The theme of this study started when companies became concerned about consumer involvement. Much of the early consumer involvement focused on advertising (King 1968; Krugman 1965; Preston 1970; Wright 1974) in which research revealed how to develop effective communication with consumers so they could understand the product prior to purchase. At this stage, consumers were considered as users or owners only and as passive, unaware and isolated. The concept of the market was a
company-centric one. The next generation in consumer involvement research was involved in how industry was developing new products in a way to find a solution that fulfilled the needs of potential users (Michaelidou and Dibb 2008). The approach was to bring the consumers’ voice into the design and manufacturing processes by involving customers in the product development processes as much and as early as possible (Hasdoğan 1996; Holt 1987; Margolin 1997; Peters and Waterman 1982; Reich et al. 1996). With a user involvement strategy and the widespread use of the personal computers and internet, the behaviour of many consumers has been altered (Mullaney et al. 2003).

The use of the internet for social media has the benefit of worldwide access and fast communication among users and/or consumers and firms (Hutton and Fosdick 2011). It offers the potential to enhance the success of consumer-company collaboration, as industries can reach their customers in a more effective and convenient manner (Sashi 2012). Those technologies then allow easy and fast communication between industries and consumers so companies can identify the consumer requirements, while the consumers express their particular needs (Brockhoff, 2003). In this way, consumers are accustomed to conveying their ideas so the numbers of consumers who want to have personalised items will increase (Piller & Kumar, 2006).

Technologies have been made available for consumers with access to unlimited amounts of information (Laroche 2010). With the rapidly expanding and emerging mobile internet markets, enterprises in the communications industry chain have been focusing on the direction of mobile internet markets (Yang 2011). These information technologies also give customers the ability to communicate with other consumers and companies. They can easily convey their needs, feedback and ideas to firms through websites, e-mail, or social media (Bolton and Saxena-Iyer 2009). This situation has empowered consumers to give a greater influence to companies (Berthon et al. 2012) which helps them to develop products or services that meet consumers’ needs; improve product quality; reduce risk; and increase market acceptance. As a result, the Marketing Science Institute ranked co-creation or
integrating consumers into innovation as one of their top research priorities for 2008-2010 (Hoyer et al. 2010).

2.1 Industrial Design, Product Design and Consumer Design

The Industrial Designers Society of America (IDSA) defines industrial design comprehensively and breaks the activities down into 32 very intricate steps.\(^1\)

Industrial Design is the professional service of creating products and systems that optimize function, value and appearance for the mutual benefit of both user and manufacturer. Industrial designers develop products and systems through collection analysis and synthesis of data guided by the special requirements of their client and manufacturer. They prepare clear and concise recommendations through drawings, models, and descriptions. Industrial designers improve as well as create, and they often work within multi-disciplinary groups that include management, marketing, engineering and manufacturing specialists.

(IDSA 2015)

Ralph Caplan (1969) predicted that even if the definition of industrial design were to be accepted among practitioners, it probably would not cover all of what industrial design would do in the future (Caplan 1969). It seems that the Caplan’s view is still relevant, the elaboration among practitioners and academics in defining industrial design and product design is still happening, for example, via discussion boards such as Core77 “Difference between Product Design and Industrial Design” (Core77 2007); email discussion lists for the UK Education and Research communities in 2011 “What’s' in a name - Industrial Design or Product Design” (JISCM@il 2011), Quora “What is the difference between product design and industrial design?” (Quora 2011); and recently posted on Linkedin “Industrial Design vs. Product Design” (Gibbons 2015).

On the International Council of Societies of Industrial Design (ICSID) website, Evans (2015) suggested:

Industrial design is the profession that takes primary responsibility for form-giving but with expertise in meeting user wants/needs and specifying the manufacturing processes required to mass produce (INDUSTRIAL) beautiful, ingenious and charismatic products (DESIGN).

(Evans 2015)

The UK Design Council outlined product design as an integral part of a wider process of developing new products. This applies to every type of product but mostly for those that are mass-produced. The product design process is much more involved at the beginning, but it should fit with every step of the process (Powell 2012). Product designers, as professionals, usually need to manage a broad range of skills and knowledge, from marketing, culture, aesthetic and sustainability issues, to ergonomics, engineering and manufacturing (Erlhoff and Marshall 2008).

A more practical definition is written by Slack (2006):

Product design is a generic term for the creation of an object that originates from design ideas – in the form of drawing, sketches, prototype, or models – through a process of design that can extend into [the] object’s production logistics and marketing.

(Slack 2006)

No single concept has been accepted, hence practitioners and academics have not achieved a consensus in defining industrial design and product design. Rodgers and Milton (2011); Slack (2006) argue that it is an ambiguous term and blurs the boundaries between specialist fields such as lighting, furniture, graphics, fashion, interaction and industrial design; then use the term ‘product design’. Campos and Asensio (2006); Hannah (2003) use both terms synonymously and interchangeably. This study synonymously uses both industrial design and product design, as consumer design is only part of what industrial/product designers do.

The term ‘consumer’ in ‘consumer design’ in this thesis refers to the end user of a product or service, which may or may not be the actual buying customer and different from retailers (Doyle 2011). Consumers purchase goods and services for their
personal use or other members of their households, and do not use them to earn further income (Black et al. 2009).

The Board of International Research in Design (BIRD), suggests that the term ‘design’ is more broadly applied to include the conception—the mental plan—for an object, action, or project; it comes from the Latin word *designare* meaning to define, to describe, or to mark out (Erlhoff and Marshall 2008). Since the early 1990s a new term, ‘service design’ has appeared; it aims at designing services for intangible products that are useful, usable and desirable from the perspective of the customer, as well as efficient, effective and distinctive from the provider’s point of view (Mager and Sung 2011). This study focuses on consumer products that are categorised by the European Committee for Standardisation, “as items intended for consumers or likely to be used by consumers, even if not intended for them” (Comité Européen de Normalisation 2014).

So to define the term ‘consumer design’ in this thesis it is “an activity of the consumer or general public to configure and/or manipulate a basic/pre-defined/unfinished product design for manufacturing purpose in which the product will be for personal use”.

### 2.2 Consumer Design

This sub-chapter will discuss the existing concepts as a background to consumer design: co-design or co-creation, personalisation, individualisation, customisation, mass customisation, craft consumption, prosumer and customerism.

#### 2.2.1 Co-design or co-creation

The use of the terms ‘co-design’ and ‘co-creation’ are often treated synonymously with one another (Steen et al. 2011). Co-creation is referred to as “any act of collective creativity, i.e. creativity that is shared by two or more people” and co-design is, in a more narrow sense, defined as “collective creativity as it is applied across the whole span of a design process” (Sanders & Stappers, 2008).
The theory of co-creation/co-design was revealed because of the belief that the general public are the experts in living, working, learning and playing; so designers should not only design for people but learn to design with people. Hence utilising consumers’ experiences will significantly influence the design process and the role of the designers (Sanders, 2006). Researchers suggest designers should work very closely with consumers and this would give benefits both for the users and the firms (Hoyer et al. 2010; Johnson 2007; Steen et al. 2011). This would create future consumers who have greater influence in NPD.

2.2.2 Personalisation, Customisation and Individualisation

One of the roots of the concept of personalisation, individualisation and customisation is in the relationship between marketing and management. Future sales opportunities depend on relationship quality, i.e. the trust and satisfaction of consumers (Crosby et al. 1990; Vesanen 2007). It is a key component of an interactive marketing strategy (Montgomery and Smith 2009). Companies are taking the benefit of interactive technology to personalise the interactions with their consumers (Ho 2006). Moreover, with the widespread use of the internet as a technology for communication and information, companies have more varied strategies for implementing relationship interactions with consumers (Shapiro et al. 2004). Personalisation may not only benefit consumers but also industries (Hoyer et al. 2010; Risdiyono and Koomsap 2011; Trentin et al. 2012). Customised products, services and the way they communicate, may increase consumer attention as well as their loyalty; therefore the content-targeting approach can potentially increase the expected number of links being followed by 62% (Ansarii and Mela 2003).

The concept of personalisation and customisation are different, according to some researchers (Allen et al. 1998; Arora et al. 2008; Edwards 2006; Kumar 2008; Montgomery and Smith 2009). Personalisation is the adaptation of products and services by the firm for the consumer, based on previously collected customer transaction data and the customer’s behaviour, as opposed to customisation that a consumer proactively requests one or more elements of the product or services (Arora et al. 2008; Ho 2006; Montgomery and Smith 2009).
Customisation is similar to personalisation and individualisation but they are differentiated by the subject who undertakes the task. With the same objective to customise the product or service, personalisation is done by companies, whereas in regard to individualisation, companies provide options that can be selected by consumers, in this case the task is completed by consumers (Gordon et al. 1998; Gros 2004). However, the terms personalisation and individualisation are often used synonymously (Houston 2010; Kennedy 2008; Riemer and Totz 2003).

Based on the understanding of the research on this area, the aim of this study relates to the concept of individualisation and customisation where the general public do the design manipulation provided by companies through the design system.

### 2.2.3 Mass customisation: the four faces and five continuum strategies

Mass customisation is defined as a production system that allows for customisation and personalisation or individualisation of products as well as services at a mass production price (Alptekinoglu and Corbett 2008). The concept was first identified by Davis (1987) and was further developed by Pine (1993b). When the needs of custom products have increased in the market, many companies use mass customisation as a strategic business operation. It has become an important trend in the manufacturing industry towards market globalisation, rapid technological innovation and intense competition (Piller and Muller 2004). Companies have to adopt strategies that embrace both a closer reaction to the consumers' needs and efficiency and mass customisation meets this challenge by offering individually customised goods and services with mass production efficiency. Thus, the capability to produce customised products, which are matched to the specific individual needs, are expected to have a major beneficial impact on quality of life (Gerrits et al. 2004).

There are three definitions of mass customisation (Broekhuizen and Alsem 2002): Pine (1993) identifies it as a strategy concerning the delivery of the desired product – on a mass scale – after the expression of consumers’ needs has taken place, more than the strategy of delivering as many product variants as possible. Duray (2002) described mass customisation as a variety of offers for consumers’ choices that do not involve the ability to specify the product. Zipkin (2001) argued that consumers,
with mass customisation, must first interact with the producer, the retailer or the product (i.e. adaptive products) to configure their product. They must be involved in specifying characteristics of the product during design, fabrication, assembly, or use. As a result, mass customisation needs to develop a mechanism that elicits individual customer needs and transforms these needs into suitable products.

Since the manufacturing technologies have become mature, with the ability to produce one-of-a-kind products, mass customisation has been greatly expanded with the potential of much greater personalisation, where consumers actively take part as co-designers (Eyers 2008). Consequently, the needs for customisation have increased from 6% (1997) to 30% (2005). Some consumer products such as computers, shoes, toys, bags, clothes and mail are increasingly customised (Silver et al. 2005).

Gilmore and Pine (1997) defined the four faces of mass customisation divided into different degrees of customisation freedom (Gilmore & Pine, 1997). Similarly, Lampel and Mintzberg (1996) structured a continuum of strategies for manufacturing classified customisation based on the possibility to perform customisation on stages in the company’s value chain: design, fabrication, assembly, and distribution. As a result, they categorised five types of mass customisation strategies comprising: pure standardisation, segmented standardisation, customised standardisation, tailored customisation and pure customisation (Lampel and Mintzberg 1996). Both Gilmore and Pine and Lampel and Mintzberg classified the customisation in gradation stages from pure standardisation to pure customisation (Figure 1-1).

![Figure 2-1: The Four Approaches to Customization](image)

**Pure standardisation**

As a comparison, before companies developed mass customisation, they produced high volumes of products by using pure standardisation. Although buyers can modify
the product afterwards, there is no special treatment for the different customers (Duguay et al. 1997). They have to use it, modify it, or switch to another product. They do not have direct influence over design, production, packaging or even distribution decisions. The entire organisation is totally dominated by the company from one stage to the next, beginning with design and ending in the marketplace. Henry Ford’s apparent comment "Any customer can have a car painted any colour that he wants so long as it is black" (Ford & Crowther 1922, p 72) is a classic example of this type of pure mass production. Ford Motor Company’s targeted approach to the largest and broadest possible group of buyers produced the Model T in as large a scale as possible, and then distributed them commonly to all (Allen 2015). Figure 2-2 shows unfinished Ford Model T at different stages of manufacturing.

![Figure 2-2: Ford Model T, first moving assembly line and standardised components to reduce production cost](image)

**Cosmetic standardisation**

In the cosmetic approach/segmented standardisation, companies produce the same product but only change the way it looks. This type is appropriate when consumers use a product in the same way, but the product is packaged, advertised, promoted and communicated in different ways. Although this approach does not involve a substantial aspect of the product, the changes are more likely to deliver value, for example packaging, as opposed to complicated product adaptations (Lee & Sundar, 2014). An example of this type is customising mobile phone covers. Companies only approach buyers at the distribution stage (Lampel and Mintzberg 1996), or
consumers can customise the product after they buy it. Consumers are now able to personalise their mobile phone covers by selecting the shape, colour, graphics and use of their own family’s photos (Photobox 2014; Vistaprint 2014). For covers which are printed by using AM/3D printing technologies, users can even choose the materials and finishing processes (Sculpteo 2014; Shapeways 2014b; Thingiverse 2014; Willans 2014).

Figure 2-3 shows examples of this approach. Using standard manufacturing, Apple offers phone cases on their official online store. Every phone cover has been tested before they are placed in the Apple Store (Apple 2015). Nokia, supported by the capabilities of AM/3D printing technology, is using this approach for one of their products, Nokia Lumia 820 (Microsoft 2013). In order to let their customers design their own covers, they have released the ‘Nokia 820 3D-printing Development Kit’ which contains 3D design templates, case description and specification, recommended materials and best practices (Willans 2014).

![Figure 2-3: Cosmetic customisation for mobile phones](image)

**Transparent customisation**

The concept of transparent customisation/customised standardisation is to provide a product to individual customers or a group of typical customers without explicitly telling them that companies have customised the products for them. Companies should accurately assess customer needs, observe their behaviour and then prepare the right options for consumers to select. Chemstation, a soap company, custom-formulate the right mixture of soap after analysing each consumer’s needs based on their previous transaction records, using H700 custom formulation blending software. In this way, customers do not need to spend their time to create and review
orders every time they want to refill their soap tank. With their customer management and auto-scheduling application, TANK software, the company always makes sure the soap is ready whenever the customer needs it (ChemStation 2008).

Adaptive customisation

In adaptive/tailored customisation, companies produce a mass customisable standard product, so consumers are able to alter the product by themselves. The advantages of this system where users want to perform in different ways and/or also perhaps on different occasions, is that the firms can keep to an affordable price with mass production costs and lead time levels (Joneja and Lee 1998). The customisation works backward to the fabrication stage but does not influence the design stage.

An example of this strategy is, shown in Figure 2-5, in automotive companies that offer consumers the possibility to configure their car before they buy.
To do collaborative/pure customisation, companies have a discussion with individual customers to determine the particular product offering that best serves their needs. This information is then used to specify and manufacture a product that suits the customer (Shamsuzzoha et al. 2011). With this customisation, customers can be involved in the design process, so that the product or service is made to order. Hence, all stages, from design, fabrication, assembly to distribution, are largely customised.

For example, the TD Tom Davies offering of customised eyewear starts with selecting from an existing range of frames; a customer works alongside a trained optician to design a custom-made frame in the TD design studio. Consumer face precision measurements and photographs are taken in order to produce a blueprint. The final design is then sent to the workshop to be made. Finally, the consumer receives the customised eyeglasses with their name engraved on the inside of the temple arm (TD Tom Davies Ltd 2011).

**Figure 2-6: Bespoke eyeglasses, from design consultation to manufacture**

**2.2.4 Craft consumption**

Based on a survey of over 2,000 craft makers in England and Wales undertaken in 2003, McAuley and Fillis (2005) define ‘craft’ as:

> an object which must have a high degree of handmade input, but not necessarily having been produced or designed using traditional materials, produced as a one-off or as part of a small batch, the design of which may or may not be culturally embedded in the country of production, and which is sold for profit.

(McAuley & Fillis, 2005, p139)

The definition does not consider the owner and the maker; it is only concerned about how the products are being made. Campbell (2005) defines the term ‘craft’ as “a
consumption activity in which the ‘product’ concerned is essentially both ‘made and designed by the same person’ and to which the consumer typically brings skill, knowledge, judgement and passion while being motivated by a desire for self-expression” (Campbell, 2005, p23). This definition is close to the DIY meaning of prosumer, which is discussed in the next chapter.

Some of the aspects of both definitions above relate to consumer design and manufacturing: a high degree of handmade input; made and designed by the same person; and self-expression. Handmade input, design and self-expression are the aspects of consumer design. Made and designed by the same person is an activity from consumer design continuing to consumer manufacturing. Therefore, emerging craft practices have united with DIY activity and technologies such as AM/3D printing (discussed in section 2.5.1 DIY, page 36) and laser cutting, in creative subcultures, such as the Make & Craft community (Makezine 2014) and Hackerspace (Hackerspace 2014).

2.2.5 From consumerism, prosumerism to customerism

Consumerism has been the subject of differing opinions and periodic reinterpretations. One of the early conceptions was by Veblen (1899), he wrote the theory of conspicuous consumption about how the leisure class realised their personal happiness through the purchase of material possessions and consumption. Consumerism is now experienced more widely, and the definitions have proliferated or combined with other concepts such as the “prosumer” (Toffler, 1980, p.266).

Prior to the industrial revolution, people consumed what they themselves produced. There were neither producers nor consumers so they might be called prosumers. This is similar to the idea of DIY, co-design and co-creation (Ritzer et al. 2012).

Another similar idea is customerism. Reddington (2008) explored and documented mass customisation as a new generation of consumerism. As there is no definitive explanation for customerism yet, and the term cannot be found in existing dictionaries, he offers a definition as: “a series of ideas that empower the customer
with a greater level of participation in deciding how products are designed and how they are produced” (Reddington 2008).

2.3 CAD progression: from industry to designer then consumer

In the product development process, design refers to aspects of 2D drawing, sketching or rendering and 3D modelling, i.e. CAD modelling. Drawing, as a design representation, may be called a universal language which is the natural method for people to convey visual images (Pentak et al. 2012). This sub-chapter explores how the progress of CAD as an aided design tool could help consumers to design their own products. The history shows the movement of CAD utilisation from manufacturers for machining; to engineers for design engineering; to designers for product concept and visualization, and ultimately, to consumers as creators and end-users of products.

2.3.1 Design tools progression

The foundation of CAD is powered by geometry, and had been invented in 350 BC by the mathematician, Euclid of Alexandria, who wrote the 13 books of Elements as a treatise of two and three dimensions (Heiberg 2008). More than 2300 years later, in 1957, there were the beginnings of CAD developments in which Dr. Patrick J. Hanratty created PRONTO (Program for Numerical Tooling Operations), the first commercial Numerical Control (NC) programming system (Sanders 2008). In 1960, Ivan Sutherland at the Lincoln Laboratory of Massachusetts Institute of Technology (MIT) created Sketchpad, which demonstrated the basic principles and feasibility of the first interactive computer aided drawing in 2D (Sutherland 1963). Since then the development of digital tools has increased in term of variety and capability that have an impact on professional industrial/product design activities (Aldoy and Evans 2011). This enables designers to make a geometric product more complex by adding more features, and allows designers to simulate and evaluate it virtually before creating a prototype to reduce iteration (Su et al. 2012).

2.3.1.1 From manufacturers to engineers

One of the first computer-aided drafting events came from a numerical control (NC) machine but a pencil was used instead of a cutting tool (Gibbs 1999). To mill complex parts, machines required the geometric input of G-code, and Boeing engineers
performed initial cuts on suitable cheap material (wood, plastic). They then substituted the cutter for a scriber to create a light scratch on paper, which could be called ‘drawing a line’. It was the first use of a NC machine tool as a computer-controlled drafting machine and could be said to be the beginning of computer aided drafting (Sanders 2008). Therefore, the first use of CAD for mathematical geometry was utilised by manufacturers. If the output of CAD that derived from NC/G-Code was physical lines on a media such as paper, Sketchpad displayed the lines on the screen and utilised a light pen for interacting with the screen. So, Sketchpad was used for helping design engineers to draw electrical, mechanical, scientific, mathematical, and animated drawings (Sutherland 1963).

CAD started to be developed in 3D after the principle of Béziers curves, B-spline, and Non-Uniform Rational B-spline surface (NURBS) were invented from the 1950s to the 1970s (Rogers 2001). Since then, CAD has been developed from only being able to display 2D representations to geometry digital models in 3D, in wireframe, surface or solid modelling formats (Farin et al. 2002). CAD can be used not only for creating computer models defined by geometrical dimensions but also other physical parameters such as weight and materials. Therefore, it can help designers to review objects under a wide variety of representations and to simulate them in real-world conditions (Robertson and Radcliffe 2009). With the capability to create a 3D complex shape and accommodate many aspects of a physical product, CAD needs to be operated by skilled and well trained users (Hamade et al. 2007).

2.3.1.2 CAD for industrial designers

Engineers typically work on the detail of engineering features of products, such as manufacturability, assembly and drawings. In contrast, industrial designers have different approaches to creative designs, they utilise CAD to visualise the product, to review its appearance and work creatively (Dorst and Cross 2001; Sarkar and Chakrabarti 2011). However, the obstacle would be to the user who may be creative but cannot use the technology (Lawson 2002). As a result, CAD needs to be developed to help designers without sacrificing their creativity (Evans et al. 2015).
It is still a fact that hand sketching is still needed at the early conceptual stages (Bilda and Demirkan 2003; van der Lugt 2005) before visualizing the concept into CAD. However, several studies have explored integrating hand sketching into the digital process by converting sketching as curves, surfaces or in CAD (Cheutet et al. 2005; Cheutet et al. 2007; Horváth et al. 2007; Mengoni et al. 2007), for instance: SMARTPAPER (Shesh and Chen 2004), freehand sketching (Masry et al. 2005), SKETCH (Zeleznik et al. 2006), A Sketch Editor (Pu et al. 2005), Direct Modelling (Naya et al. 2002) and Teddy, a freeform digital sketching for designing toys (Igarashi 1999).

![Image](image_url)

**Figure 2-7**: (A) Sketch to 3D reconstruction; (B) transform Teddy sketch to 3D model (Igarashi 1999; Masry et al. 2005)

In terms of creating a 3D model, the technologies above are sophisticated but easy to operate. However, as Wohlers (2007) said “most people cannot design” so those technologies only help users to convert the sketch but cannot help them to build a beautiful 3D shape.

### 2.3.1.3 CAD for consumers

According to Moore’s law (1965) the number of transistors on a chip roughly doubles every two years, and it is followed by every measure of the capabilities of computers: processing speed and memory capacity (Moore 1965). The trend of computer power will continue, as well as the trend of computer components’ size will continue to
shrink (Cuthbertson 2015). It helps software developers to create user-friendly computer programs at the consumer level. As it is a crucial aspect for AM/3D printing to have a 3D model as an input and the fact that AM3D printing will become a device for the layperson, CAD, previously a tool for designers/engineers would have to contain design software for the general public.

This type of CAD program that is being developed for use by the general public, has fewer features; is less expensive, or even free; is designed for helping people to develop simple 3D models and objects; and is more intuitive, flexible, and easier to use than other 3D CAD programs for engineers or for designers. This type of CAD must be user-friendly, and enable people to create easy virtual models, which are usually based on six primitive shapes i.e. block, triangular prism, sphere, cylinder, cone and torus. Figure 2-8 shows TinkerCad, a web-based CAD with a menu that offers basic shapes that can be combined and manipulated.

![Figure 2-8: Building a model using primitive shapes](image)

To give access for the general public, CAD developers offer free versions such as SketchUp, formerly Google SketchUp (Trimble 2014), 3DVIA Shape (Dassault Systemes 2014), Sculptris (Pixologic 2014). Although there are fewer features compared to the paid version, users can still produce manufacturable 3D models.
Before creating a model, the program has to be downloaded and installed via the company's website for free.

Installing software is sometimes not practical and also not flexible, especially for people who have more than one device. It can be assumed that most computers now have a browser on their system. With the capability of Web 2.0 to support 3D applications CAD programs are now available as browser-based applications (Di Blas et al. 2009). A browser-based application is defined as a computer program which runs on a web browser through the Internet without the need to access or install the operating system (Grove 2009). Examples of this CAD are TinkerCAD (Autodesk 2014b) and 3DTin (Lagoa 2014). To help users cope with the software, CAD developers support them with dozens of video tutorials, extensive help centres and a worldwide user community, for instance SketchUp Video Tutorials: Getting Started (Sketchup 2013), Tips & Tricks – 3DVIA Shape Mini-Tutorials (3DVIA 2012).

With less flexibility in creating CAD running on browsers, developers can still offer design tools but only for specific products. For instance, Shapeways Sake Set Creator for designing pottery; Shapeways Easy Creator for customising jewellery; 123D®charms for personalising pendants; and 123D®Project Shapeshifter for manipulating ornaments (Autodesk 123D 2014b; Shapeways 2014a).

2.3.2 CAD and human computer interaction (HCI) devices

CAD software needs machines to run on and HCI devices to interact with. Machines can be PCs or mobile computers including laptop and tablet. To interact with the CAD, the interface devices can be a two or three buttons mouse or 3D mouse (3Dconnexion 2009), haptic for PC (Evans et al. 2000); and stylus pen or fingers for tablets (Radhakrishnan et al. 2013).

2.3.2.1 From desktop PC to mobile computer

A tablet computer is designed to enable users to interact with a PC using a finger or stylus pen directly on the screen. From this capability, application developers create programs so users can benefit from that feature, for example digital sketching software. This opens up a new possibility and the potentiality to push the boundaries
of how designers make a design (Chin and Tan 2007). With the digital technology, many new capabilities can be developed such as modelling and capturing complex geometry from a real object by 3D scanning; photorealistic rendering; walkthrough animation, engineering simulation and analysis; communication and collaboration (Evans et al. 2015). Although the use of digital sketching is not as flexible as paper-based sketching, it is easier to learn, quicker, gives more freedom and is low cost (Aldoy and Evans 2011).

Unlike 2D graphic program, 3D CAD consumes a lot of processing power (Szczepaniak 2014). Previously, it could only be run on workstations, but since 1980s PCs have been able to run CAD packages (Bird 1985). The progression of 3D modelling on tablets was behind, compared with the 2D design applications, until the processor power of mobile computing increased, and CAD is now available on tablets (Gonzales 2015).

There are two approaches for CAD to become available on tablets, firstly via the operating system, for instance Windows 8. By enabling Windows 8 on tablets, CAD applications are able to run on the OS automatically (Mings 2012). Secondly, the software is developed on the cloud system. Onshape, is the first full-cloud parametric 3D CAD system that lets everyone on a design team simultaneously work together using a web browser on a PC, laptop, tablet or a phone app. It is useful for collaboration projects because it is free, no installation or licence is required (DEVELOP3D 2015).

In 2014, 314 million PC units were sold in total worldwide, a 1.1% decrease from 2013, where the mobile computing market of tablets, 229 million, increased 9.6% (Gartner 2014). This trend has led CAD developers to anticipate the next customers’ need, therefore CAD packages are going mobile. Autodesk started this movement by releasing viewers, the DWG Viewer first; now they offer 123D*Design, 123D*Sculpt and 123D*Catch for converting photos into 3D models (Autodesk 123D 2014a).

### 2.3.2.2 3D modelling by Haptic

Virtual product design as a design solution is undeniable (Ye et al. 2006). Various technologies have made the outcome closer to reality. However, most CAD programs
are not user-friendly, because they require well-trained and experienced operators to become proficient users, especially for freeform surface design (Lim et al. 2004). To answer this, CAD and its supporting technology have almost reached the point at which the user is able to directly touch and manipulate native 3D CAD models in mainstream CAD systems with force/touch feedback, by using a haptic device (Figure 2-9). This lays the foundation for future tasks such as direct CAD model modification, dynamic simulation, and virtual assembly (Zhu 2008).

Figure 2-9: 3D modelling by haptic (Geomagic 2014)

The study findings identify that the haptic modelling has greatest potential during concept generation, especially the capability in replicating a model, then making some additional forms or just modifying the base form (Evans et al. 2000). With haptic modelling devices, there is no need to learn some sort of commands to change 3D shapes. For example, in 3D modelling CAD, users usually need to understand a concept of Boolean operation to make a hole in an object, with haptic modelling, users just simply push the object with their hand via the haptic arm or pull it for extrusion. Based on those advantages, with the haptic system, users should be able to easily produce 3D models. However, some research studies on the use of haptic modelling devices by product design students and practitioners concluded that there was a tension between acquiring the skills of form creation and understanding the digital skills required (Malins et al. 2007). Therefore clay and foam modelling are still preferred methods for practitioners as they found difficulties interacting with the digital models via haptic (Sener et al. 2002). Evans et al. (2005) tested one haptic device, the FreeForm/Phantom system and found limitations in producing acceptable
Chapter 2 Literature Review: Consumer Design and Manufacturing

curved surfaces when it was used for sculpting forms. In conclusion, as some practitioners and design students still found haptic modelling difficult to use, this study did not propose it as a consumer design tool.

2.4 Current CAD capability to build consumer design software

The development of CAD/CAM/CAE show two main trends, firstly toward lower-cost software packages without reducing capabilities, and secondly, toward easy to use but still sophisticated systems (De Gaspari 1997; Horváth and Vroom 2015). The progression of entry-level CAD software has increased interest and participation by the general public, or at least hobbyists in the kind of activities normally associated with the professional practice of industrial design for mass-manufactured products (Gershenfeld 2007).

At the time of writing this report, there were five basic alternatives available for the development platform:

2.4.1 A geometric modelling kernel

The development of a completely new system from scratch using a geometric modelling kernel: the core of many CAD systems is a geometric modelling kernel, it is also referred as a modelling engine (Potter 1997). Using mathematical functions, a kernel library stores and defines 3D objects based on input from the user’s commands (Chang 2015; Stroud and Nagy 2011). Figure 2-10 shows the process when the command input through the user interface application is followed by the geometric modelling kernel calculating the result in CSG\(^2\) or B-rep\(^3\) and sending the graphics output to be displayed on the screen.

![Diagram: A CAD interface to geometric modeling kernels (Chang 2015)](image)

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\(^2\) CSG, constructive solid geometry, is a method to represent a solid object as a set of Boolean operation: union, subtraction and intersection (Chang 2015).

\(^3\) B-Rep, boundary representation, is also a method of solid representation where a 3D model is bounded by a set of faces, edges and vertices; they are linked to each other by incidence and adjacency.
The Convergence Geometric Modeller (CGM), Alan Charles Ian System (ACIS) and Parasolid are some examples that are used in well-known CAD systems. CGM and ACIS are three dimensional geometric modellers developed by Spatial, a company owned by Dassault Systèmes (Spatial 2015). ACIS is widely adopted in many CAD systems such as AutoCAD, Inventor from Autodesk, SpaceClaim, CoCreate from PTC (Autodesk 2014a; Maher 2013). Parasolid is developed by ShapeData and owned by Siemens PLM Software (Siemens 2015). It is also used and licensed to many CAD packages such as NX, Solidedge and SolidWorks (Fang and Li 2008).

### 2.4.2 Application programming interface (API)

API is a method for two computer applications to communicate with each other using language that can be understood by both sides (Jacobson et al. 2011). With API, a computer program developer allows a third party (a service or a product) to have access to its library (Lane 2015). To broaden the usage, CAD packages offer their API for developers to extend and expand applications. For instance, SolidWorks API, AutoCAD .NET API, Solid Edge API, Catia API, NX Open, Crep PTC API Wizards, etc.

Figure 2-11 is an example of an API being used for customising of SolidWorks commands. Normally, to build the gear, a user needs to calculate the number of teeth and diameter of gear, then in SolidWorks create a circle, a gear tooth sketch, circular array them, and finally extrude the sketch to get the gear in 3D. By writing a program in API, the programmer can simplify the stage of gear creation and make a control panel as an interface for the user to provide the input of gear parameters.
2.4.3 Programming language

All CAD packages are written in programming languages. To begin with, most of them were written in FORTRAN (Stark 1986), which stands for Formula Translation. It was designed to solve numeric computational problems (Chivers and Sleightholme 2012). With regards to the development of graphical interfaces and the programs becoming more interactive, most CAD programs are now written in C and its descendants, C++ and C# (Schoonmaker 2002).

Figure 2-12 shows one example of a 3D CAD app, Gravity Sketch, running on an iOS/iPad, which was written using C# (Gravity Sketch 2015).
2.4.4 Visual Programming Language (VPL)

A VPL is an application development tool that uses graphical components to develop a program, instead of using text-based codes. The environment of the tool is very user-friendly, requires only a very basic understanding of concepts like logic and variables, so that novices can operate it (Microsoft 2012). One example is Grasshopper, as a VPL for Rhinoceros.

From previous research, the capability of using Grasshopper to manipulate Rhino CAD models was already known to be powerful and easy-to-use (Cazon et al. 2014). Rhinoceros is usually abbreviated as Rhino or Rhino3D, and is a commercial CAD application program with 3D capability developed by Robert McNeel & Associates (Rhino3D 2014). The geometry system is based on Non-Uniform Rational B-Splines (NURBS), a mathematical model. With NURBS, the system can generate mathematical representations of 3D geometry and precisely describe any shape, from a simple 2D curve to a complex 3D freeform surface and solid (Ellerin 2004).

Grasshopper is a graphical algorithm editor and a plugin for Rhino3D. This add-on offers new ways for interacting with 3D models including generating geometry through mathematical functions, changing the 3D shape by dragging control points or sliding the buttons (Grasshopper 2014). Unlike other 3D programming languages and libraries such as JavaScript, Python or Three.js, Grasshopper does not require scripting skills. As a visual programming editor, users write a script by using command blocks. By combining Rhino3D and Grasshopper, designers can make a 3D model with open parameters that can be easily modified later on.

It can be used to convert explicit Rhino models into parametric models, where parameter values can be typed in or selected by means of slider bars or using the control points of curves. These become the inputs to a procedural program that regenerates the Rhino model with new dimensions or other values. The program itself is created in a visually intuitive flow-diagram interface (Figure 2-13). Using Grasshopper, it is possible to generate a simple user-interface that can be used to directly modify the size and shape of a Rhino CAD model, in real-time.
Rhino3D and Grasshopper have to be installed on the computer. Although Grasshopper is free, Rhino3D is around £700. This means the system is not yet affordable for the general public. To make it accessible to the public, the system can utilise Platypus, an add on for Grasshopper that can allow the Rhino model to stream the geometry to the web in real time (Platypus 2014).

In conclusion, Rhino3D, Grasshopper and Platypus can give access to the general public to modify a design through the web browser without any additional cost on the top of the broadband connection rate.

2.4.5 3D app creators ODO-UCODO

Digital Forming is built and dedicated for designers to create apps that allow consumers to tweak the shape, size, colour, and/or configure the design aspects and select material of a pre-defined basic object (Digital Forming 2014). UCODO stands
for ‘User Co-Design Objects’ and is a platform that allows professional product designers and design orientated businesses to set up an online business for mass customisation. It allows access to anyone without a programming background and without the costs associated with setting up a new business.

Original Design Objects (ODO) software is used to customise existing 3D designs rather than to create new products, so that designers can carry on using their preferred CAD system. Using this tool, designers can upload their creation to the CODO Showcase using technology on Digital Forming’s server. After uploading the 3D customisable model, designers can invite their customers to interactively co-design a virtual lifestyle product, which can then be manufactured into bespoke products. Figure 2-14 shows the relationship of ODO to CODO in a Digital Forming platform and illustrates how consumers can customise the product and print it.

![Digital Forming platform](image)

**Figure 2-14:** Digital Forming platform (top); CODO showcase at Digital Forming website: customisable 3D model toy car (bottom left) and 3D printed toy car (bottom right), designed and created by the author

This software uses a facet-based modeller to work on an stereolithography (STL) files (Campbell et al. 2014). In the definition stage, a designer works on an STL file of

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4 A facet-based modeller creates a geometric which is represented by collections of points, edges and triangles, respectively (Smith et al. 2010).

5 An STL is a file format that can be accepted by most AM/3D printing, the format approximates surfaces of a solid model with oriented triangles (facets) (Rypl and Bittnar 2006).
a product to create features and options that the consumer will be able to modify or select. This model is then published on the internet where the consumer can access it, make changes to the product’s form or configuration (e.g. number of petals on a flower), and then ask for their design to be printed. The advantages of ODO are its ability to work with STL files and to create an internet accessible model. The disadvantages are the time it takes to create the features and options and the inherent difficulties of working with a facet-based modeller compared to a conventional modeller. There are no standard features or parameters to work with and so everything must be defined by the user.

2.5 Consumer Manufacturing

Today, people have various emerging technologies which impact their lives in different ways and they implement them in almost every aspect of everyday activities (Gooday 2008). For example, the camera industry produces cameras for amateur use with digital features that can create photographs like professionals (Grotta and Grotta 1999). Some gadgets and software are now so affordable and help people to perform any application in everyday activities, for instance, photography and photo printing. Digital cameras with all sorts of facilities and flexibilities have made the picture-making process easier. It is possible to shoot the object easily and review the result instantly after taking the picture. Pictures can then be touched up using digital image software on a tablet, laptop or mobile phone. There are many free image editing apps on the internet, although the commercial software packages tend to have more features, greater flexibility and much better results (Glines 2014). After the editing process, the consumer no longer has the need to bring it to the print shop. Since the 1990s, the printing process can be done directly from a home computer, as easily as taking the picture, so consumers can manufacture the printed photos at home using a photo quality 2D printer (Wildstrom 1996).

Another example of this technology relates to sculpture. Statues are known as art work and not many people are able to perform and duplicate the human shape, because it is very unique (Wilson 2001). However, with 3D scanning technology used to capture a full body scan, Pinla3D can print full size statues of people within four to
six weeks by using AM/3D printing technology (Sevenson 2014). The scanning technology devices capture the 3D data that can be used to ‘print’ the statue (Kopf et al. 2013). Cameras on smartphones can be turned into 3D scanners. Either using 123 Catch, a free app from Autodesk (Autodesk 123D 2014a); by taking up to 40 photos the app will convert them into a 3D model, then 3D print it (Fedreheim and Bjørnstad 2012); or for an additional £359 3D camera from iSense, by attaching to an iPad or iPhone, without any post-processing like the 123 catch app, iSense displays the 3D image directly on the tablet screen (Cubify 2014). With the gadgets that we already have, people can actually create their own product without the need for any artistic skill. Figure 2-15 below shows the camera positions for taking pictures (a) and an iPad with iSense that can turn a 3D object directly into 3D model.

![Figure 2-15: (a) Using a digital camera with 123 catch app; (b) iSense and iPad for 3D scanning (Cubify 2014; Instructables 2014)](image)

2.5.1 DIY

As discussed in sub-chapter 2.1 page 11, industrial/product designers take primary responsibility for form-giving through design to manufacturing processes. DIY is used as its antithesis where the DIYers believe that this activity brings a more self-driven, democratic design process, as well as manufacturing activity carried out more closely to the end user who developed the product (Petrie 2013). DIY allows consumers to engage actively with the design and production process to express a more personal view, unbounded by the limitation of mass production and passive consumption (Atkinson 2006).
The definition of DIY is still problematic since the boundaries range across different levels of activity: handicraft (Edwards 2006); home maintenance; decorating; self-build house and garden design (Brown 2008); vehicle repair (Clapper 2006); and of relevance here, customisation (Khalid 2000). The boundaries are blurring, but Atkinson (2006) attempted to categorise DIY into four distinct areas (Atkinson 2006):

1. Essential DIY, is an economic necessity, consisting of home maintenance activities carried out due to unavailability of professional labour. It often involves instruction manuals.

2. Lifestyle DIY, is conspicuous consumption consisting of home improvement or building activities. It usually employs one’s own labour.

3. Reactive DIY, is a motivation that might range from the occupation of spare time to personal pleasure, consisting of a hobby, handicraft or building activities. A user engages with predetermined components or kits and assembles or builds them through patterns or templates.

4. Pro-active DIY, is a motivation of personal pleasure and sometimes financial gain containing strong elements of self-directed, creative design, or might involve skill to adapt or manipulate existing products.

One of the interpretations of DIY is scoped in the fields of design, art and craft (Greenhalgh 1997). In the United States, crafts and hobbies are often meant as a break from work and those activities are to reflect and reproduce these values and bring utilitarianism into the home. This brings a new perspective on the meaning of leisure, namely productive leisure (Gelber 1999). Today this development has its place in places such as Home Depot outlets (Johnson 2004) and B&Q shops in many countries (Williams 2008). B&Q has provided “You Can Do It” centres to help adults to learn, and for children they run “Kids Can Do It” classes at their shops and in schools (B&Q 2009; Clark 2009).

According to the progression of DIY users expanding the areas that they are able to operate in, AM/3D printing technology and its advantages will have plenty of room to encourage DIYers (Armstrong 2013). This kind of manufacturing technology will influence and increase their capability (Hughes and Sinclair 2010). Nowadays, they
are fully equipped with tools and kits that they can buy from DIY stores, but in the future they may even have mini, or personal manufacturing capability in their garage (Wallich 2010).

2.5.2 AM/3D printing for consumer manufacturing

To assist the general public in manufacturing their own products, there have been a number of tools that have been available for decades. In woodworking for example, besides producing industrial level equipment, companies also provide machines for consumers (Figure 2-16). Nevertheless, people need to learn skills and have a lot of practice in order to master them. They need to learn woodworking techniques such as measuring, marking, cutting, jointing, polishing, and painting (Education Scotland 2012). With the AM/3D printing technologies, the need to be highly skilled in craft is not necessary because the process of shaping the object will be done by the machine itself relying on the creation of 3D models.

![Figure 2-16: Portable table saw (left) and woodworking hand tools (toolstop.co.uk 2016)](image)

AM/3D printing was not readily accessible to the general public until 2007 when the first RepRap Darwin was released at under £1,000 (3D printing industry 2014) and the Fab@Home Model 1 (Malone and Lipson 2007). Researchers and industries have contributed greatly to the improvement of AM/3D printing technology and have made it more simple, adaptable, user-friendly and accessible for the general public (Jones et al. 2011). This trend is following a similar path as the personal computer.
Before the implementation of the integrated circuit and microprocessor in the 1970s, computers were generally large, requiring a special room. The mainframe computer processor had to be shared among many people, to be economically practical. It was a costly system and usually owned by large companies (Abbate 1999). Now, the computer components have become much smaller, cheaper, lower cost and, as a result, computers have become distributed in the form of desktops, laptops or tablets. The same trend will occur with 3D manufacturing technology, as it moves from the plant to the desktop (Benthien 2008; May 2009). Users are not merely replicating industrial processes, but having access to manipulating and experimenting with machines and materials. It can be done by remotely accessing the design and manufacturing process through browser interfaces, or as the well-established home knitting or printing solutions are now available as home appliances, they can access them directly (Hughes and Sinclair 2010). Reeves (2015) envisages that the manufacturer-consumer relationship as shown in Figure 2-17 has moved from “consumer[s] who buy everything on demand and companies make to stock”, to “consumers who personalise everything and companies serve on demand” to “consumers would make everything and brands make nothing” (Reeves 2015).

![Figure 2-17: manufacturer - consumer relationship evolution](image)

### 2.5.3 Manufacturing technology progression

Consumers, marketing and production technologies have a push-pull inter-relation (Brem and Voigt 2009). Consumers can influence how the marketing is conducted
and urge researchers to observe new technology to accommodate their requirements (Nemet 2009). This can be achieved through manufacturing technologies which are able to produce high quality products at an affordable price (Swanson and Lankford 1998). As a result, consumer needs, marketing methods and production knowledge have evolved during this time, and this evolution is illustrated in Figure 2-18. It shows that the manufacturing technologies have moved respectively from craft customisation (before 1783), fragmented production (1784-1889), mass production (1890-1974), and mass production with variety at low cost (1975-1990), to mass customisation (after 1990).

![Figure 2-18: Manufacturing progression: from craft customisation to mass customisation (Westbrook and Williamson 1993)](image)

The way products are created has changed. After the industrial revolution, mass production became the most popular system for creating products for the marketplace. However, with regards to the need for personalisation, mass customisation has the capacity to serve the consumer as an individual.

Figure 2-19 explains the change of production from craft customisation to mass customisation, based on Feinstein (1972) above, then the study suggests the continuation to consumer manufacturing.
2.5.3.1 **Craft customisation**

Before the industrial revolution, people only consumed their basic needs such as food, drink, clothes and housing (Maslow 1954). Households produced some kinds of goods and brought them to market where they could be traded with other products that they did not make (Casson and Lee 2011). These economic activities are commonly referred to as a pure subsistence economy (Quilter and Stocker 1983). In the production context, a product was initially made one-by-one by hand, according to each individual’s need, and this procedure was carried out by individuals or home industries (Applebaum 1992). Consumers and producers met directly, face to face, to make and trade products, so the relationship was close and strong, and led to the production of customised products, made by artisans for each customer (Sheth and Parvatiyar 1995).

2.5.3.2 **Fragmented production**

After 1783, as a consequence of economic activities, entrepreneurs started to bloom and organised manufacturing activities, such as dividing the production of products that have many parts attached, based on skills of makers and/or the different materials (Christy 1992). The parts were therefore produced by artisans and home-scale manufacturers or workshops. People often practiced their trades out of shops that were attached to, or a part of the houses in which they lived (Bythell 1983). The fragmented production, often called cottage industries or putting-out system, became common in the rural areas in the pre and early industrial period (Sokoloff...
and Dollar 1997). Figure 2-18 shows how, as the system was implemented, the number of product variants decreased.

2.5.3.3 Mass Production
Manufacturing technology was the cause of the industrial revolution. Machine-based industries gradually replaced manual labour-based manufacturing. It started with the mechanisation of textile manufacturing, the creation of iron-making techniques and the invention of steam power (Berg 1985). Distribution was a key to spread the mass manufactured products, so to support trade expansion, canals, roads and railways were rapidly developed (Turnbull 1987). It could be said that the concepts of economics was born at that time, considering how many businesses were founded, established and grown (Browne 2003). As a result, the number of products that were made by the mass production system started to increase.

The most significant step towards mass production was the introduction of the assembly line to increase volume and speed. A prominent example was the production of the Ford automobile, the first affordable car in the world (Weitzman 2002). Henry Ford pioneered the use of Just-In-Time, a method for automotive industries (Yates 2008). This production system typically divides production into easy and simple tasks. Utilising moving tracks or conveyor belts, the partially completed products are transferred to workers on a special task. Whilst the products are moving along, workers perform repetitive tasks. Many techniques of producing parts to make the main product were invented. For example, moulds and dies. By combining moving tracks, moulds and dies, these techniques allow very high volumes of production (Crowson and Walker 1996). Ford was the first automotive industry that employed moving tracks by using horses pulling the partially complete cars (Abrams 2011). It was believed that they revolutionised the way of car manufacturing where previously they built a car base on request for every customer (Hounshell 1984).

2.5.3.4 Mass production with variety at low cost
Chain production systems have contributed improvement needed to reduce costs and time of production. As a consequence, the number of variants of products declined. After the mass production era, production systems were required to
provide various products to fulfil consumers’ needs at any different market segment and keep the same level of pricing as that of mass production (Fisher et al. 1995).

This system was a metamorphosis of mass production arrangements and started the move towards the next trend of production, mass customisation. From the very few numbers of variants, or even only one type, as Ford offered, a company differentiates products: a wide range of exclusive high-quality products for the upper class and a more narrow range of low-quality products for the middle class (Foellmi et al. 2014). The improvement of mass production was achieved by reducing the cost of variety and hence still allowing the company to offer a larger set of products (Fisher and Ittner 1999).

This flexible manufacturing method successfully increased the number of product variants and in turn companies’ attention to consumers grew more and more.

2.5.3.5 Mass customisation
Companies strived to produce products and services to meet individual customer's needs with near mass production efficiency. After 1990, simplification of product variants was criticised, and consumers required industries to hear their expectation with regard to style, size, need or even schedule (Berry and Cooper 1999). This system was popularly known as flexible manufacturing to support mass customisation. Flexible manufacturing has a perfectly flexible production technology and thus can offer improved variety, reduce costs, develop products quicker, speed delivery and satisfy unique customer needs (Anderson 1997).

Customised products and low cost production have been mutually exclusive, mass production provided low cost but at the expense of uniformity and customisation offered individual products. Mass customisation can combine two opposite technologies into one, and interactive technologies, such as the internet, allow customers to interact with a company and specify their unique, specific and individual requirements which are then manufactured by automated systems (Pine 1993a).

One of the success stories in this field is the National Bicycle Industrial Company (NBIC) in Japan. The firm stated that a customer can choose from eight million
possible variations, based on model types, colour, frame size, and other features, when ordering a custom-made bicycle. In this mass customisation factory system, the production process begins after the arrival of the customer's order and specifications. Once the individualised bicycle order is manufactured, the bicycle is shipped the same day (Kotha et al. 1996).

Another example of the changes that have taken place is in dressmaking. For instance, a person who wanted a new item of clothing could make their own or engage someone to make it only for them. They would have to be measured and the dress would be custom-made to their proportions. This traditional method seems similar to the customised products that are made today where, for example, Intellifit, a garment company, has recently utilised 3D full body scanners to measure and tailor clothes for the fitting of individual customers (Intellifit 2009; Piller 2008).

2.5.3.6 Manufacturing by consumer
The trend to integrate technology with business strategies and consumer preference has simplified and shortened the process of obtaining products or services. In terms of creating a product, production systems, historically, evolve from craft customisation as an individual fabrication to mass production then back again with the help of AM/3D printing, because of its capabilities to serve consumers as individuals the same as craft customisation but with new techniques (Berman 2012). Customers can be treated individually as in the pre-industrial era (Davis 1987).

One of the advantages of AM/3D printing is that people can build a one-off-product. As technologies have the ability to build a single unique product, a company does not need to rely on designers to handle every consumer who wants to personalise their own products. Thus, many companies solve the problem by providing consumers some sort of tools that can be easily operated.

The term ‘consumer manufacturing’ in this thesis means: “an activity of the consumer or general public to manufacture their products either through online services, rented manufacturing system or their own production machine; in which the product will be for personal use by themselves”.
2.5.4 Consumer manufacturing via internet

The use of the internet to offer manufacturing services makes the technologies, such as Shapeways, Ponoko, Kraftwurx and iMaterialise, accessible to the general public. They have created a market for customised products where anybody, from an individual to a company, regardless of size, can create and sell a design or a product, as well as manufacture it on demand. The system attempts to eliminate the need for a centralised product development process and manufacturing plant. These systems recruit a community of digital manufacturers – AM/3D printing machines, CNC routers, and computerised laser cutters - scattered around the world. The production site is located as close as possible to the point of purchase to reduce shipping costs. As a result, consumers can obtain products quicker at lower cost.

Figure 2-20 shows the process of ordering a product through Shapeways and Ponoko. Both of them explain the same stages that consumers can follow. Step 1 – Design it, they can start with a ready-to-print product, design using any 3D CAD or use one of the browser-based design tools on their website. Step 2 – Upload it, upload the 3D model. Step 3 – Choose it, material selection in which the customer can choose available materials depending on the shape of the model, and review the price. The rest, Step 4 – Make it, manufacturing the product, and Step 5 – Ship it, dispatching to the consumer’s address will be done by the manufacturer.

![Figure 2-20: Consumer manufacturing portal](Ponoko 2014; Shapeways 2014a)

Nowadays, the general public can have an affordable AM/3D printer at home, but it is unlikely, it can print everything they need (Diegel 2015). This can be solved by using
online AM/3D printing services, such as 3D Hubs. Online AM/3D Printing is served by growing numbers of professional companies and a crowdsourcing type portal to facilitate transactions between 3D printer owners and people who want to 3D print their designs. Through 3D Hubs, printer owners can join by registering their machines and city to offer 3D printing services in their neighbourhood, and people can locate printer owners to get products printed nearby (3D Hubs 2014). This service offers not only 3D printing at a consumer level but also high-end industrial-grade services; the full spectrum of 3D printing is becoming accessible. Based on the data in October 2015, 3D Hubs lists 23,000 3D printers in more than 150 countries in their network, or about 15% of total 3D printers sold today (compared to Wohlers report data which indicates that 152,434 AM/3D printing systems were sold in 2014). Figure 2-21 shows the locations of all AM/3D printing systems on the 3D Hubs network. Consumers can write their location to find the makers nearby or by zooming the map.

![AM/3D printers location map under 3D Hubs network](image)

**Figure 2-21: AM/3D printers location map under 3D Hubs network**

### 2.5.4.1 Internet of things AM/3D printers

The concept of the internet of things is also applied on the AM/3D printers. Astroprint makes AM/3D printers available on the cloud where users can control it remotely using a web-browser at any device such as a phone, tablet, laptop or PC; it eliminates the need to transfer 3D models via a SD card or USB memory (AstroPrint 2014). Similar to Astroprint, PrinToPeer also developed the system that enables the AM/3D printers to be remotely controlled by users anywhere and anytime, it also offers a camera, allowing users to watch the build real time and pause the process if something is going wrong (PrintToPeer 2015). These IoT AM/3D printers would help the community to share their 3D AM/3D printing machines through websites such as
3D Hubs. All the AM/3D printer owners need to do is to make sure the machine and materials are ready and let users do the rest.

### 2.5.4.2 Online tool for reviewing AM/3D printing results

Willit 3D print also uses browser-based system as the platform of their program, so users do not need to install the program. It offers a capability to check the 3D model (stl or amf file format) before users print it: test whether the parts can be AM/3D printed or not; preview the surface roughness based on the build orientation and selected machine; show the support structure; calculate building time and cost; estimate carbon footprint; scale and export to stl/amf format (willit3dprint 2011). The database of the machines is still limited, but the idea and the potential can support AM/3D printing communities. Figure 2-22 shows how the product would look like if the user is using a MakerBot 3D printer, material ABS and 0.27 standard layer thickness.

![Figure 2-22: Willit 3D print, analysis 3D model before print](image)

### 2.5.5 The availability of AM/3D printing technologies for consumer manufacturing

AM/3D PRINTING has contributed to the shift in design paradigms and potential radical change in the way products are designed and manufactured because AM/3D printing is able to build components with a complex intricate geometric, and process considerations are much less prominent (Campbell 2015). The simplification of the
way of producing a product has started to change the way of manufacturing them, for instance individuals are able to create household goods on an AM/3D printing machine (Prindle 2015). Developments are continually growing, and a set line of flexible material has also been developed (Meisel and Williams 2015). This invention also offers the completely unique ability to build the products and assemblies made (Calì et al. 2012) of multiple kinds of materials (Sitthi-Amorn et al. 2015), with different mechanical or physical properties, all in one-shot. Moreover, to create more sophisticated products, 3D printers that print in multiple materials and colours have also been released to the market (Stratasys 2014a).

One of the factors that makes the system of manufacturing 3D printing expensive, is patents. There are now many low cost 3D printers on the market using material extrusion technology. Crump (1992) predicted this would happen because the patent, which was filed in 1989 and published in 1992, expired in 2009 after 20 years. After this, sales of these printers grew significantly.

Another factor, which is significantly contributing to the growing of consumer levels of AM/3D printers, is the RepRap project, initiated by Bowyer in 2005. Most of the low-cost 3D printers are developed and improved from RepRap design (Peels 2015). It is because the concept of the machine design, hardware and software, is open-source and its components can be produced by anyone. Therefore, anyone can replicate any number of RepRap machines ether for themselves or for others, without royalty payments (Wittbrodt et al. 2013). Self-replicating ability has grown from 50% of its own parts to 73% (RepRap 2015). It is clear that AM/3D printing machines are now becoming an affordable option to small businesses and potentially to the individual consumer (Anderson and Sherman 2007; Collins n.d.). RepRap Tricolour Mendel, offer a kit for assembly for £740 (RepRap 2014); Solidoodle sells a ready-to-print Press 3D printer for £450 (Solidoodle 2015); and Printrbot, produces Play 3D printer for only £260 (Printrbot 2015).

Powder bed fusion and material jetting are considered to offer better surface finish and wider materials; these technologies have not been implemented yet for such low cost 3D printers but soon will be employed by makers, due to the coming expiration
of the patents for these methods (Almquist and Smalley 1996; Deckard 1997). Moreover, the technique that offers full colour 3D prints based on 2D printing inkjet technology also expired in 2013 (Sachs et al. 1993), which means the market will have wider options to use or buy AM/3D printers.

In 2012, Committee F42a on Additive Manufacturing Technologies from the American Society for Testing and Materials (ASTM) defined a set of standards that classify the range AM/3D printing based on the similarities in processing. There are seven categories: (1) binder jetting, (2) direct energy deposition, (3) material extrusion, (4) material jetting, (5) powder bed fusion, (6) sheet lamination, (7) vat photopolymerization.

2.5.5.1 Binder jetting

“An additive manufacturing process in which a liquid bonding agent is selectively deposited to join powder materials” (ASTM International 2012).

The technology was originally developed at MIT in the late 1980s and was called 3D printing (3DP) (Sachs et al. 1993). As shown in Figure 2-23, the machine works by spreading a thin layer of powdered material at a time then selectively spraying a binder through an inkjet print head nozzle to join powder material in a bed. After one layer is completed, the powder bed is moved down incrementally so the next layer of powder material can be applied. The process is repeated until the entire 3D object is created within the powder chamber. The loose powder that is not bounded remains and is used as support material for subsequent layers.

![Figure 2-23: Basic system of Binder jetting](image-url)
The advantage of using this technique lies in the ability to manufacture complex 3D objects without the external supports required during the processes since the powder bed itself supports overhangs. It also offers the advantages of speedy fabrication, low materials cost, and colour output. However there are limitations on resolution, surface finish, product fragility and materials availability (Dimitrov et al. 2006). To increase the strength, binder jetting printed products need to be infiltrated with epoxy/resin (xlaFORM 2008).

The binder jetting technologies can process diverse materials: metals, including copper, bronze, aluminium, cobalt chrome, stainless steel, and tooling steel, have all been cast in ceramic shells produced through this process (McMains 2005). Samples of AM/3D printing machines that employ this method are ZPrinter, Projet, Voxeljet Technology GmbH, ExOne.

2.5.5.2 Direct energy deposition

"An additive manufacturing process in which focused thermal energy is used to fuse materials by melting as they are being deposited” (ASTM International 2012).

Sandia National Laboratories first developed the direct energy deposition and patented it in 1987 with the trademark name Laser Engineered Net Shaping (LENS). Figure 2-24 shows that the print head contains a focused laser beam and powder delivery nozzle. The focused laser beam melts the target surface and develops a pool of molten metal and then the powder feeder deposits the powder metal on to the surface (Grylls 2003).

Figure 2-24: Basic system of direct energy deposition (3D printing industry 2014)
The benefits of using this process are: it can be used for repairing products and can add new topological features and functionalities on existing components. The downside of the system is design limitation, such as lattice structures and internal chambers (EPMA 2015). Examples of systems that utilise this technique are Laser-engineered net shaping (LENS), electronic beam welding (EBW), direct metal deposition (DMD), and EasyCLAD machine. The National Research Council Canada produces laser consolidation, and EBDM and DMG MORI Seiki combines this system with CNC and manufactures hybrid manufacturing technology. This system only accepts metal as a material (Gibson et al. 2010).

2.5.5.3 Material extrusion

“An additive manufacturing process in which material is selectively dispensed through a nozzle or orifice” (ASTM International 2012).

Crump from Stratasys Ltd, developed and patented this method in 1989 (Crump 1992). Material extrusion is a solid based process meaning that the material employed to build the final product is solid when in its raw state. The system consists of a movable head unit that deposits a thread of molten material onto a substrate. This process builds parts mostly using a filament or viscous liquid of material. During the physical process of building a product, this filament/liquid is fed through a heating element and becomes semi-molten on the build platform (Figure 2-25). Then, the filament is fed through a nozzle and deposited onto the partially layered construction part (Gibson et al. 2010).

![Fused Deposition Modelling basic system](3D printing industry 2014)
The strengths of this process are: as Crump predicted (1992), the patent ended in 2009 so the machines built based on this system are sold at an affordable price and are relatively easy to operate. The weaknesses of the method are: the need of a support structure and poor surface finish.

Various materials can be extruded in this process: thermoplastics, ceramics, metal-filled clay, concrete, food and living cells suspended in hydrogel or other substance; in state of filament, viscous liquid or slurries. Examples of this category are fused deposition modelling (FDM) and contour crafting. Desktop 3D printers and AM/3D printing at consumer level, available on the market, employ FDM. Forty six out of 53 (87%) machines are used from this system (Bredemeyer 2015).

2.5.5.4 Material jetting

“An additive manufacturing process in which droplets of build material are selectively deposited” (ASTM International 2012).

The process uses multiple printing heads (for main and supporting material) simultaneously and selectively jetted liquid or molten state photopolymer (Kruth et al. 2004). The main material is cured to solid state with a trailing UV light that passes over the deposited material. The same thing happens to the support material but it is cured to a gel state that can be removed easily afterwards (Hopkinson and Dickens 2006). The advantage of this system is the ability to adjust the composition of the materials so it can construct a different range of mechanical and physical properties gradually, from rubber to rigid, and opaque to transparent (Meisel and Williams
Examples of machines that use this system are Connex series and Projet 5500X. Photopolymer resin based, including elastomeric materials, can be processed by this system.

2.5.5.5 **Powder bed fusion**

“An additive manufacturing process in which thermal energy selectively fuses regions of a powder bed” (ASTM International 2012).

It was developed and patented by Deckard and Beaman in 1992 (Deckard et al. 1992). Figure 2-27 explains the principle work of the system. The fine powder material is swept by a roller from a tank of powder material next to the build tank and it is spread evenly over the build platform. A piston on the material supply tank moves upward incrementally, inversely, a piston of the build platform moves down one object layer thickness to accommodate the new layer of powder. A laser beam is then scanned over the surface of this powder material to fuse it together to form a layer of the object. The build platform chamber is maintained at a temperature just below the melting point of the powder material therefore the temperature only needs to be raised slightly to cause sintering. Finally, the process is repeated in every powder layer until the entire 3D object is created. After the object is fully formed, the piston is raised to elevate it. Extra powder is simply brushed away (Kruth et al. 2003).

![Figure 2-27: Selective Laser Sintering typical layout](3D printing industry 2014)

The strong point offered by this technology is that no supports are required with this method since overhangs and undercuts are supported by the solid powder in the
materials chamber. Also, as the lose powder acting as support can be used again, there is no waste material from this method. The downside of this process is the surface finish is not as smooth as in the material jetting process, but still better than the material extrusion system. Powder bed fusion can process thermoplastics, modelling and investment casting wax, metal powders, sand and ceramics. Examples of this method are selective laser sintering (SLS), selective laser melting (SLM) and electron beam melting (EBM).

2.5.5.6 Sheet lamination

“An additive manufacturing process in which sheets of material are bonded to form an object” (ASTM International 2012).

The system builds a product layer by layer by cutting the sheet, and bonding/welding it to the previous sheet (Obikawa et al. 1999; Park et al. 2000). Helisys initiated and patented the process in 1987, which uses a roll of one side adhesive-coated craft paper (Feygin et al. 1998).

![Sheet lamination schematic layout](image)

**Figure 2-28: Sheet lamination schematic layout (3D printing industry 2014)**

Unlike other methods in which the material needs to be prepared at a state that can be accepted to the system, one of the sheet lamination machines can use standard sheets of office paper as a build material. This machine is capable of printing full colours ink on the parts. To make the part moisture-proof, it needs to be coated by a waterproof sealant (Reece 2014).
The machines that use this method are Cubic Technologies (formerly known as Helisys) LOM, Fabrisonic-UAM (combined with CNC-machining capabilities), and Mcor. In principle, any sheet can that can be cut, stuck and bonded can be used for this process, such as paper, aluminium foil (Himmer et al. 1999) and sheet steel (Obikawa et al. 1999; Yi et al. 2004).

2.5.5.7 Vat photo-polymerization

"An additive manufacturing process in which liquid photopolymer in a vat is selectively cured by light-activated polymerization" (ASTM International 2012).

It was patented by Charles Hull from 3D Systems Corp. in 1984, using the name stereolithography (SLA) (Hull 1986). The system is similar to material jetting but in liquid state. Figure 2-29 shows that the machine consists of a movable build platform mounted in a vat of photocurable liquid resin, which means the liquid will be hardened under exposure to a low-level energy UV-light source. To process the liquid to a solid state, a moving laser beam driven by computer cures the surface of the photocurable liquid resin. Once the process of solidification of a cured layer has been done, either the interior of the 2D cross sectional is hatched or solidly filled, the movable platform is then moved up to one layer thickness below the surface and left until the liquid has settled. Then a next layer is traced right on top of the previous one. The hardening process of the solid object layer is repeated until the whole object is complete. After that, the parts require post processing for complete cure, surface finish and stability (Pham and Gault 1998).

![Figure 2-29: Vat photo-polymerization schematic layout (3D printing industry 2014)](image-url)
This method can produce very fine detail and smooth surface finish. Based on Wohlers’ Report (2015), 7 out of 53 (13%) models of desktop 3D printers are developed based on this system: B9 creator, Peachy, Pegasus Touch, Miicraft, LightForge and ProJet 1200.

2.5.6 Additional post-processing: Enhancing AM/3D printing to produce consumer products

Due to the way of building a product in AM, the roughness of a product is considerably higher than other conventional manufacturing, such as injection or blow moulding. Therefore, not all consumer products can be replaced by AM/3D printing products. It is still the case that surface finish, accuracy, and materials are one set of obstacles that persist (Ahn et al. 2008; Kim and Oh 2008). The term ‘additional post-processing’ in this thesis refers to a further process not required by the system, to differentiate from ‘post-processing’ required by the system, for example removing the support structure.

One of the challenges of AM/3D printing that needs to be improved is surface finish and colours. As explained in the sub-chapter previously, there are only a few technologies that can give many colour options. The paragraphs below will give alternative solutions to make the surface performance better in term of smoothness, strength and colours.

2.5.6.1 Smoothing

Manual polishing is the obvious solution, but it would consume a lot time and needs patience. Tumbling is an alternative technique that can be used for smoothing and polishing rough surfaces of AM/3D printed products. The products are placed in a barrel with some media (water and ceramic) and rotated for a few hours. During tumbling the media abrades the part thereby polishing it.

Figure 2-30, as an example of the tumbling process, and shows how it can improve the grainy rough surface from the powder based fusion category, SLS technology.
Shapeways uses tumbling machines with little grains of plastics and ceramics in soap and water that vibrates against the products. The process takes about 3 hours.

![Figure 2-30: Tumbling process: (a) before and (b) after (Shapeways 2011)](image)

### 2.5.6.2 Colouring

Not so much 3D AM/3D printing offer multi-colours materials, especially for consumer level machines. There are some existing process such as painting, coating and dyeing, which are applied to plastic products that can be used. Although painting can be an option to change the colour of AM/3D printed product it needs hand skills in order to obtain good result.

Dyeing is the process of infusing colour pigment into a surface or material as deeply as possible by soaking the products at 90 degree Celsius in a mixture of dye pigment and water. Figure 2-31 shows the result of converting white material into four different colours.

![Figure 2-31: Dyeing process: infiltrated colour pigments on the 3D printed products (Shapeways 2011)](image)

A coating is a covering on the surface with the purpose of colour preference or surface finish smoothness using paint or composite metal materials. A specially adapted electroplating process, developed by AT-3D Squared, plates a composite metal material onto a plastic offering a structural coating and an improved surface performance (Figure 2-32) (3DDC 2014).
2.5.6.3 Strengthening

Strengthening post processing is applied for powder the bed fusion category, i.e. SLS, 3DP and sheet lamination that uses paper. Infiltration is a method to increase the strength of parts and also can make the colour brighter. For products made from paper, this method seals the surface, thereby parts can be used in a high moisture environment. To achieve it, this post processing can be done manually or using xlaFORM machine. Resin and epoxy would be used for products which are required to be strong and durable; and an elastomer for flexible characteristic parts (Reece 2014; RPT 2004).

2.6 Recent development in areas of consumer design and manufacturing

Sinclair (2012) describes a consumer designer as “an interested participant in design of his or her own, unique, products” (Sinclair 2012, p.79). It is in line with the conception of ‘lay design’ introduced by Guido (2015), “a layperson or the non-professional or consumer who engages in design” (cited in Hermans 2015, p.4). The concept is similar to the term consumer design used in this thesis.

Herd (2012) focused on co-design experience, as an important stage of and integral part of the mass customiser journey. Figure 2-33 shows the area of Herd’s research where she added a series of co-design experiences into the mass customisation journey developed by Watkins (2007) (Herd et al. 2010; Watkins 2007), and the place of her PhD research. The conceptual models and design tools were built to support the co-design experience journey, which comprises: co-design activity, product
purchase and receipt of product, and this research explores the specific tools for the consumer in designing AM/3D printing products.

![Figure 2-33: Co-design experience as an integral part of the mass customisation journey](image)

Piller and Ihl (2009) categorised three different modes of intensity for how customers can contribute to products and/or services: design for customers, design with customers and design by customers:

**Mode 1 – Design for customers:** Products are designed by the company on behalf of the customers using information from varied input channels such as sales feedback, consumer input or market research.

**Mode 2 – Design with customers:** The company observes customers’ responses to a proposed design, functional prototype or beta product and then amend the design when necessary.

**Mode 3 – Design by customers:** Companies let users become actively involved in giving feedback in the development process, by providing them with tools. Examples for this mode include co-design toolkits, user idea contests or lead user workshops.

This study extended Mode 3 – Design by customers, because the aim of this research is to help consumers became actively involved in designing their own products.

Vaisnory and Petraite (2011), in their research on customer-business company interaction in the innovation process, found that it changes across Mode 1 to Mode
3, from closed innovation to open innovation (Figure 2-34). As this PhD research aims to facilitate the general public in the design process, it will explore open innovation. This is also in line with the research conducted by Townsend et al. (2015) showing that niche marketing has been rising, as mass marketing has been decreasing; and with it there has been a greater consumer involvement as a consequence of companies equipping their customers with design customisation tools.

Figure 2-34: Modes of customer involvement and consumer-company interaction, adapted from Piller and Ihl (2009); Vaisnore and Petraite (2011)

The level of consumer participation in creating a product is varied, thereby to clarify it Sinclair and Campbell (2014) classify the degree of consumer involvement in the product development process from conception, specification, design to manufacture. As the aim of this study was to examine the potential of consumers to actively engage in designing a product, this research fits with the level of participation at the design level, prior to manufacture.
Figure 2-35: A classification of consumer involvement in New Product Development and the area of this PhD research (Sinclair and Campbell 2014)

Sinclair (2012) explored more the involvement of consumers in the design process, which is usually done by industrial designers. He let participants, as consumer designers, complete several tasks to hand-sketch their own product and interact with a CAD expert to build and visualise in 3D digital models. After evaluating the process with the consumer designers, he suggested the concept of a toolkit for consumer design. The design tool was presented using Adobe Flash, so it was not a working prototype.

Hermans (2015) extended the work in this area by offering a concept of design tools for the general public, which he refers to as “digital-physical toolkits”. The toolkit is meant to enable a layperson to create a design using computer-aided tools and then the output can be produced using AM/3D printing. Using 3D Studio Max, Rhinoceros 3D and Grasshopper for building digital-physical toolkits, consumers can change design parameters using a set of sliders Figure 2-36-A). The purpose of this method, which focused on design output and process, was to identify the behaviour of participants (Figure 2-36-B).
Therefore the investigation of consumer preferences in manipulating a product shape has not been identified yet. This PhD research also created a toolkit using sliders with type input capability, and a drag point type as an alternative. Consumers can change the 3D models either using slider bar controls or drag points. The reason users were offered two ways of manipulating 3D models is to uncover consumer preferences. The existing consumer design tools currently provide those two types: direct manipulation and indirect where the direct manipulation of a control point might give a more intuitive and natural feel rather than the slider type. This is because for the indirect manipulation, slider type, the place on the screen to modify the dimension is not in the same area as the result of manipulation, so users need to watch two different areas simultaneously.

Research on consumer participation in design and product realisation shows that engaging participants at stage one enhances affective commitment to the product (Atakan et al. 2014). However, involving them at both stages did not generate added value for users compared to the effects obtained for high levels of participation in either stage. The marginal effect of consumer involvement might actually decrease as the level of participation increases (Franke et al. 2010). These findings helped to drive the aim and objectives of this research, which focus on consumer participation in the design stage, rather than the manufacturing stage.
CHAPTER 3  Research Methodology

The focus of this research is an exploration of potential for consumers to design their own products, by facilitating them using CaCODE and AM/3D printing, therefore it aims to assess which systems are suitable for the consumers, in this case laypersons, to undertake design actions, then manufacture by themselves within the current available systems.

3.1 Theoretical foundation

The study is concerned with the evolution of the manufacturing industry from mass production and mass customisation progressing to individualised design and manufacturing in which a product is designed and manufactured by and for a market of one. To facilitate this, it explores ways in which consumers might interact with a 3D model along with the willingness to use consumer design software, and the views of consumers on the appearance of AM/3D printed products.

Based on knowledge gained from the literature review, the research standpoint on the theoretical foundation can be seen as:
The progress of AM/3D printing technology shows that the capability has moved from developing prototypes, then functional prototypes and now end-use products. At the industrial level, Nokia has released open-source files, containing mechanical drawings, case measurements and recommended materials, that will let Lumia 820 smartphone users 3D print their own customised case (Campbell 2013). At the consumer level, many products can be 3D printed through websites such as Shapeways, Ponoko, Cubify, iMaterialise and Sculpteo.

AM/3D printers have reduced in cost and become affordable for the general public to have in their homes as a home appliance. However, these technologies do require a level of skill, especially as AM/3D printing needs a 3D model as an input; and one of the systems that can produce the model is 3D CAD. The progression of CAD shows that its utilisation has moved from manufacturers, to engineers, to industrial designers, and now to consumers.

3.2 Research design stages

To select the most suitable methodological approaches, the following sub-chapters discuss the appropriate choices adopted and how the particular methods were applied. Figure 3-1 shows the stages of research outlining the relationship within the steps.

![Figure 3-1: Research stages adapted from Gray 2014; Robson 2011](image)

3.2.1 Research paradigm

A research paradigm is a basic set of beliefs, theories or assumptions which guides the study and how it should be studied (Denzin and Lincoln 2013; Robson 2011). There are three paradigms for structuring research that can be employed: Positivism
and post-positivism, constructivism/interpretivism and critical approaches (Robson 2011).

Positivism and post-positivism are the view that social research exists externally and objectively; that the researcher and observed persons are independent of each other and that the reality can be discovered through the adoption of experiments and surveys with qualitative methodologies (Denzin and Lincoln 2013).

In the constructivist/interpretivist view, the reality is socially constructed by participants acting on their knowledge of it. So, participants help the researcher interpret a view of reality using a naturalistic set of research methods such as case studies, interviews and observation. This is needed in order to acquire multiple perspectives where the research findings are commonly presented in terms of criteria of grounded theory (Robson 2011).

The critical approaches view criticizes both positivism/post-positivism and constructivism/interpretivism. The researcher is viewed as a relatively powerful expert researching relatively powerless participants and trying to find ways to overcome this imbalance in power. This category includes feminism, neo-Marxism and anti-racism (Blaxter et al. 2010).

This study has involved the development of understanding of the general public’s values, motivation and behavioural change. Therefore, it would have been difficult to find only one reality with controlled scientific ways as with positivism/post-positivism. Moreover, critical approaches are also not suitable as the topic of this thesis is not about exploring power. As a result, the constructivist paradigm has been adopted as the most appropriate approach as it enables a creation of knowledge mutually developed by researcher and participants.

3.2.2 Research purpose
There are four types of purpose that can guide a research study: exploratory, descriptive, explanatory and emancipatory (Robson 2011).
Table 3-1: Classification of purposes of enquiry (Robson 2011)

<table>
<thead>
<tr>
<th>Type</th>
<th>Description</th>
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<tbody>
<tr>
<td>Exploratory</td>
<td>- To find out what is happening particularly in little understood situations.</td>
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<td></td>
<td>- To seek new insights.</td>
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<td></td>
<td>- To ask questions</td>
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<td></td>
<td>- To generate ideas and hypotheses for future research.</td>
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<td></td>
<td>- Almost exclusively of flexible design.</td>
</tr>
<tr>
<td>Descriptive</td>
<td>- To portray an accurate profile of persons, events or situations.</td>
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<tr>
<td></td>
<td>- Requires extensive previous knowledge of the situation etc. to be researched or described, so that the researcher knows the appropriate aspects on which to gather information.</td>
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<tr>
<td></td>
<td>- May be of flexible and/or fixed design.</td>
</tr>
<tr>
<td>Explanatory</td>
<td>- To seek an explanation of a situation or problem, traditionally but not necessarily in the form of causal relationships.</td>
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<tr>
<td></td>
<td>- To explain patterns relating to the phenomenon being researched.</td>
</tr>
<tr>
<td></td>
<td>- To identify relationships between aspects of the phenomenon.</td>
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<tr>
<td></td>
<td>- May be of flexible and/or fixed design.</td>
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<tr>
<td>Emancipatory</td>
<td>- To create opportunity and the will to engage in social action.</td>
</tr>
<tr>
<td></td>
<td>- Almost exclusively of flexible design.</td>
</tr>
</tbody>
</table>

This research used an exploratory and explanatory approach because consumer led design and manufacturing is a relatively new area. Also, this study did not have any intention to prove or disapprove any existing knowledge, but to build understanding of how to develop a system and strategy that can enhance, motivate and assist the general public in designing and creating their own products.

3.2.3 Research strategy

Robson (2012) presents two possible strategies: fixed or flexible. The fixed strategy is associated with methods that result in quantitative data, hence it is also often referred to as a quantitative strategy. There is a high level of pre-specification before researchers reach the main data collection stage. The flexible strategy is more associated with methods that support the collection of qualitative data with a low level of pre-specification, and the research design evolves and changes during data collection. This type of strategy is often commonly referred to as a qualitative strategy. The flexible strategy includes case study, ethnographic study and grounded theory (Robson 2011). Regarding the research objectives, the flexible strategy was selected.
A case study is expected to capture the complexity of a single case and has been widely used, not only in social sciences such as psychology, sociology, anthropology and economics, but also in environmental studies, education and business studies (Johansson 2003). Typically, case study research starts from the desire to derive a close/an up-close or otherwise in-depth understanding of a single case, or small number of related cases, especially when the boundaries between phenomenon and context are not clearly evident (Yin 2012).

Ethnographic study involves observation of an intact cultural group and their natural activities over time (Creswell 2002). It aims to explain the ways that culture is constructed by the behaviours and experiences of its members. In consumer research areas, this methodology tends to be particularistic for specific cultures rather than generalizable for the whole population (Arnold 1998).

Grounded theory is traditionally associated with sociology, health and organisational studies, although it has also been applied for marketing and consumer research (Goulding 2005). It is also useful in new and applied areas where there is a lack of existing theory and concepts, to build theory through analysis of data (Robson 2011). As the research to uncover the intention of the general public towards designing and manufacturing a product by themselves, and whether the design system developed by this study could enhance and motivate them to lead to design and fabrication, the theory will be built based on data collected and analysed.

### 3.2.4 Research type

In quantitative research, a quantity or amount is measured and it is appropriate to phenomena that can be analysed in terms of quantity. On the other hand, qualitative phenomenon is the main concern in qualitative research, i.e., phenomena are related to or involve quality or kind (Kothari, 2004).

Creswell summarises and compares quantitative, qualitative and mixed methods approaches (Creswell 2003) and Table 3-2 was used to select the appropriate method for this study.
### Table 3-2: The appropriateness of the three approaches to the research objectives

<table>
<thead>
<tr>
<th>No</th>
<th>The researcher uses these practices of research:</th>
<th>Appropriateness for Research objectives</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Quantitative Approach</td>
<td></td>
</tr>
<tr>
<td>1.1</td>
<td>Tests or verifies theories or explanations.</td>
<td>×</td>
</tr>
<tr>
<td>1.2</td>
<td>Identifies variables to study. Relates variables to questions.</td>
<td>×</td>
</tr>
<tr>
<td>1.3</td>
<td>Uses standards of validity and reliability.</td>
<td>×</td>
</tr>
<tr>
<td>1.4</td>
<td>Observes and measures information numerically.</td>
<td>✓</td>
</tr>
<tr>
<td>1.5</td>
<td>Uses unbiased approaches. Employs statistical procedures.</td>
<td>×</td>
</tr>
<tr>
<td>2</td>
<td>Qualitative Approach</td>
<td></td>
</tr>
<tr>
<td>2.1</td>
<td>Positions himself or herself. Collects participants’ meaning. Focuses on a single concept or phenomenon.</td>
<td>✓</td>
</tr>
<tr>
<td>2.2</td>
<td>Brings personal values into the study.</td>
<td>✓</td>
</tr>
<tr>
<td>2.3</td>
<td>Studies the context or setting of participants.</td>
<td>✓</td>
</tr>
<tr>
<td>2.4</td>
<td>Validates the accuracy of the findings.</td>
<td>✓</td>
</tr>
<tr>
<td>2.5</td>
<td>Makes interpretations of the data.</td>
<td>✓</td>
</tr>
<tr>
<td>2.6</td>
<td>Creates an agenda for change or reform.</td>
<td>×</td>
</tr>
<tr>
<td>2.7</td>
<td>Collaborates with the participants.</td>
<td>✓</td>
</tr>
<tr>
<td>3</td>
<td>Mixed Methods Approach</td>
<td></td>
</tr>
<tr>
<td>3.1</td>
<td>Collects both qualitative and quantitative data.</td>
<td>×</td>
</tr>
<tr>
<td>3.2</td>
<td>Develops rationale for mixing. Integrates the data at different stages of inquiry.</td>
<td>×</td>
</tr>
<tr>
<td>3.3</td>
<td>Presents visual pictures of the procedures in the study.</td>
<td>×</td>
</tr>
<tr>
<td>3.4</td>
<td>Employs the practices of both qualitative and quantitative research.</td>
<td>×</td>
</tr>
</tbody>
</table>

✓ = applicable  × = not applicable

Almost all of the qualitative approach criteria are applicable for this study except for creating an agenda for change or reform. These criteria may apply to social-political science or economics. Therefore, this research involved qualitative methods.

### 3.2.5 Research method

This stage explains what research methods were selected to enable the study to collect the data, which is needed to answer the research objectives.

#### 3.2.5.1 Selecting research participants

In qualitative research, participants should be intentionally determined by the needs to achieve the aim of the study; this is commonly referred to as ‘purposive sampling’ (Boeije 2010). As designing and ordering an AM/3D printing product is another way of buying goods, the sampling was taken based on consideration of factors affecting consumer buying behaviour.
Chapter 3 Research Methodology

Tanner and Raymond (2012) suggest that personal, psychological, culture/societal and physical/situational factors influence consumer behaviour for purchasing a product. A personal factor is a consumer’s character as other people see it; this includes gender, age and life stage. The psychological factor is based on Maslow’s theory, where humans fulfil their basic needs, such as food, water and sleep, before they can begin satisfying higher-level needs. Culture influences the way in which people live within a community, hence to some degree, consumers in the same social class show similar buying behaviour. This factor includes economic classes and educational status. Situational influences are temporary conditions and cover physical factors such as a store’s environment (location, layout, music, lighting and even scent), time and also mood.

To limit the size of this study, this research dropped three factors and focussed on personal factors. The physical/situational factor was not selected because there are too many aspects not directly related to AM/3D printing. Psychological, culture/societal and personal factors are actually related to each other. These would lead to the need to have many more participants, because it would require having samples of each psychological category, culture/socioeconomic class, educational status, age and gender.

This thesis profiled the participants on age and gender as two sub-aspects of personal factor. Age can be used as a central and a socio-demographic variable, as it serves to purify other variables into causal factors or to highlight structures (Rughiniș and Humă 2015). In theory, each generation should not be treated in the same way, because they have unique expectations, experiences, generational history, lifestyles, values, and demographics that influence their buying behaviours (Williams & Page, 2011). A generation or age cohort is a group of persons going through similar life experiences and have a common social, political, historical, and economic environment, hence produce unique shared values and behaviours, they are often classified as unique market segments (Wellner 2000). Sociological research has also indicated that each generation has their own characteristics that cannot be simply related to the stage of their life (Browning and Worman 2008). The characteristics
would be useful for researchers and industries to segment the target and/or the market:

Table 3-3: Generations adapted from William & Page 2011

<table>
<thead>
<tr>
<th>Generation</th>
<th>Birth</th>
<th>Age in 2015</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-Depression</td>
<td>Before 1930</td>
<td>86 and above</td>
</tr>
<tr>
<td>Depression</td>
<td>1930 – 1945</td>
<td>70 – 85</td>
</tr>
<tr>
<td>Baby Boom</td>
<td>1946 – 1964</td>
<td>51 – 69</td>
</tr>
<tr>
<td>Generation Z</td>
<td>After 1994</td>
<td>Less than 21</td>
</tr>
</tbody>
</table>

Based on the 2010 Office for National Statistics (ONS) summary of findings, senior citizens over 65 years of age are most likely to miss ‘older’ technologies, i.e. television (60%), radio (18%), and printed newspaper/magazines (11%); compared to the ‘newer’ technologies such as the internet (3%) and mobile phones (1%) (Milligan and Passey 2011). Therefore, those over the age of 65 were excluded when this thesis was being written, were excluded. For the lower limit, the study recruited children from 5 years old, because at this stage pupils start learning design and technology (D&T) formally in school (Department for Education 2013).

Gender data was taken because some research results compare gender and creativity. In some research, males’ performance surpassed females’ on creativity tasks (Stoltzfus, Nibbelink, Vredenburg, & Thyrum, 2011; Cox, 2002; Dollinger, Dollinger & Centeno, 2005). However, other research shows no significant differences between males and females (Kaufman, Baer and Gentile, 2004) and in terms of creative personalities, some researchers have found similarities (Chavez-Eakle, Lara & Cruz-Fuentes, 2006; Szobiova, 2006). At least two studies found women’s creative ability exceeded men’s (Reuter et al., 2005; Wolfradt & Pretz, 2001). This study wanted to consider the gender issue and therefore recruited equal numbers of men and women.
Creswell (2007) and Marshall et al. (2013) recommend 20 to 30 interviews should generally be included in this type of study, whereas Denzin and Lincoln (2005) suggest 30 to 50 participants. The study recruited 40 participants with equal numbers of female and male respondents, between 5 and 65 years old and grouped in 10 year-age-groups. The number of participants was chosen because it satisfied the criteria suggested by the previous researchers. Also, it has convenient as it fitted with the Design Practice Research Group’s budget. To make sure the samples of each 10-year age-group were well distributed there has a balance of males and females in each group.

With all of the generations represented and the genders well distributed, the result should indicate the potential for the general public to design and manufacture consumer products similar to the consumer product studied by this research, i.e. a pen.

3.2.5.2 Questionnaires/structured interviews

Questionnaires or structured interviews are one of the most widely used social research techniques that can produce both quantitative and qualitative methods including mixed-method, the research type that has been chosen used in this research. Consumer acceptance questionnaires were undertaken for both the AM/3D printing consumer product and CaCODE evaluation to explore the intention of the general public in developing a product. Also, the participants were asked to try to use CaCODE and evaluated the software by answering a series of questions. For evaluation of the AM/3D printed products, respondents were shown a range of consumer products, in this case study a pen, to let them look, see, use and feel the shape, surface finish as well as the colour quality.

3.2.5.3 Observation through usability test

Besides sampling and structured interviews/questionnaires that have been discussed in the previous sections, this study also used observation methods to determine what most users liked and did not like. There is another method to gather information using observation of participants, which is a focus group discussion (Robson 2011).
In focus group discussion, a number of people, typically 5 to 10 real users, sit around the table, led by a professional moderator, and respond to ideas and/or designs that are displayed using sketches, digital models, prototypes or product samples (Krug 2014). It provides information about users’ opinions or preferences, but it does not usually indicate how participants actually behave with software (George 2008). A usability test has several people as testers, one user at a time, to operate with the tool, each one being observed by a researcher (Krug 2014). It gives detail information about the behaviour of participants while interacting with software (Dumas and Redish 2011).

Therefore a usability testing method was selected in this research. The purpose of this test is to confirm the assumptions made when building the design software prototype; and to identify problems and use them as input for improvement. During the test, quantitative data was also taken to support qualitative analysis, i.e. how long participants took to learn and complete the design.
CHAPTER 4 Development of Consumer Design Software and an AM/3D Printed Consumer Product

This chapter discusses the development of consumer design software and AM/3D printed pens, as stated on the research objectives (page 6), first “to identify the state of the art in consumer design tool development software and AM/3D printing with capacity to facilitate this” and second “to examine the level at which consumers will accept the material and production properties of AM/3D printing”. The purpose of this task is to examine whether the general public can operate the design software and ascertain the strengths and weaknesses of the system to see which features still need to be improved. After development, the software was used in the consumer acceptance study, the results of which can be seen in Chapter 5.

Several samples of one consumer product were built as artefacts to be assessed by participants acting as consumers. A pen was selected as a sample of a consumer product in this study. It was chosen because a pen is relatively simple, has an everyday use, and can be very personal. It is also a kind of product that has a large
range in price from possibly very cheap, or even disposable to very expensive and precious.

4.1 CaCODE Development

To answer the first research question, a design tool called Computer-aided Consumer Design (CaCODE) was built. The name of the program is derived from the term, ‘Computer Aided Design’, where the word ‘Design’ is replaced by the words ‘Consumer Design’. The aim is to help consumers do much of the design process. The concept of the design tools is described in Figure 4-1 and Figure 4-2 below. As previously mentioned, CaCODE should be easily operated by the general public without CAD skills.

One type of consumer design tool available today is a design configuration program. These programs are also called co-design tools and are defined as software applications that create particular products where consumers can build a certain version by choosing some elements. This type of tool is limited by the choices of design configuration provided and can often be confined to choosing colours, patterns and performance options. Examples are NikeiD for personalising shoes (NIKEiD 2008) and Fabido for customising 3D products such as USB memory sticks and key rings (Fabido 2015).

Web-based ‘easy’ CAD tools have been released, which consumers can access through the Internet with no installation required. These are 3D CAD systems where users are required to build 3D models from scratch. A certain degree of design skill is still required, which can be a problem, since some people believe that not everyone can be a designer (Bradley 2014; Duffy and Keen 2006; Wohlers 2007). In fact, from a study involving the general public designing a consumer product, 27 out of 30 participants would prefer to start designing using a template rather than a blank screen (Yavari 2015). To overcome this problem, this research offers an easy CAD system that does not require consumers to start from a blank screen. Instead, they are given a starting point product that they can manipulate until they achieve a shape with which they are happy. Therefore, it will fill the gap between the existing
design tools (design configuration tools and blank screen CAD) for consumers in terms of producing 3D data for making AM/3D printing products (Figure 4-1) (Campbell et al. 2014).

![Figure 4-1: CaCODE’s area of development](image)

Figure 4-1: CaCODE’s area of development

Figure 4-2 describes the concept of ranges in design skill needed to operate the tool, what product can be produced and type of manufacturing. For design skill, the tool is targeting hobbyists to non-technical users. The CaCODE can only create specific products, not general products; and can be manufactured using AM/3D printing technologies.

![Figure 4-2: CaCODE’s range of development](image)

Figure 4-2: CaCODE’s range of development

To simplify the tools CaCODE is made specifically for one particular product or similar shape. This study will offer a CaCODE-Pen, which enables users to modify its shape by sliding buttons or directly modifying the control points of the 3D model.
4.1.1 Creating the pen design

Before creating the modifiable starting point 3D model pen, it was necessary to have an idea of what the pen should look like. This stage required an experienced designer to produce a 2D sketch (Figure 4-3, see also Appendix A – Pen development, page 192)

Afterwards, a 3D CAD model was built in the Rhinoceros CAD system by interpreting the 2D sketches.

![Figure 4-3: 2D sketches of the starting point pen design](image)

After generating the 3D model, it was then reconstructed by reducing the number of loft surface components, i.e. the profile curves, to a minimum (Figure 4-4). They could then be used by consumers as modifiable parameters. The number of curves determines the degree of freedom. The more parameters that can be changed by consumers, the more design freedom they have, but also the higher the level of difficulty. On the other hand, having fewer parameters will limit consumers' freedom in playing with the shape while presenting a lower level of difficulty.

![Figure 4-4: Simplifying the profile curves used for CAD construction](image)
4.1.2 Building the CaCODE:PenCAD

CaCODE:PenCAD was programmed using the Grasshopper software extension to Rhinoceros. Grasshopper is a graphical algorithm editor integrated with Rhinoceros 3D modelling tools. This software creates a ‘programmable’ CAD model but it requires no knowledge of programming or scripting. Although Grasshopper requires substantial effort in building the model definition, the result can be easily operated by non-designers to modify even very complicated 3D constructions (Grasshopper 2014). With this feature, a design tool was created where consumers could modify the shape of the pen either by sliding buttons or by directly modifying the control points of the 3D model.

To keep the development and use of CaCODE simple, it was decided to cater for one particular product or application at a time. This would mean that the number of user inputs could be kept to a minimum, making the system easy enough to use for someone with no prior CAD skills. Eventually, CaCODE variations were created for several products including plates, vases and beakers (discussed on section 4.1.2.3 CaCODE for other application, page 80). All of these products were rotationally symmetrical, meaning that only a 2D profile had to be manipulated by the user. Consumers can change the 3D models either using slider bar controls or drag points. Besides offering two different methods, it also gave two styles of pen: asymmetrical and symmetrical.

4.1.2.1 PenCAD type 1: asymmetrical pen

The aim of this research was to involve consumers in 3D design manipulation so what were effectively “2.5” dimensional components were considered too simple. Therefore, a slightly more complicated product was chosen as the vehicle for the first user trials of CaCODE. The product was a curved pen, as shown in Fig. 3. It was truly 3 dimensional and yet its shape could still be controlled fully using a reasonable number of parameters.

The first stage of the CaCODE development process was to build a Rhino CAD model of the pen design. This was fairly straightforward and only required the placement of a few points, four circular or elliptical profiles and a lofted surface. The designer then
had to decide which parameters were to be fixed and which could be modified by the consumer. This is an important aspect of any consumer design system since there are certain elements of the design that must be protected for functional, safety or brand requirements (Sinclair et al. 2011). The selected parameters were then given appropriate names to be used in two ways, firstly as variables inside the Grasshopper flow-diagram program and secondly, as slider bar inputs on the Grasshopper user-interface. The program was then constructed as a series of boxes either representing algorithmic procedures (e.g. calculations) or Rhino modelling functions. For example, X, Y and Z values were first used to generate a point at the top of the pen and this in turn was used with two radial values to generate an ellipse, which finally became part of the lofted exterior surface of the pen. Limits were set on the slider bars to ensure that no unreasonable values could be selected that would result in an unrealisable or self-intersecting model.

**Figure 4-5** shows that the pen was built by four sections of circles where the top and middle circle positions were movable and the diameter of each circle was changeable (detail script available on Appendix B – Grasshopper script, page 194). Also, by using another parameter, the circles could be modified to become ellipses. The bottom and end circles were fixed, because they had to match the ink refill. The sliders presented in the top left box are the top circle parameters and those in the bottom left box are for the middle circle parameters. The larger box on the right is the algorithm definition, which processes the input from the sliders and thus creates the surface of the pen.
Chapter 4 Development of Consumer Design Software and an AM/3D Printed Consumer Product

Figure 4-5: Grasshopper: Building a script for the CaCODE:Pen tool

The completed user-interface including graphics windows, is shown in Figure 4-6. The consumer designer simply needs to move the sliders on the right and watch the pen design change in the three graphics windows. Figure 4-6 shows how the CaCODE:Pen interface appeared to the users. There is a control panel on the right and, by using the mouse, users could change the pen by sliding the small buttons on the sliders. In addition, the interface has three display views, front, right and isometric, so users could evaluate the appearance of the pen that they were designing.

Figure 4-6: The user interface of the CaCODE:PenCAD
4.1.2.2 PenCAD type 2: symmetrical pen
The pen was built by one curve with five points as controls. However, one point of curve control points at the bottom was fixed as a hard point because it had to match the ink barrel. Therefore, users have four points to manipulate. The modifiable curve could then be revolved using the script as shown in Figure 4-7 (A). The script written in Grasshopper and interfaced to Rhinoceros was quite simple, but it was sufficient to give freedom for users to manipulate the pen as they wished Figure 4-8 (B) (detail script available on Appendix B – Grasshopper script, page 194).

![Figure 4-7: PenCAD2, symmetrical pen (A) user interface and (B) Grasshopper script](image)

4.1.2.3 CaCODE for other applications
This study also explored possibilities for creating CAD for other consumer products, which can be built using this system. Three different applications have been built: household products: tableware; wearable consumer products: shoes; and hobbyist/electronic products: drones.

**TablewareCAD**
The CaCODE: TablewareCAD enables consumers to create revolved shape such as tableware, from shot glass, whiskey glass, pint glass to dinner plate, dog plate or bowl (Figure 4-8).
Chapter 4 Development of Consumer Design Software and an AM/3D Printed Consumer Product

Figure 4-8: CaCODE: TableWare, creating dining equipment 3D models

ShoesCAD
It is common for shoe-makers to offer the same style but different sizes. This ShoeCAD accommodated the requirement allowing users to change the size without changing the style. It is challenging when regular scale functions cannot be applied in this case. Figure 4-9 demonstrates the script to parameterise the shoe surface and size.

Figure 4-9: CaCODE:ShoesCAD, customising the size of 3D model of shoes

DroneCAD
DroneCAD allows hobbyists to change the parameters of a drone - the position of the propellers in the x, y and z axis. By changing the size of the propeller arms, users can add a camera, or just change the shape for style reasons. The drone body shell can also be shaped by dragging the control points. In addition, it offers ‘snap-on’ fittings, so the users are able to assemble them without using any tools.

81
Figure 4-10: DroneCAD, design and prototyping

Figure 4-10: shows the CaCODE:DroneCAD, customising shell body and adjusting the propellers’ arm length; printing with material jetting polyjet Connex500; assembling components; and first fly trial

4.2 Creating a range of samples

For the second research objectives “to examine the level in which consumers will accept the material and production properties of AM/3D printing”, several samples were built.

4.2.1 Process and material selection

Virtually all AM/3D printing technologies can fulfil all of the characteristics of end use product creation (Cantú et al. 2012). However, regarding the topic of this research where the outcomes would be made available to the general public, it is necessary to find suitable processes and materials that would be readily accepted by them. This section will explain how the processes and materials have been selected for the study.
This research used process methodology approaches as defined by ASTM International Standard Terminology for Additive Manufacturing Technologies (ASTM International 2012).

Although all of the technologies above can be used to produce a consumer product, this thesis focuses on the systems, which can produce a product (a useable pen) directly, with minimum hand-finishing and/or post-processing.

The study used material finish as an approach, with the assumption that a consumer would not actually consider what processes and what materials input are, as long as the material finish is good enough for a pen. The table below is adopted from a selection of AM/3D printing technologies in specific materials used to make direct consumer products created by Grenda, this approach was used as a source of ASTM bibliography (Grenda 2009).

Table 4-1: AM/3D printing technologies for consumer product adapted from Grenda (2009)

<table>
<thead>
<tr>
<th></th>
<th>Plastic</th>
<th>Metal</th>
<th>Ceramic/gypsum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Binder jetting</td>
<td></td>
<td>3DP</td>
<td>3DP</td>
</tr>
<tr>
<td>Directed energy deposition</td>
<td></td>
<td>LENS</td>
<td>SLS</td>
</tr>
<tr>
<td>Material extrusion</td>
<td>FDM</td>
<td></td>
<td>FDM</td>
</tr>
<tr>
<td>Material jetting</td>
<td>Polyjet</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Powder bed fusion</td>
<td>SLS</td>
<td>SLS, SLM, EBM</td>
<td></td>
</tr>
<tr>
<td>Sheet lamination</td>
<td>Vat photopolymerization</td>
<td>SLA</td>
<td>SLA</td>
</tr>
</tbody>
</table>

Material extrusion uses thermoplastics such as ABS, PLA, PA and PC, which are also commonly used in many other consumer products, so their strength is well proven. As material jetting uses curable liquid photopolymers, the materials composition can be varied to form rigid and rubberlike materials to simulate a range of Shore A
hardness values\(^6\) (Sherman 2014). This characteristic gives more possibilities for creating a pen; the hardest material is similar to ABS and the softest material is comparable with rubber bands (Stratasys 2014b). Vat photo-polymerization is also categorised as a photopolymer-based method and is considered to produce the same quality as material-jetting (Grenda 2009), but needs a support structure. As this research explored processes with minimum hand-finishing and/or post-processing, this method excluded from this study. The study also used powder bed fusion, because the typical material for this process is Polyamide or Nylon which is strong enough for a pen (Kruth et al. 2003).

Binder jetting for metal material needs post-processing using high pressure heat treatment to solidify and achieve high density metals. Direct energy deposition parts tend to have a rough surface finish and low resolution that needs to have a special finishing process such as CNC milling. This process was therefore excluded from this study. Powder bed fusion for metal is a very expensive process. Therefore, this study selected only one of these processes, SLM, and printed the sample for free at Lancaster Product Development Unit, Lancaster University.

The gypsum material product made by non-metal binder jetting is not strong enough as a finished product. One sample was built using this technology and infiltrated using an acrylic resin liquid, but it was broken after being snapped by hands. All of the AM/3D printing processes that use ceramic materials can be categorised as indirect fabrication, as the ceramic parts need to undergo the same processes as any ceramic part made using traditional methods of production such as kilning, firing and glazing. As a result, ceramic material was excluded from this study. Table 4-2 shows the summary of material and process selection for creating pens.

---

\(^6\) Shore A hardness value is used to determine the relative hardness of soft materials, such as plastic or rubber (ASTM International 2015).
Table 4-2: Material and process assessment for pen development

<table>
<thead>
<tr>
<th>No</th>
<th>Material</th>
<th>Process</th>
<th>Direct</th>
<th>Post-processing</th>
<th>Strength</th>
<th>others</th>
<th>Selection</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Plastic</td>
<td>SLS</td>
<td>Y</td>
<td>N</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>2</td>
<td>Plastic</td>
<td>FDM</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>3</td>
<td>Polyjet</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Multi-material</td>
<td>Y</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>SLA</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td></td>
<td>N</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Metal</td>
<td>SLS/SLM</td>
<td>Y</td>
<td>Y/N</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>6</td>
<td>Metal</td>
<td>3DP</td>
<td>N</td>
<td>Y/N</td>
<td>Y</td>
<td>N</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Metal</td>
<td>EBM</td>
<td>Y</td>
<td>Y/N</td>
<td>Y</td>
<td>N</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Metal</td>
<td>LENS</td>
<td>Y</td>
<td>Y/N</td>
<td>Y</td>
<td>N</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Ceramic</td>
<td>3DP</td>
<td>N</td>
<td>Y</td>
<td>N</td>
<td>N</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>Ceramic</td>
<td>SLS</td>
<td>N</td>
<td>Y</td>
<td>N</td>
<td>N</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>Ceramic</td>
<td>FDM</td>
<td>N</td>
<td>Y</td>
<td>N</td>
<td>N</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>Ceramic</td>
<td>SLA</td>
<td>N</td>
<td>Y</td>
<td>N</td>
<td>N</td>
<td></td>
</tr>
</tbody>
</table>

Y = Yes  N = No

4.2.2 Developing pens with different processes, materials and additional post-processing

Although the approaches explained in the previous section state that the systems should not let the user do too much work, the study extended the possibility of additional post-processing the products but with very little effort. As described in the additional post-processing section of the literature review, the study used all of the available options at that time, which were dyeing, tumbling and coating.

Samples have been created based on 3 parameters: materials, AM/3D printing technologies and post processing or finishing. The first parameter is based on Table 4-2, and samples were built from plastics and metal. Due to material properties, this case study did not use ceramics because they are fragile. Sample pens were built in many kinds of available processes, materials and post processing to get a better surface finish. The whole matrix of the range of sample pens is shown in table 4-3.
### Table 4-3: Additive Manufactured pens matrix

<table>
<thead>
<tr>
<th>Material</th>
<th>AM/3D Printing Tech's</th>
<th>Poly</th>
<th>SLS</th>
<th>FDM</th>
<th>Metal</th>
<th>Colour</th>
<th>Material</th>
<th>Additional post-processing</th>
<th>Remark</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Objet Connex 500 LDS</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>self-colour white</td>
<td>x</td>
<td>ABS-like</td>
<td>x</td>
</tr>
<tr>
<td>2</td>
<td>Objet Connex 500 LDS</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>self-colour white</td>
<td>x</td>
<td>ABS-like</td>
<td>x</td>
</tr>
<tr>
<td>3</td>
<td>DATUM, PRINTED BY OBIET CONNEX500/LDS, MANUALLY POLISHED AND METALISATION</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Objet Connex 500 HK</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>Dual</td>
<td>x</td>
<td>ABS-like &amp; rubber-like</td>
<td>x</td>
</tr>
<tr>
<td>5</td>
<td>EDSint P730 Shape ways</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>self-colour white</td>
<td>x</td>
<td>Polyamide PA2 200</td>
<td>x</td>
</tr>
<tr>
<td>6</td>
<td>EDSint P730 Shape ways</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>self-colour white</td>
<td>x</td>
<td>Polyamide PA2 200</td>
<td>✓</td>
</tr>
<tr>
<td>7</td>
<td>EDSint P730 Shape ways</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>self-colour white</td>
<td>x</td>
<td>Polyamide PA2 200</td>
<td>✓</td>
</tr>
<tr>
<td>8</td>
<td>EDSint P730 Shape ways</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>self-colour white</td>
<td>x</td>
<td>Polyamide PA2 200</td>
<td>✓</td>
</tr>
<tr>
<td>9</td>
<td>Dimension Laser lines</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>self-colour blue</td>
<td>x</td>
<td>ABS</td>
<td>x</td>
</tr>
<tr>
<td>10</td>
<td>Dimension LDS</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>self-colour blue</td>
<td>x</td>
<td>ABS</td>
<td>x</td>
</tr>
<tr>
<td>11</td>
<td>Realizer SLM100 LPDU</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>multi Stain</td>
<td>x</td>
<td>Stainless Steel</td>
<td>x</td>
</tr>
<tr>
<td>12</td>
<td>DATUM (MATTE), PRINTED BY OBIET CONNEX500/LDS, POLISHED AND PAINTED MANUALLY</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>DATUM (GLOSS), PRINTED BY OBIET CONNEX500/LDS, POLISHED AND PAINTED MANUALLY</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

86
4.2.2.1  **Datum pens (pen 3, 12, 13): Injection moulded pen quality**

The purpose of the development of pens was to evaluate whether their quality, in terms of surface finish, could be acceptable to consumers according to how the pen looked and felt. So, there was no exact measurement such as surface roughness because there may be a possibility where the current AM/3D printing capability could fulfil consumers’ requirements even though the surface finish was less smooth than the conventional method, i.e. injection moulding. However, it was still necessary to have a standard as a datum to see how far or close the evaluated pens were.

The datum pens were built manually and acted as injection moulded products. Three pens were created using AM/3D printing PolyJet Connex 500 at Loughborough Design School laboratory. Then they were polished using 300 grit then finished by 600 grit sandpaper. The first datum pen was sprayed matt purple and the second one glossy purple. Purple was chosen to make the pens look the same as other evaluated pens printed by Shapeways. The reason to equate the colours was to avoid participants’ preference for a specific colour.

The third datum pen was polished in the same way with the two previous datum pens, using 300 and 600 grits, but then it was sent to 3DDC, a company that specialises in metal coating for products that have been produced using AM/3D printing technologies. Metalisation is common process for injection moulded parts.

![Figure 4-11: Datum pens, material jetting – PolyJet, hand-polished, painted and metalized](image-url)
4.2.2.2 **Pen 1, 2 and 4: Material jetting - Polyjet, single plastic and multi-materials, with and without additional post-processing tumbling**

These pens represented the technology of Polyjet. One of the advantages of this technology is the ability to mix materials gradually from hard plastic to rubber characteristic. The first two pens, pen 1 and 2 (Figure 4-12) were single hard plastic materials (ABS-like VeroWhite). There was no additional post-processing for pen 1, but all of the products that were printed by this system needed to be post-processed by removing the support material. To simulate the situation at the consumer’s home, which would not have a water jet, the pen was cleaned manually using tap water.

Pen 2 is made from exactly the same material and process as pen 1 but with an additional tumbling process. The tumbling process was done by 3TRPD using a vibro-finishing machine. This was done to examine the viability of the option of increasing the quality of AM/3D printed products without overburdening consumers because they would not have to polish a product manually.

![Figure 4-12: Material jetting Polyjet plastic pens, additional post-processing and multi-materials](image)

4.2.2.3 **Pen 9 and pen 10: FDM, built vertically and horizontally**

These two pens (Figure 4-13) were printed using the most popular cheap and affordable AM/3D printing machine, FDM. Pen 9 was printed by Laser Lines using a Dimension 1200 machine with a vertical orientation using blue ABS, whereas pen 10 was created at Loughborough Design School laboratory, also using the a Dimension machine but in horizontal build orientation with white ABS.
4.2.2.4 Pens 5, 6, 7 and 8: SLS, with and without additional post-processing and; with and without dyeing

Shapeways printed these pens using the SLS method on EOSint P730. No post-processing is required. However, to give more choices of colours, this method still allows colour pigments to infiltrate the products by using an additional post-processing dyeing process (Pen 6 and 7 in Figure 4-14). For smoothness, tumbling was done by 3TRPD running the process on a vibro-finishing machine (Pen 6 and 8 in Figure 4-14). It can be seen on the Figure 4-14, there is a colour difference between Pen 6 and Pen 7. Pen 6 was the same colour as Pen 7 before being tumbled.
4.2.2.5 Pen 11: metal, manual finishing

A metal pen was printed at Lancaster Product Development Unit laboratory using SLM Realizer 100 Figure 4-15. Due to the limit of build envelop and aesthetic, the pen was divided into three pieces and joined later. It needed manual finishing in the area of the support structure. Post-processing was needed to remove the support structure using a vice and pliers and to hand polish the area where the support structure had been.

![Pen 11](image)

*Figure 4-15: Powder bed fusion SLM metal pen*
CHAPTER 5  Consumers’ acceptance of CaCODE and AM/3D printed pens

From the research questions and the literature review, two main areas needed to be investigated: (1) consumer design and (2) consumer manufacturing. For consumer design, the study’s aims were to uncover whether consumers were motivated to design their own product or not, and whether the CaCODE system that has been developed was a factor in this. In addition, in the consumer manufacturing area, the study’s aims were to investigate whether consumers had motivation to create their own product or not, and whether they wanted to use AM/3D printing technology for creating their own designed products.

5.1 Recruitment and strategy

In this section, the strategy, from recruiting participants, questionnaire building and development of a web-based survey, and analyse data method will be explained. Recruiting suitable respondents was important in order to uncover the potential of product development motivation among the general public in respect to gender and age. Questionnaire development will be explained to show the relation with the study’s objectives (Appendix E – Main study questionnaire, page 206).
As explained at section 3.2.5, page 68, the study recruited 40 participants with equal numbers of female and male respondents, between 5 and 65 years old and grouped in 10 year-age-groups (Figure 5-11 at page 112). Due to quite deep and intensive survey activities, answering questions, operating design software and evaluating the pens, a £10 voucher was offered as an incentive for the participants’ contribution.

Flyers were made to advertise the survey. It was highlighted that only non-designers could participate in the survey. To avoid refusing participants they were asked to complete an online registration form made on SurveyGizmo. On the first page, after the participant candidates entered the URL, SurveyGizmo asked the basic demographic data: gender and age. Then the website, set up by the author, automatically calculated whether the required number of participants of the group had been selected or not. If so, they could not enter the next page to register and participate. Successful candidates were given a chance to state their preferences for conducting the survey: at one of the Loughborough campuses or any other place they wanted e.g. at a coffee shop or at their house or office, and also at a time slot of their choice. For those participants under 18 a special consent form signed by their parents or carers was needed.

To identify the participants the following questions were asked:

1) Are you? ○ Female ○ Male

2) Please select your age-group:

5.1.1 Study protocol

Figure 5-1 explains the study protocol to ensure that the questionnaire, usability test and product evaluation were covered. At first, a participant was introduced to the study, the consumer product was defined and they were asked to read and sign the consent form if they were willing to continue to participate. The next section required the demographic data. Then participants were asked to answer questions relating to their willingness to design and make a product. At the end, they were asked whether
the personalised design and manufacture would possibly change their attitude towards consumer products.

1. **Registration.** Participant recruitment was announced using flyers and emails within the University. If someone was interested, they had to register online. The reason to do this was to filter the number of participants based on age and gender. Once the quota of each age group and gender had been fulfilled, such candidates could not register. This feature was provided by SurveyGizmo. If the registration was accepted, they were asked to select the slot available through YouCanBookMe website, which was connected to researcher’s Outlook calendar. Participants could also choose the place convenient for them to meet and do the survey, either at the Design School, their office or their home.
2. **Meeting.** Participants met at an agreed time and place and they did not need to bring anything, as the study data collection would be done via the SurveyGizmo website.

3. **Introduction.** Researcher introduced himself, the school and the research then asked participants whether they wanted to continue or not. If yes, participants were asked to sign the consent form, except for those under 18, who needed to be accompanied by their carer/parent.

4. **Willingness to design.** Participants started answering questions related to willingness to design a consumer product.

5. **Willingness to making.** Participants started answering questions related to willingness to make a consumer product.

6. **CaCODE trial.** In this session, participants were asked to operate CaCODE and required to produce two pen designs. Hence, the researcher and participants needed to perform:
   a. Training session: the researcher explained the software and how to use it. As the design tool was very easy, the PenCAD1 took one minute and PenCAD2 took 30 seconds.
   b. Then the participant did the design, the researcher observed and recorded the start and end time.
   c. After the participant was happy with the designs, their work was saved then they were asked related questions.

7. **AM/3D printed product evaluation.** In this session AM/3D printing and how it works was explained, then participants were required to rank the pens.

8. **Willingness to use CaCODE.** After participants had experienced using the software, the researcher explained other ways to obtain the 3D data as an input for AM/3D printing; participants then answered the questions related to this session topic.

9. **Willingness to use AM/3D printing technology.** After they evaluated the pens by ranking them, they were asked whether they would like to use the technology or not.
10. **Willingness to pay.** After they showed their preference, they were asked to give a price on the pens they like.

11. **Willingness to keep product longer.** Finally, the study needed to know about the emotional attachment of participants to the product they had designed.

### 5.1.2 Willingness to design

To uncover the potential of CaCODE to help laypersons, the participants were asked about their motivation before CaCODE was introduced, and their awareness of CAD. This was to make sure that they were unfamiliar with CAD. After that, the researcher explained the definition of consumer product intended in this study. To make an easy explanation, some consumer products that can be made by AM 3D printing were shown to the participants. In this case, consumer products mean solid physical objects that have three dimensions; common ready to use objects such as a mobile phone cover, bicycle handle bar grip, measuring cups, a plastic toy cat, a plastic mug, an egg cup and an ice cream spoon.

After the participant and researcher had the same understanding of the definition of consumer products in this research then the discussion about willingness to do design started. They were asked, “*Have you ever wanted to design a consumer product? OYes ONo*”. If the answer was “yes” they would be asked the following question “*Did you go on to design the consumer product? OYes ONo*”. For those who had an intention to design, they answered a following question whether they actually went on to design or not. As a result, there would be three profiles:

**Table 5-1: Grouping participants based on their intention and experience in design**

<table>
<thead>
<tr>
<th></th>
<th>Have intention to design</th>
<th>Have experience in design</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Group 1</td>
<td>✓</td>
<td>✓</td>
<td>have intention to design and experienced at least once</td>
</tr>
<tr>
<td>Group 2</td>
<td>✓</td>
<td>✗</td>
<td>have intention to design but have never designed</td>
</tr>
<tr>
<td>Group 3</td>
<td>✗</td>
<td>✗</td>
<td>do not have design intention</td>
</tr>
</tbody>
</table>
The study then explored more about their profiles. In this section, the participants who had design intention were asked “Please write the desired consumer product”. This was meant to try to understand what product was in the laypersons’ mind that they wanted to make, and to confirm their understanding of the meaning of product design.

The next questions explored the causes behind their profile. For profile 1, they were asked why they had never thought about design: ○ I cannot design or ○ I never thought about it, it is outside my area. Those with profile 2 were asked why they did not go on to design: ○ I cannot design or ○ I never thought about it, it is outside my area. Those with profile 3 were asked what tools they use to design the product: ○ Hand-sketching, ○ 2D design software/program, please specify_________, ○ 3D design software/program, please specify_________.

5.1.3 Willingness to use CaCODE

After all of the questions on the willingness to do design had been conveyed to the respondents, the CaCODE was then introduced. Using the script participants were trained how to use the design tool. Then they were asked to design by themselves until they were happy with the design. The researcher observed how they used the system, whether they seemed to be enjoying themselves or were frustrated using the tools. Also, the time they spent on the design software was also recorded.

Besides the observation from the researcher, the questionnaires also asked their opinion of the two types of PenCAD and how they felt about the user-friendliness of the software:

- I found it is easy to change the shape using sliders (PenCAD-type1)
- I found it is easy to change the shape using click & drag (PenCAD-type2)
- Using a 'ruler' is helpful when changing the shape

The following multiple choice answers on the Likert scale were given:

○ Strongly disagree ○ Disagree ○ Neutral ○ Agree ○ Strongly agree

There were open questions as well to let them add a comment:

“Are there any feature(s) of PenCAD that are difficult to use?”
“Are there any feature(s) you would like to add to PenCAD?”

After they had operated the CaCODE, the researcher explained that to get the product to be printed by AM/3D printing, it is not necessary to design by themselves. They can just easily download from many available websites providing 3D printable files online. In term of personalisation, the disadvantages of downloading a ready to print file is there is no option for laypersons to customise it. They will get the shape they download. The respondents were asked: “If you want to manufacture your desired product, would you prefer to: O design your own product using consumer design software, O download a ready-to-print product file, or O no preference.

From profile 1, where they have the intention and have done at least one design either using hand-sketching, 2D design software/program or 3D design software/program, the study would examine whether the CaCODE can fulfil their need comparing the tools that they have previously used. For profile 2, where participants have already had the motivation, the answer would show whether the design system could help them to realise their design intention. Moreover, for profile 3, the study would see whether the CaCODE system would motivate them to do a design.

5.1.4 Willingness to make a consumer product

A similar strategy above was also applied to unveil the willingness of the participants to manufacture their own product using AM/3D printing. Before the AM/3D printing technologies and samples of AM/3D printed products, the pens, were introduced, participants were asked whether they had ever had the intention to create their own product or not,

Therefore, regarding the first question “Have you ever wanted to make a product?”, if the answer was “Yes” they were asked to “Please write the desired product”. Also, they were asked the following question “Did you actually make the product?”. If the answer was “Yes”, they were asked “How did you make the product?”, with the following multiple choice options: O By hand, O Using (computer) machine tools, O
Chapter 5 Consumers’ acceptance of CaCODE and AM/3D printed pens

Used an expert / a technician / a service, ☐ Other, please specify_________. This set of questions and answers would categorise people as profile 1.

The next set of questions and answers was for participants who answered “Yes” for “Have you ever wanted to make a product?” but said “No” for “Did you actually make the product?”. The situation behind that profile was investigated by asking “Why not?” with the choices of answer: ☐ I was too busy, ☐ I did not have the skill to make it, ☐ It was too expensive and needed investment, ☐ I did not have the facilities/tools, ☐ Other, please specify_________.

As a result, there were three profiles:

Table 5-2: Grouping participants based on their intention and experience in making a consumer product

<table>
<thead>
<tr>
<th>Have intention to make a consumer product</th>
<th>Have experience in making a consumer product</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Group 1</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Group 2</td>
<td>✓</td>
<td>✗</td>
</tr>
<tr>
<td>Group 3</td>
<td>✗</td>
<td>✗</td>
</tr>
</tbody>
</table>

The next questions explored why some participants do not have the motivation to manufacture their own product and for those who have the intention, why they did not make it. From profile 1, the study would see whether the AM/3D printing system would motivate them to create a product. For profile 2, where respondents have already had the intention, whether the AM machines/3D printers could help them to make a product. Moreover, for profile 3, where they have the intention and have made at least one product either ☐ By hand, ☐ Using (computer) machine tools, ☐ Used an expert / a technician / a service, or ☐ Other, please __________, the study examined whether the AM/3D printing technology could fulfil their need comparing the tools that they have used.
5.1.5 Evaluating the appearance of the AM/3D printing pen

In a material perspective, AM/3D printing can produce the same strength level as any other conventional technique (Tymrak et al. 2014), i.e. this case injection mould. However, as the method involves building layer by layer, the most challenging problem of this technology is the surface finish (Armillotta 2006; Boschetto and Bottini 2015; Zinniel 2014). With this reason, this research explored how consumers can accept this limitation of AM/3D printing.

To make the comparison clearer, the study also placed pens with injection mould quality level (Pen 3, 12 and 13 as explained on the Sub-chapter 4.2.2.1, page 87) as datum without informing the participants how the pens were finished. This would position the injection mould quality pens within other AM/3D printed pens to compare how much they need to improve.

To make the task easy for participants to mark the pens, the study asked respondents to rank them in order. With this method, the researcher could get marks for every pen by giving a mark of 13 for rank 1 and gradually decreasing to a mark of 1 for rank 13. There was no guidance about what particular aspects of pens to rank, so they were just ranked based on participants’ perceived quality. Perceived quality is defined as consumer’s perception of a product’s overall excellence, quality and superiority, based-on his/her intention to use, compared to alternatives; and it can be different from actual objective quality, product-based quality or manufacturing quality (Aaker 1991). Therefore, it is not necessarily objectively determined, because it is merely a value judgement about what customers think is important. This way would show how the AM/3D printing could fulfil consumers’ preferences and the gap between conventional manufacturing and AM/3D printing.

After they finished ranking the pens, the preference aspects were asked. This was to avoid influencing participants’ thought by using preferences mentioned by the researcher for undertaking the task. The question “Why do you like it (the best one)?” was asked, with the following multiple choices where they could select more than one answer as well as give an open answer: Surface finish, Surface texture, Rubbery, Shiny, Matt, Colour, Weight, Other, please
specify:__________. This would help in understanding the most important preferences of the general public and uncover the gap with the AM/3D printing capabilities.

The study also explored the least preferences by asking “Why do you NOT like it (the worst one)?”, followed by more than one possible answer including an open answer:

- Surface finish
- Surface texture
- Rubbery
- Shiny
- Matt
- Colour
- Weight
- Other

Please specify:__________. This would help in understanding what needs to be avoided in developing a pen in particular and/or consumer products in general.

5.1.6 Willingness to use AM/3D printing to manufacture their own products

After participants evaluated the AM/3D printed pens and watched the video explaining how the printers work, they were asked to answer “Having now seen the quality of the 3D printed pens (EXCLUDING Pen3, 12 and 13); and the benefits of 3D printing which allow you to customise a product. Would you prefer to: O buy your own customised product made using a 3D printer, O buy a standard manufactured product, O no preference.

From profile 1, the study would see whether the AM/3D printing system would motivate them to make a product; for profile 2, where participants have already had the motivation, whether the AM machines/3D printers could help them to make their own product; and for profile 3, where they have the intention and have made at least one product, the study would examine whether the AM/3D printing technologies can fulfil their need.

The next two questionnaire sections, 5.1.7 willingness to pay and 5.1.8 Keep the product longer, were not applied for the youngest age group, 5-14, with the assumption that they are not capable of answering for those kind of questions.

5.1.7 Willingness to pay

Continuing the evaluation of the 3D printed pens, participants were asked their willingness to pay, that is, the maximum price which a consumer would pay for a
product or service (Gall-ely 2009). To reduce the effort from respondents to estimate the price, the survey asked them only to rank the top six of the AM/3D printed pens: “What price would you be prepared to pay for your top six pens?” This is to ensure the top three AM/3D printed pens were priced, in case they put the three datum pen on the top. The purpose was to evaluate what is a reasonable price for the AM/3D printed pens as judged by participants.

To check whether it could be achieved, considering the cost of AM/3D printing production, the result was compared to the actual cost of printing by an AM/3D printing service. The reason for comparing from one manufacture was to avoid the different factors such as handling, shipping and tax. Table 5-3 shows the comparison of five AM/3D printing manufacturers. Sculpteo offered the lowest cost for printing in PA material, but did not offer a steel material. i.materialise could manufacture it in steel for £25.4, the lowest compared to others, but the price for PA was ranked third. Shapeways was selected as they offered the second best price for both PA and metal (see also Appendix C – Cost for manufacturing a pen in PA and metal material by AM/3D printing manufacturers, page 196).

Table 5-3: AM/3D printing manufacturers comparison for PA and steel materials

<table>
<thead>
<tr>
<th>Plastic</th>
<th>Price rank</th>
<th>Metal</th>
<th>Price rank</th>
</tr>
</thead>
<tbody>
<tr>
<td>i.materialise PA £9.95</td>
<td>3</td>
<td>Steel £25.4</td>
<td>1</td>
</tr>
<tr>
<td>Kraftwurx PA £67.77 ($99.13)</td>
<td>5</td>
<td>Stainless steel £345.82 ($505.81)</td>
<td>4</td>
</tr>
<tr>
<td>Ponoko PA 12.7 ($18.58)</td>
<td>4</td>
<td>Stainless Steel £64.91 ($94.94)</td>
<td>3</td>
</tr>
<tr>
<td>Sculpteo PA £5.04</td>
<td>1</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Shapeways PA £5.79</td>
<td>2</td>
<td>Stainless Steel £30.60</td>
<td>2</td>
</tr>
</tbody>
</table>

5.1.8 Keep the product longer

Experiencing design and manufacturing our own product may increase emotional bonding to the product (Mugge et al. 2009). As this study is closely related to the issue, the survey also questioned how the consumer-led design and manufacturing can motivate people to keep the product longer than other methods. “If you could design and/or print products for yourself, would you like to use them longer than previous standard products that you have used?” Based on (Mugge et al. 2006) the
questionnaire explored their motivation if they answered “Yes”, they were asked to answer on a Likert scale if it was because “I have designed it myself”, “The product I designed expresses my Identity” and “I have a bond with the product I designed”.

5.1.9 Using web-based survey

The reason a web-based survey was chosen is the data would automatically be recorded to the database. Not only that, they also help surveyors to process the data and export the result to common file formats, such as csv, xls and xml, that can be read by statistic programs such as SPSS or spreadsheet software packages such as Microsoft Excel and Open Office Calc.

5.1.9.1 SurveyGizmo

SurveyGizmo is one of the survey creators which are available online. It offers a range of services from the very basic ($25/month), professional ($65/month), premier ($65/month), to the enterprise level which can be customised, based on the company’s needs so prices are dependent on the project. The website also offers a student version which allows researchers to use the website for free but still gives features that are really needed and important to this study (SurveyGizmo, 2013):

- Filter: with this feature some requirements can be used as constraints for the study, in this case a number of participants based on their gender and age. The system can calculate whether the quota for each gender in each age-group has been fulfilled or not, then the questionnaire developer can set the system to stop accepting participants. This has been applied to this study to make sure that all of the slots are filled and do not exceed the quota.

- Intelligent skip logic and page jumping: with this feature the survey can be made more responsive by using advanced skip logic and page jumping features. It can show and hide questions based on previous responses from respondents, or skip to a new page.

- Piping question and answer content: The survey maker uses collected answers to automatically populate content in later questions. A data analyser is able to trace more information in a previous answer, or just to directly call a respondent by their ID name.
5.1.9.2 YouCanBook.me
YouCanBook.me is online booking software that can be integrated and synched with Google Calendar so it really helps to manage projects. The website offers different levels of service: standard (free), premium ($16/month), professional ($48/month), and enterprise (£144/month). The standard free version is enough for this study as it only needed the time and date slot, which is included in the basic service.

5.1.9.3 Google calendar
Google Calendar is one of the free services from Google where it can record daily activities to help organise the schedule. It can sync to other devices such as PC, laptop, tablet and mobile through a web browser and/or app. By linking the YouCanBookMe to the Google Calendar, once a participant selects the place, date and time it goes automatically to Google calendar and notifies the researcher. This could avoid appointment clashes as well as missed and/or late meetings.

5.1.10 Presenting data
Data result of the values recorded on a group of individuals are summarised as the percentages and proportions of the total falling into each category or group. A proportion and a percentage are just different ways of displaying the information where both of them are actually the same. To avoid misleading by only expressing the percentage, where the number of participants as a fraction is relatively small, this report also uses a proportion value, e.g. 25% (2 out of 8).

The data results are divided into three categories (Profile 1: have intention to design and experienced at least once; Profile 2: have intention to design but have never designed; Profile 3: do not have design intention), as explained in section 5.1.3 Willingness to use CaCODE, page 96. Gender and age-group perspectives are also extracted from the data to see whether there is a correlation with and influence on the trends.

Data is displayed in a chart rather than a table to make it easier to identify patterns, trends or relations. Pie charts are used to represent percentage or proportion of the whole. Bar charts are utilised to compare several series data, i.e. gender and age-
group. To describe Likert scale type answers, this research uses diverging stacked bar charts. The percentages of participants who give positive answers are shown on the right zero line, and those who have negative answers are placed on the left. The percentages of respondents with neither positive nor negative responses are split down the middle. In this way, the trend result can be easily identified, by observing the position of the bar in relation to the baseline of zero.

5.1.11 Pilot Study

As this study involves participants of different backgrounds and ages, pre-testing is an important step to ensure that the questions are clear and simple (Robson 2011). Therefore the next phase of the work was to present the software to a reasonably representative sample of the general population and ask them to design their own pens. Initially, ten participants were recruited. Their ages ranged from late twenties to early forties and their backgrounds ranged from research fellows through to homemakers. The participants were introduced to the software and asked to use it to create their own pen design. They were then asked to evaluate their experience by completing a questionnaire (see Appendix D – Pilot Study questionnaire, page 201). Research participants were also asked to evaluate the appearance of the range of AM/3D printing made pens.

5.1.11.1 Result

A summary of the questions and answers in the questionnaire is as follows:

Section A: Demographic

The participants’ demographic profiles (Error! Reference source not found., point A) show gender and age, which were not evenly distributed, and dominated by females and age-groups 31-35. This was because the Pilot Study only focused on whether the data was informative enough for participants, not misleading and could be coded. Moreover, the raw data was also processed to test whether it was suitable for analysis.
Section B: Design intention.

Section B asked the questions “Have you ever wanted to design a product, if not, why not?” and “Have you ever actually designed a product, if not, why not?”. The result from these questions can be seen in Figure 5-3 and it shows that the objective to obtain 3 profiles (as explained in Table 5-1 page 95) was achieved although the data was not sufficient to make a conclusion.

The reasons of Group 2 (1 participant) for not going on to design were my design ability was very low (1/1 participant); other (0/1). The reasons of Group 3 (5 participants) for never wanting to design are: I cannot design (0/5); I never thought about it, it's outside my area (5/5); other (0/5).

Participants gave the following reasons for not going on to design: My design ability was very low, other (0/1), (Group 2, 1 participant, 1/1); and for never wanting to
design: I cannot design (0/5); I never thought about it, it's outside my area, (5/5), other (0/5) (Group 3, 5 participants, 5/5).

Participants were asked to write an example of a product that they had designed (5 participants): game (snakes & ladders), lamp, furniture, paper tray, and lab equipment. They were also required to state how they had designed it (4 participants): hand sketching (1/4); 2D design software (1/4); 3D design software (2/4).

**Section C: Intention to make a product**

Section B asked the questions “Have you ever wanted to create/modify a product, if not, why not?” and “Have you ever actually created/modified a product by yourself, if not, why not?” The result from these questions can be seen in Figure 5-4, which illustrates the 3 profiles (as explained in Table 5-2 page 98), although the data was too small to be conclusive.

The reasons Group 3 (5 participants) gave for never wanting to make a product are: I am too busy (1/5); I don’t have the skills to hand make things (4/5); it’s expensive and needs investment (0/5); I don’t have facilities/tools (0/5).

They were also asked to write an example of a product that they had made (5 participants): game (snakes & ladders), lamp, furniture, paper tray, lab equipment, fruit juice and how they made it (5 participants): by hand (2/5); using (computer) machine tools (0/5); used an expert/a technician/a service (3/5); other (0/5).
Section D: CaCODE usability test

A series of questions were asked in a way that enabled them to be answered using a 5 point Likert scale ranging from “strongly disagree” through to “strongly agree”. After participants operated CaCODE, section D asked, “Having now used PenCAD as consumer design software, how do you rate its usability?” The answers can be seen in Figure 5-5: Pilot Study: CaCODE usability. The values given by the participants are shown as colour-coded bars, where each horizontal bar represents equal answers, in this case ten. Based on the results, the most important findings were that sliders were seen as the most useful interaction tool.

![Figure 5-5: Pilot Study: CaCODE usability](image)

Open questions to get feedback were asked, “Are there any feature(s) of PenCAD that you feel are inconvenient?” and the answers were: it was difficult to pick points (sliders and drag points) (3 participants), unit conversion (currently using millimetre) (1 participant) and real scale (1 participant). For the question, “Are there any feature(s) you would like added to PenCAD?” the answers were: rotating, panning and zooming (1 participant) and colour options (1 participant).

Section E: Willingness to use CaCODE

This section questioned participants whether they wanted to use CaCODE:PenCAD or not. “Having now used consumer design software, how much would you like to design a pen?” The responses can be seen in Figure 5-6 where downloading a ready-to-print design was slightly more desirable than designing one using PenCAD.

![Figure 5-6: Pilot Study: Willingness to use CaCODE](image)
Section F: Willingness to use AM/3D printing

Similar to Section W, this section examined whether participants wanted to buy a product made by AM/3D printing. “Having now seen pens built using 3D printing, how much would you like to buy one?” The answers are shown in Figure 5-7.

![Figure 5-7: Pilot Study: Willingness to buy an AM/3D printing product](image)

Section G: Sustainability

This section explored whether there is a positive relationship between designing one’s own product and sustainability. The question was “If you could design and/or print products for yourself, would you keep/use/maintain them longer than previous standard products that you have used?” Most of the participants thought they would keep a customised AM pen longer than a conventional product.

![Figure 5-8: Pilot Study: Willingness to keep the customized product longer](image)

Section H: Ranking the pens

Section H aimed to understand participants’ preference in comparison to datum pens. Ranking 14 pens was considered too complicated for participants. Therefore, they were asked to rank 10 out of 14 by making a rank of their top five and bottom five. The question was, “Having now seen the 3D printed products, considering the surface finish and the colours, could you please rank your 5 most preferred pens and your 5 least preferred pens”. The participants’ pen ranking values were inverted to give each one a score out of 14 (i.e. a top ranked pen was given a score of 14, a bottom ranked pen was given a score of 1 and unranked pens were given a score of 7.5 (see Error! Reference source not found. point I) and used to calculate the total score given to each pen by the 10 participants. These scores are shown in Figure 5-9 next to a brief description of each pen, i.e. how it was made and finished. The two injection moulding quality pens came out top but several of the AM/3D printing made and
finished pens came close, specifically those made with laser sintering with tumble and dyed finish and Polyjet with tumbling. It is interesting to note that the uncoloured, untumbled laser sintered pen gained a higher score than the uncoloured tumbled version. In general, pens with a rougher finish or more visible layers seem to have a lower score. The only pen made of metal received the lowest score with several participants commenting that it was too heavy.

![Figure 5-9: Pilot Study: Pen ranking](image)

**Section I: willingness to pay**

Section I asked, “From your 5 favourite pens, what price would you pay for them?” to understand participants’ willingness to pay. Figure 5-10 shows the result where the pens were ranked according to what the participants would be willing to pay.

![Figure 5-10: Pilot Study: willingness to pay](image)

Consumers said they would pay for personalised pens, and valued almost all of them at between £1 and £5 on average. Although such a price is more than that of a standard injection moulded pen, it would not justify the use of high-end AM machines.
5.1.11.2 Feedback for main study

Based on this pilot survey, there are 6 items that needed to be improved for the main survey:

1. Define ‘consumer product’ for this study. On the pilot study, a participant thought about fruit juice and very specific lab equipment as a consumer product she/he wanted to make.

2. Pen 3 – metallised, was classified as an alternative for consumers to improve the surface of AM/3D printed pen. The metallization service is available for consumers, but at the moment this study was prepared, the company did not offer polishing of the pen before it was metallised.

3. As a consequence of point no. 2 above, there would three datum pens. So, to prevent participants selecting the three datum pens only, they were required to select a total of six.

4. Rank the AM/3D printed pens. The assumption had been made not to burden participants with a very hard task. Hence, the pilot study would test whether asking to rank 10 pens out of 14 was very hard or not. To make it easier for the participants to rank the pen, the task was divided into two similar tasks by asking them the following questions: “Could you please select your 5 preferred options for surface finish/colour and rank them in order (No. 1 is better than no. 2)” and vice versa for another task “Could you please select your 5 least preferred options for surface finish/colour and rank them in order (No. 6 is better than no. 7)”. This would have reduced the pens to be ranked by 4. By piloting this task, it was decided whether the number of pens being ranked would be increased, decreased or kept at 10. However, based on the observation, it seemed that the task had been easily done by the participants, as a result the main survey asked the participants to do the ranking for all of the evaluated pens. Also, by skipping 4 pens the pilot survey failed to get all of the marks for every pen, this would give an inaccurate rank result.

5. Remove the gypsum material of Pen 11 made by binder jetting 3DP as it is not strong enough as a finished product.
6. Create a script. Giving all participants the same information would give a fairer result. So, for the main survey a script was written for that reason.

7. Using an online survey program. To support the no. 4 improvement, an online survey program was developed and used, so the study could use the same pictures and videos for explaining the technologies.

8. Recording the design time using PenCAD1 and PenCAD2. This is to uncover how quickly participants can produce a design they want.

5.2 Survey results

As explained in Table 5-1 page 95 and Table 5-2 page 98, the survey result is presented, focusing on three levels of participants’ intention to design and/or manufacture their own products. The first level, Group 1, consists of laypersons that intend to design and/or manufacture and have experienced designing and/or creating at least one consumer product. The second level, Group 2, consists of those who have an intention to design and/or develop their own product but have never done so. The third level, Group 3, consists of those who have never thought of designing and/or creating a consumer product.

As the aim of this research is to help laypersons to design and develop their own products, the pie and bar charts display the response of every profile group on the CaCODE and/or AM/3D printing acceptance test. The results also show the detail of each profile group according to 10-year-age-groups and gender to uncover whether there is a correlation between gender/generation and design/manufacturing intention, as well as how the profile (generation/gender) responses differ to the CaCODE and AM/3D printing. This would help developer to consider the situation in order to market the technologies.

5.2.1 Participants’ profiles

The total sample of non-designer participants in this research was 40. There was an even split on as the pie chart below illustrates. The bar chart compares the females and males in ten-year-age-groups, it shows that the proportion was very well balanced, both for the total number of participants in each group, as well as the
number of females and males. There are six to seven participants and three to four females or males in every ten-year-age-group.

![Figure 5-11: Participants’ gender and 10-year-age-group composition](image)

<table>
<thead>
<tr>
<th>No</th>
<th>Id</th>
<th>Gender</th>
<th>5 year age group</th>
<th>10 year age group</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>P28</td>
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<td>5-9</td>
<td>05-14</td>
</tr>
<tr>
<td>2</td>
<td>P26</td>
<td>Female</td>
<td>10-14</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>P34</td>
<td>Female</td>
<td>15-19</td>
<td>15-24</td>
</tr>
<tr>
<td>4</td>
<td>P30</td>
<td>Male</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>P36</td>
<td>Male</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>P13</td>
<td>Female</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>P38</td>
<td>Male</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>P40</td>
<td>Male</td>
<td>20-24</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>P01</td>
<td>Female</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>P39</td>
<td>Male</td>
<td>25-29</td>
<td>25-34</td>
</tr>
<tr>
<td>11</td>
<td>P15</td>
<td>Male</td>
<td></td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>P03</td>
<td>Female</td>
<td></td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>P05</td>
<td>Female</td>
<td></td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>P02</td>
<td>Male</td>
<td></td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>P31</td>
<td>Male</td>
<td></td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>P21</td>
<td>Female</td>
<td></td>
<td></td>
</tr>
<tr>
<td>17</td>
<td>P24</td>
<td>Female</td>
<td></td>
<td></td>
</tr>
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<td>P07</td>
<td>Male</td>
<td></td>
<td></td>
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<td>P32</td>
<td>Male</td>
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<tr>
<td>20</td>
<td>P16</td>
<td>Female</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

5.2.2 Intention to design a consumer product

The following section gives a breakdown of the responses to the survey question “Have you ever wanted to design a consumer product?”

Slightly more than half of the participants, 52.5% (21 participants out of 40), did not have an intention to design a consumer product whereas 47.5% (19 out of 40) did.
Figure 5-12: Have you ever wanted to design a consumer product?

Figure 5-3 above also shows there is only a marginal difference between genders. Men’s intention to design a product is only slightly higher 52.6% (10/19) than the women’s 47.4% (9/19).

Figure 5-5 below compares the participants’ intention to design profile of different 10-year-age-groups and each group is divided into male-female composition. The largest number is in the 5-14 age-group, 26.3% (5/19). The second is the 35-44 age-group, 21.1% (4/19). The third is the 45-54 and 55-64 age-groups, 15.8% (3/19) each. Finally, the smallest numbers are from the 15-24 and 25-34 age-groups, where each group has 10.5% (2/19) participants with an intention to design.

Figure 5-13: Intention to design profile in 10-year-age-group and divided into gender

As opposed to Figure 5-4 above, Figure 5-5 shows the profile of participants without design intention. The two groups with the highest number were from the 15-24 and 25-34 age group, 23.8% (5/21) from each group. The second largest is the 45-54 age-group, which is 19% (4/21). The third is from the 35-44 and 56-64 groups, 14.3% (3/21) each. Finally, the smallest number on this profile is from the 5-15 year-old
group, where only 4.8% (1/21) said they had never wanted to design a consumer product.

![Pie chart showing design intention](image)

**Figure 5-14: No design intention profile in 10-year-age-group and divided in to gender**

The pie chart below shows the three different groups’ design intention based on answers to 2 questions: “Have you ever wanted to design a consumer product?” and “(If ‘yes’) Did you go on to design the consumer product?”.

![Bar chart showing design intention](image)

**Figure 5-15: Three main profile groups for design intention**

The smallest number of participants is in Group 1; there are 20% of the respondents (8 out of 40) who have design intention and experience. In Group 2, there are 27.5% of total respondents (11 out of 40) who have design intention but no design experience. The largest number of participants is in Group 3, accounting for more than half of the survey participants. 52.5% (21 respondents from 40) do not have design intention nor experience (Figure 5-6). The following paragraphs break down the profile in terms of gender and 10-year-age-groups.
5.2.2.1 Profile of Group 1: Participants with design intention and experience

The next charts show Group 1’s profile.

The rightmost bar chart above shows the composition of the members in terms of age-group. 62.5% (5/8) is from the 5-14 age-group, 25% (2/8) is from the 35-44 age-group and 12.5% (1/8) is from the 45-54 age-group. None are from the 15-24 and 25-34 age-groups.

Unlike other groups, the members of Group 1 have experience in designing at least one customer product. Figure 5-8 shows that 75% of participants (6 out of 8) of this group have used conventional drawing tools, pen and paper or hand sketching, to visualise their imagination of a consumer product they wanted. The rest, 25% (2 out of 8), have used 2D design software, i.e. Corel draw. From six participants who hand-sketched, four of them are children and teenagers from 5 to 14 year-old. Two of them are from the 35-44 age-group. In addition, one person from 5-14 and one from 45-54 have used 2D design software.
5.2.2.2 Profile of Group 2: Participants with design intention but have never designed

The charts below explain Group 2’s profile. There are more males, 63.6% (7/11) than females, 36.4% (4/11).

Figure 5-18: Group 2 Participants with design intention, but who have never designed, by gender and age-group composition

The rightmost bar chart in Figure above shows the distribution of the age-groups from the youngest to the oldest. Apart from the 5-14 age-group (0), it shows that the 15-24, 25-34, 35-44 and 45-54 each has 18.2% (2/11). The 55-64 age-group, is the largest at 27.3% (3/11).
5.2.2.3 Profile of Group 3: Participants who have not had design intention

The next bar charts describe the composition of Group 3, which comprises more females, 57.1% (12/21) than males, 42.9% (9/21).

![Bar chart showing gender and age group composition of Group 3 participants.](image)

Figure 5-19: Group 3 Participants who have not had design intention, by gender and age-group composition

From the right bar chart above, it can be seen that there is no dominant age-group. From the largest to the smallest, the 15-24 and 25-34 age-groups have 23.8%, the 45-54 age-group has 19%, the 35-44 and 55-64 age-groups have 14.3% and the 5-14 age-group has 4.8%.

5.2.2.4 Reasons for not designing

In total, 80% of all the participants that is Group 2 and 3 never went on to design a consumer product. Figure 5-9 describes how most people, 20 out of 32, never considered designing as they thought it was outside of their area of expertise. 5 participants said they could not design and 7 gave other reasons.
Figure 5-20: Why did you never (want to) design a consumer product?

5.2.2.5 Desired products to design

Groups 1 and 2 who said they wanted to design a consumer product, regardless of whether they went on to design or not, were asked what consumer products they wanted to design. Figure 5-12 shows the number of participants from every age-group and the products they wanted to design.

Figure 5-21: What is your desired consumer product to design?
5.2.3 Willingness to use CaCODE
The following section will describe the participants’ willingness to use the design software, CaCODE. It describes the number of people who want to use it according to their gender and age-group.

5.2.3.1 Overall
In total, 75% (30/40) participants wanted to design their own product using design software after they had experienced using CaCODE. 17.5% (7/40) respondents would prefer to download a ready-to-print 3D CAD file and 8% (3/40) do not have any preference.

If you wanted to manufacture your desired product, would you prefer to: (1) Design my own product using CaCODE; (2) Download a ready-to-print file; (3) No preference.

Figure 5-22: Willingness to use CaCODE from a gender and age-group perspective
In terms of gender perspective, 14 females versus 16 males wanted to design their own product using consumer design software. Four females and three males just wanted to download the 3D printable file. Two females and two males had no preference.
The following paragraphs explore in detail how CaCODE could fulfil the needs of Group 1 and 2, as well as whether Group 3 can be motivated to do their own design after operating it.

5.2.3.2 **Group 1**

Figure 5-14 shows that 87.5% of Group 1 wanted to use CaCODE to produce their own design. Only 12.5% had no preference and none chose “download a ready-to-print product file” option. The top bar chart presents the breakdown by gender. There were three females and four males who wanted to design their own product using CaCODE. In addition, one female respondent had no preference.

![Bar chart showing Group 1's willingness to use CaCODE](image.png)

If you wanted to manufacture your desired product, would you prefer to: (1) Design my own product using CaCODE; (2) Download a ready-to-print file; (3) No preference

**Figure 5-23: Group 1’s willingness to use CaCODE from a gender and age-group perspective**

The bottom bar chart of Figure 5-14 above divides each preference into age-group. Five out of eight participants were children 5-14 year-old, three of them were females and two males. There was only one male in the 25-44 and 45-44 age-groups. The right bar chart shows one female did not have a preference.
5.2.3.3 Group 2

63.6% of Group 2 wanted to use CaCODE to produce their own design, 18.2% prefer to download a-ready-to-print file and the same number do not have any preference. Figure 5-15, the top bar chart, divides each choice into a female-male perspective. Five males out of seven participants dominate the sub-group of participants who want to use CaCODE. There is no gender dominance in the next two choices.

Figure 5-24: Group 2’s willingness to use CaCODE from a gender and age-group perspective

Figure 5-15 shows that there was one female from the 5-14 age-group and one male from the 55-64 year age-group who would prefer to download a ready-to-print file to produce their own product, there was only one male from the 25-34 age-group and one female from the 45-54 age-group who had no preferences.
5.2.3.5 Group 3

Figure 5-16 shows that 76.2% of Group 3 want to use CaCODE to produce their own design, 23.8% would prefer to download a-ready-to-print file and none selected “no preference” from this group.

The top bar chart in Figure 5-16 shows that from the participants of Group 3 who wanted to use CaCODE to produce their own design, nine were females and seven were males. From respondents who would prefer to download a-ready-to-print file, three were females and two were males.

If you want to manufacture your desired product, would you prefer to: (1) Design my own product using CaCODE; (2) Download a ready-to-print file; (3) No preference

Figure 5-25: Group 3’s willingness to use CaCODE from a gender and age-group perspective

Figure 5-16 presents the age-group distribution of participants’ preferences (the bottom bar chart). Four from the 15-24 and 25-34 age-groups, three each from the 35-44 and 45-54 age-groups, and two respondents from the oldest group said they would prefer to use CaCODE. None from the 5-14 group did. Two respondents from
the 15-24 age group, and one each from the other groups would choose “download a ready-to-print file”.

5.2.4 Participants’ preference for 3D manipulation methods
As decided in the survey strategy section 5.1.3, Evaluate interaction tool for 3D model manipulation, page 96, participants were asked to rate how much they agreed with the statement “I found it is easy to change the shape” when using the two systems, on a scale of “strongly disagree” to “strongly agree”. The result is displayed in Figure 5-26. For the PenCAD1, 27% (11/40) strongly agree that using sliders type was easy, 42% (17/40) agree, 17% (7/40) was neutral and 12.5% (5/40) disagree. For the PenCAD2, 62.5% (25/40) strongly agreed that using the dragging type was easy, 27.5% (11/40) agreed, 7.5% (3/40) was neutral and 2.5% (1/40) disagreed. In brief, there is a marked difference between the systems, with click and drag scoring much higher in the “strongly agree” category. It would appear that many users found clicking on an object to change its shape and size much more intuitive than using slider bars.

![Figure 5-26: Ease of making design changes](image)

When the participants were designing the pen, the experience of using the two systems was rated by the researcher on a scale of 1 “very frustrating” to 5 “very enjoyable”. The results are shown in Figure 5-18. For 32.5% (13/40) it was very enjoyable when using the slider type, for 17.5% (7/40) it was enjoyable, 47.5% (19/40) was neutral and 2.5% (1/40) said it was very frustrating. For comparison, it also shows the Likert scale chart of how the author assessed participants’ experience on PenCAD2. For 22.5% (9/40) it was very enjoyable when using the drag point type, for 37.5% (15/40) it was enjoyable, for 37.5% (15/40) it was neutral and only 2.5% (1/40), said it was frustrating. It can be seen that there was not a great deal of difference between the two systems, with the vast majority of users having a neutral to positive experience.
Figure 5-27: Participants’ experience of the system

Participants were also observed on how fast they learned the two systems on a scale of 1 “very slow” to 5 “very fast”. The results are shown in Figure 5-19. Here there is a marked difference between the systems with drag point type scoring much higher in the “very fast” category. For 45% (18/40) it was very fast when using slider type, 30% (12/40) was fast, 20% (8/40) was neutral and 5% (2/40) was very slow. For comparison, it also shows the result of how the researcher assessed participants’ speed of learning on PenCAD2. 80% (32/40) was very fast when using the drag point type, 12.5% (5/40) was fast, only 2.5% (1/40) was neutral, 5% (2/40) was slow and none was very slow. It would appear that the majority of users found clicking on an object to change its shape and size quicker to learn than using slider bars, i.e. direct rather than indirect manipulation of parameters.

Figure 5-28: Participants’ learning speed

During the test, the time taken by participants to complete the tasks using both PenCAD was observed. The objective of the task was to design a pen until participants were happy with the design. Figure 5-20 shows that users spent 38% longer with the slider type (or indirect manipulation) compared to the drag point type (direct manipulation).
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There was a virtual ruler added to the CaCODE that might help or guide participants to imagine when they change the shape. They were asked whether they actually were guided by the rule or not. Figure 5-30 describes how 5% (2/40) of participants disagreed that the ruler was useful, 35% (14/40) was neutral, 28% (11/40) agreed and 32% (13/40) strongly agreed.

5.2.5 Intention to make a consumer product

The following section gives a breakdown of the responses to the survey question:

“Have you ever wanted to make a product?”

Figure 5-31 pie chart below compares the number of participants who said they had wanted to make a product (45%, 18 out of 40), and those who said they had not. (55%, 22 out of 40), after seeing AM/3D printing processes and products.

It can be clearly seen that more men than women intended to make a product. From the group of laypersons who wanted to make a consumer product, 72.8% (13 out of 18) were males and 27.8% (5 out of 18) were females. Perhaps not surprisingly,
more females 68.2% (12 out of 22) than males 31.8% (7 out of 22) did not have any design intention.

Figure 5-31: An intention to make a consumer product in general and gender perspective

Figure 5-32 below compares design intention of different 10-year-age-groups for participants who had an intention to make a consumer product. 33% was from the 5-14 age-group, 16.7% each were from the 15-24 and 55-64 age-groups, and 11.1% each was from the 25-34, 35-44 and 45-54 age-groups.

Figure 5-32: Intention to make a product in 10-year-age-group and divided in to gender

From the participants who did not have an intention to make a consumer product, 22.7% of people were from the 25-34, 35-44 and 45-54 age-groups, 18.2% from the 15-24 age-group and 13.7% from the 55-64 age-group said they had never wanted to make a consumer product. No one from the 5-14 age-group was in this category.
Figure 5-33: Profile without intention of making a product in 10-year-age-group and divided in to gender

The pie chart below shows the three different groups’ making intention based on answers to 2 questions: “Have you ever wanted to make a consumer product?” and “(If ‘yes’) Did you actually make the consumer product?”.  

Figure 5-34: Three main profile groups for intention to make a consumer product

The smallest number of participants is in Group 1; there are 20% of the respondents (8 out of 40) who have design intention to make a consumer product and experience of doing so. In Group 2, there are 25% of total respondents (10 out of 40) who have intention to make, but have never made one. The largest number of participants is in Group 3, more than half of the survey participants, 55% (22 respondents from 40) did not have intention to make nor experience (Figure 5-34). The following paragraphs break down the profile in terms of gender and 10-year-age-groups.

5.2.5.1 Profile of Group 1: Participants with intention to make a consumer product and experience of doing so

The two bar charts below (Figure 5-24) illustrate the gender and generation of Group 1. There were four females and four males (middle bar chart).
The right bar chart above indicates the age-group distribution. It shows that the youngest age-group, 5-14 is the largest of this Group 1 profile. There were 75% (6/8 participants), three males and three females. There were only two participants outside of this age group 5-14, one female between 15-24 and one male between 45-54.

All the members of Group 1 had experienced making at least one customer product. From Figure 5-25, 75% (7/8) of this group had used their hands to make a product they wanted and only one (1/8, male) from the 45-54 age group had utilised computer machine tools. Based on the age-group bar chart below, 75% (6/7) who used manual methods were 5-14 year-old participants and only one was from the 15-24 age-group.
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5.2.5.2 Profile of Group 2: Participants with intention to make a consumer product but have never made one

The following bar charts (Figure 5-26) display the distribution in terms of gender and 10-year age group. Males, 90% (9/10) dominate this group.

Figure 5-37: Group 2 had making intention, but had never made - by gender and age-group perspective

The right bar chart of Figure 5-26 shows that three members of this group were from the 55-64 age group, two were from the 15-24, 25-34 and 35-44 age groups and one was from the 45-54 age group
5.2.5.3 Profile of Group 3: Participants who have not had an intention to make a consumer product

The middle chart from Figure 5-38 shows that Group 3 consisted of 68.2% (15/22) females, and only 31.8% (7/22) males. From the rightmost chart, the largest groups of five persons were from age-groups: 25-34 (three females and two males), 35-44 (one female and four males) and 45-54 (3 females and 2 males). The second largest was from the 15-24 age group (three females and one male) and the smallest was from the 55-64 age group, three persons (two females and one male). There was nobody from the 5-14 age-group.

![Figure 5-38: Group 3 (did not have making intention) from a gender and age-group perspective](image)

5.2.5.4 Reasons for not making a consumer product

Group 2 and 3 participants, who had never made a consumer product and made up 80% of the whole participants, were asked about their motivation. The top bar chart of Figure 5-39 divides each answer into gender perspective and the bottom shows each answer according to 10-year-age-groups. It shows that most of people, 43.7% (14 out of 32) had never manufactured as they thought they did not have the skill. 21.9% (7/32) said they never thought about doing it as it was outside of their area of expertise. 9.4% (3/32) of them said they “did not have the facilities” and 6.3% (2/32) said it “was too expensive and needed investment” and the rest, 18.7% (6/32) had various other reasons.
5.2.5.5 Desired products to make

Groups 1 and 2 who wanted to make their own consumer product, regardless of whether they actually really made one or not, were asked what consumer products they wanted to manufacture. Figure 5-39 shows the number of participants from every age-group and the products they wanted to design.

![Chart showing desired products to make]

Figure 5-40: What is your desired consumer product to make?

5.2.6 AM/3D printed pens rank

The bar chart below shows how participants ranked the pens printed by different types of AM/3D printers. The survey respondents evaluated them based on their perceived quality.
From Figure 5-41 above, the three datum pens were placed at ranking 1, 3 and 5 (A) in which the metallized pen was the most favourable. It clearly identified that participants would prefer injection mould quality. Multi material (Pen4) was a good option to compete with injection mould products, regarding the fact that in this study it was ranked no. 2 (B).

Post processing tumbling proved that the method can improve the performance of powder bed fusion and material jetting pens, considering the facts that it moved up the rank from 12 to 6 and 10 to 7 (C). However, the tumbling process did not always increase the consumer preference, because the powder bed fusion dyed pen, was ranked down. It may be because the colour faded as a result of the abrasive process (D). Depending on the shape of the product, for pens, participants prefer a vertical build for the material extrusion pen rather than a horizontal one (E). The metal pen was ranked 11, maybe because of the very rough surface after the support structure was broken away (F).
The rank of preferences that participants used for evaluating the pens can be seen from the Figure 5-42 below. It can be clearly seen that most of participants selected Pen 3 because of the shiny surface finish and good weight.

![Figure 5-42: Participants’ reasons for ranking the pens](image)

5.2.7 Willingness to pay for AM/3D printing products

Following the evaluation of the pens, participants were asked how much they would be willing to pay for the top 6 pens they ranked. Figure 5-43 placed the willingness to pay bar (red) and real cost bar (green) side by side. This is to compare and see the gap between how much money they would want to pay for the pen and the real cost to manufacture it using AM/3D printing. The line graph of the rank is also displayed to see the relationship.

Only the top two (metallized pen and mixed-materials pen) are in line with the rank. Participants who liked them would be willing to pay more. The rest showed no
relation with the rank, they only wanted to pay between £2.52 to £1.37 the lowest), except for the metal pen. The metal pen showed an anomaly, as can be seen from Figure 5-43. There were participants who liked the pen because of the weight, surface finish and texture. They assumed metal pens would be more expensive than the plastic pens. Therefore, participants who selected the metal pen as their favourite gave a high rank for the willingness to pay.

For the comparison of willingness to pay and actual cost, all of the AM/3D printed pens show gaps. The actual cost of all of the pens was more expensive than the maximum price given by participants. The lowest gap was Pen05, made by powder-based fusion, SLS with PA as a material. On average, the consumer would pay £1.94 whereas the real price was £5.79, about three times higher. The highest gap was with regard to the material jetting Polyjet (Pen1) where the willingness to pay was £1.48 and the genuine cost was £17.40, more than 11 times higher.

Figure 5-43: Willingness to pay and actual cost based on rank
5.2.8 Willingness to use AM/3D printing

The following sections explain the results for participants’ willingness to use AM/3D printing, after they had evaluated the AM/3D printed pens. The following pie charts and bar charts describe the total number of people who wanted to use it by gender and age-group.

5.2.8.1 Overall

Just over half of the participants, 52.5% (21 out of 40), would prefer to buy their own customised product made using an AM machine/3D printer. 32.5% (13 out of 40) would prefer to buy standard/conventional manufacturing consumer products. 15% (6 out of 40) of the whole survey respondents did not have any preference (Figure 5-33).

The top bar chart of Figure 5-44 above shows that more females, twelve, than males, nine wanted to manufacture their own product using AM/3D printing. More males (eight) than females (five) would prefer to buy standard/conventional manufactured products. Three males and three females did not have any preference.
Having now seen the quality of the 3D printed pens (EXCLUDING Pen 3, 12 and 13); and the benefits of 3D printing which allow you to customise a product. Would you prefer to: (1) buy your own customised product made using a 3D printer, (2) buy a standard manufactured product, (3) no preference.

Figure 5-44: Willingness to use AM/3D printing from a gender and age-group perspective

The bottom bar chart above shows that four people from each of the 5-14, 15-24, 25-34 and 35-44 age-group, three from the 45-54 age-group and two from the 55-64 age-group wanted to manufacture a product using AM/3D printing. Three participants each from the 15-24, 45-44 and 55-64 age-group and two participants from each 25-34 and 35-44 age-group did not want to use AM/3D printing and would prefer to buy a standard manufactured product. There are two persons from the 5-14 age group and one each from 25-34, 35-44, 45-54, 55-64 age-group without any preference.

The next paragraphs explore in detail how AM/3D printing can fulfil the need of Group 1 and 2, as well as whether AM/3D printing could motivate Group 3 to manufacture their own product after they evaluate the performance of the AM/3D printed pens.
5.2.8.2  **Group 1**

The bar chart in Figure 5-45 shows that 62.5% (5 out of 8) of Group 3 want to use AM/3D printing to produce their own product, it comprises three females and two males. 12.5% (1/8) selected the “buy a standard manufactured product” option and 25% (2/8, one female and one male) do not have any preference.

![Bar chart showing Group 1's willingness to use AM/3D printing](image)

Having now seen the quality of the 3D printed pens (EXCLUDING Pen 3, 12 and 13); and the benefits of 3D printing which allow you to customise a product. Would you prefer to: (1) buy your own customised product made using a 3D printer, (2) buy a standard manufactured product, (3) no preference.

**Figure 5-45**: Group 1’s willingness to use AM/3D printing from a gender and age-group perspective

There were only two age-groups that would prefer to use AM/3D printing technologies, 5-14 (four persons) and 15-24 (one person) although two from the 5-14 age-group did not have any preference. One person from the 45-54 age-group selected a standard manufactured product.

5.2.8.3  **Group 2**

Figure 5-46 shows that only 30% (3 out of 10, all males), wanted to manufacture their own product using AM/3D printing and all of them were males. 50% (5/10, one
female and four males) of Group 2 would prefer to use standard manufacturing technologies. In addition, 20% (2/10, all males) did not choose either AM/3D printing or conventional manufacturing.

![Graph showing Group 2's preferences](image)

Having now seen the quality of the 3D printed pens (EXCLUDING Pen 3, 12 and 13); and the benefits of 3D printing which allow you to customise a product. Would you prefer to:

1. buy your own customised product made using a 3D printer,
2. buy a standard manufactured product,
3. no preference.

**Figure 5-46: Group 2’s willingness to use AM/3D printing from a gender and age-group perspective**

The Figure 5-46 above shows there were two participants from the 5-14 age-group and one person from the 35-44 age-group who want to utilise AM/3D printing. There was one participant from each of the 25-34, 35-44 and 45-54 age-groups, plus two from the 55-64 age-group who would prefer to use standard manufactured products. One person from the 25-34 group and one from 55-64 had no preference.

**5.2.8.4 Group 3**

Figure 5-47 (top bar chart) below shows that most of Group 3 would like to use AM/3D printing. 59.1% (13 out of 22, 9 females and 4 males). 31.8% (7 out of 22, 4
females and 3 males) would prefer to buy the standard manufactured products. 9.1% (2/22, all females) did not have any preference.

Having now seen the quality of the 3D printed pens (EXCLUDING Pen 3, 12 and 13); and the benefits of 3D printing which allow you to customise a product. Would you prefer to: (1) buy your own customised product made using a 3D printer, (2) buy a standard manufactured product, (3) no preference.

**Figure 5-47: Group 3’s willingness to use AM/3D printing from a gender and age-group perspective**

The bottom bar chart above shows that four people from the 25-34 age-group, three each from the 35-44 and 45-54 age-group, two from the 55-64 age-group and one from the 5-14, age-group want to manufacture a product using AM/3D printing, three people from the 15-24 age-group, one person each from 25-34, 35-44, 45-54 and 55-64 do not want to use AM/3D printing and would prefer to buy a standard manufactured product. There were two persons without any preference from the 35-44 and 45-54 age-groups.
5.2.9 Personalisation and sustainability

Finally, the participants were asked some questions to see if using a consumer design system had possibly changed their attitude towards consumer products. They were asked if designing and/or making a product for themselves would make them want to use it longer than a standard product. As explained above, the questions on personalisation and sustainability were excluded for the participants in the 5-14 age group. The number of users giving “yes”, “no” and “do not know” answers are shown in Figure 5-48. The overwhelmingly positive response is an encouraging result in terms of the potential impact that consumer design could have upon sustainability, i.e. this could encourage a move away from disposable products.

![Figure 5-48: If you could design and/or print products for yourself, would you like to use them longer than previous standard products that you have used?](image)

Some possible reasons for this from Mugge et al. (2009) were suggested to the 30 participants who said yes and they were asked to agree or disagree with them. Their ratings are given in Figure 5-49 shows their motivation. All three reasons received strong positive answers. Coincidently, the motivation “I have a bond with the product I designed” and “The product I designed expresses my identity” have the same result. 46.7% (14/30) strongly agree with the motivations, 36.7% (11/30) agree, 13.3% (4/30) neither agree nor disagree and 3.3% (1/3) disagree and none of them strongly disagree. For the reason “I have designed it myself” all of the answers are positive,
slightly more than half 53.3% (16/40) strongly agree and the rest, 46.7% (14/30) agree.

![Figure 5-49: Why do you want to keep them longer?](image)

5.2.10 Participants’ feedback

There was some feedback from participants’ answers which might be useful for design software development.

“Are there any feature(s) of PenCAD that are difficult to use?”

“Are there any feature(s) you would like to add to PenCAD?”

- Full scale on screen. Zoom in and out are useful for reviewing a product in detail, but sometimes a user lost the real dimension and needs to see what the product will look like.
- Undo and redo buttons. The easier way to reverse to the previous design is using undo button, or vice versa.
- Save and compare. Besides the undo-redo buttons can help users to iterate the designs, save and compare would also be useful to keep the alternative designs safely, where in undo-redo method users can lose the steps.
- Preview AM/3D printed product. It would be useful to use the technology of ‘Willit 3D Print’ to let users review the final product before manufacture, especially for the processes that have a ‘stair-stepping effect’ and support structure.
CHAPTER 6 Discussion

This chapter discusses the potential that this research has identified for consumers to design and manufacture a consumer product. In general, the survey indicated that children were more interested in designing and making. This finding may reflect to the phenomenon of creativity, as according to Kudryavtsev (2011), children’s creativity is different from adults’. Children discover for themselves and the outcomes are mostly to reinvent concepts as part of their learning process. To adults, creativity means to discover for others. This may include adults creating something as part of general culture, such as a product that reflects socioeconomic class. These differences mean children enjoy design and making more than adults. In addition, it may also be because primary education teaches creativity and develops creative ability (Trotman 2014).

This study shows a trend that males are more interested in designing and making a product compared to females. Although the sample is too small to be conclusive, this is in line with the findings suggested by Proudfoot et al. (2015). Their research indicated that the work and achievements of males tends to be evaluated as more creative than similar tasks undertaken by women. This trend was particularly apparent when participants assumed that the creativity meant ‘thinking outside the box’.
6.1 Consumer design software and its potential market

After using the software, 75% (30/40 – 16 males and 14 females) wanted to use CaCODE, regardless of whether they previously had an intention to design or not. 17.5% (7/40) just wanted to download a ready-to-print-file and 7.5% (3/40) did not have any preference. This gives the impression that the general public is actually willing to design if there is a suitable tool available. Gender does not affect preference for how 3D data is obtained prior to printing a product. The age range is spread almost evenly, 4-6 and 5 persons on average, in every 10-year-age-group between 5 and 64, can accept and may use CaCODE.

In order to understand the consumer acceptance of CaCODE, the participants were segmented into 3 groups. The two main parameters used were whether they had an intention to design a consumer product and whether they had experience of designing a consumer product.

The following paragraphs discuss the detail of these three segments and elaborate whether there is any significant effect of gender and/or age-group.

6.1.1 Group 1, who had both design intention and experience and their response on CaCODE

Group 1, the first profile, consisted of people who had an intention to design a consumer product and had designed one at least once. Gender is not dominant in this profile, therefore both gender equally fulfil the above parameters. In the age-group perspective, the youngest group dominates. More than half of Group 1, 62.5% (5/8) were from the 5-14 age-group. This could be due to the fact that pupils in the UK start learning D&T from age 5 (Department for Education 2013) although it could also be related to general creativity of younger people (Moody 2002).

For this group, the study wanted to uncover whether the CaCODE system can fulfil their need of design tools. The challenge for this group was that they had already used design tools, 75% (6 out of 8) participants had used conventional design tools, pen and paper, and 25% (2 out of 8) had used 2D design software (one of them had
used Corel Draw). Therefore, with their experience they could compare the CaCODE with the design tools that they had operated previously.

After they experienced designing using CaCODE, 87.5% (7/8) of Group 1 wanted to the “use CaCODE to produce their own design”. Only 12.5% (1/8) respondent had “no preference” and none chose “download a ready-to-print product file” option. This shows that CaCODE can attract most of the participants in this group and can replace the previous design tools they used. Another positive result is that none chose “download a ready-to-print file”, so all of this group would be prepared to accept CaCODE as a tool for designing a product.

6.1.2 Group 2, who have had design intention, but never went on to design, and their response to CaCODE

Group 2, the second profile, was for people from every age group, except the 5-14 one, who had an intention to design a consumer product but never went on to design one. Gender does appear to be more significant in this profile, as there were more males, 63.6% (7 out of 11), than females, 36.4% (4 out of 11) in total. This result is in line with the previous study on gender and creativity, where male participants’ performance on creativity was generally better than that of females (Stoltzfus et al. 2011). Although this group had never designed before, their intention showed males were potentially more creative than females. The study wants to uncover whether the CaCODE system can help users to realise their intention to design.

After they experienced designing using CaCODE, 63.6% (7/11) of Group 2 wanted to “use CaCODE to produce their own design”. Only 18.2% (2/11) would prefer to “download a ready-to-print product file” option and the same number had “no preference”. Although the percentage result is less favourable than Group 1, it still shows that for the majority of the group CaCODE could help them to undertake design.
6.1.3 Group 3, who did not have an intention to design and their response to CaCODE

Group 3, the third profile, was for people who did not have an intention to design a consumer product. This is the biggest in the whole sample, approximately 52.5% (21 out of 40). There are more females, 57.1% (12/21), than males, 42.9% (9/21).

After they operated the CaCODE system, 76.2% (16) of Group 3 wants to “use CaCODE to produce their own design”. 23.8% (5) would prefer to “download a ready-to-print product file” option and none said they had “no preference”. The result is quite promising where more than 75% can be motivated by the CaCODE.

6.1.4 Three groups acceptance of CaCODE comparison

If those three groups are compared to understand their acceptance, Group 1, who had used design tools before contains the most people who wish to use CaCODE. It may be because they felt CaCODE was easier than other design tools they have used. In general, CaCODE potentially could help the general public to design their own product.

![Figure 6-1: Participants' acceptance of CaCODE from each group](image)

6.2 AM/3D printing and its potential market for general public

After they evaluated the AM/3D printed pens in total, only slightly more than half of the participants, 52.5% (21 out of 40) wanted to buy customised products using AM/3D printing technologies. 32.5% (13) would prefer to just buy a standard manufactured product. 15% (6) did not select either customised or manufactured product. This outcome may be in line with the results of pen ranking by participants where the study uses a datum approach (as explained on page 87, 4.2.2.1 Datum pens...
(pen 3, 12, 13): Injection moulded pen quality) as the strategy to uncover participants’ preference on their perceived quality of the pens. The result (page 131) shows that the datum pens had been ranked as no. 1, no. 3 and no 6 of the AM/3D printed 13 pens. It means that participants still expect the quality of the pens to be the same as those produced by a conventional technique such as the injection mould process.

In order to uncover more detail about the consumer acceptance of AM/3D printing technologies, the participants were segmented into 3 groups. Two main parameters were used: whether they had an intention to make a consumer product and whether they have experience of manufacturing a consumer product.

The following paragraphs discuss the detail of the three segments and elaborate whether there is any significant effect of gender and/or age-group.

6.2.1 **Group 1, had intention and experience in making a consumer product, and their response to AM/3D printing technologies**

Group 1, the first profile, four males and four females, was for people who had an intention to make a consumer product and had made at least one. There was no gender significance. Similar to those with design intention, in terms of the age-group perspective, the youngest group dominated.

For this group, the study wanted to uncover whether AM/3D printing technology, as a consumer manufacturing tool, could produce the product they want in terms of part quality. This group had an understanding how to create a consumer product, although they were not professionals.

AM/3D printing could probably help these participants since 87.5% (7 out of 8) had already used conventional tools, hand tools, and one had employed CNC. Hence, these people would understand the difference when using the AM/3D printing techniques and how easy these manufacturing technologies are.

After they evaluated the result of AM/3D printing, more than half 62.5% (5 out of 8), wanted to buy customised products made using AM/3D printers. 25% (2 out of 8) had no preference and only 12.5% (1 out of 8) would prefer standard manufacturing
products. This suggests that some of the members of this group felt that AM/3D printers were an easier solution for making a product compared with the tools they had operated.

6.2.2 Group 2, had intention to make but never produced a consumer product and their response to AM/3D printing technologies

Group 2, the second profile, was for people who had an intention to make a consumer product but had never made one. Significantly, males, 90% (9/10), dominated this group, compared to females, 10% (1/10). This result has a similar trend of design intention to Group 2, where more males would like to do more in making a product. From the age-group perspective, as all the 5-14 age-group were in Group 1, none of them were in this group.

After they evaluated the sample pens, only 30% (3/10) wanted to make and buy a product made by AM/3D printing. 50% (5/10) would prefer to buy a standard manufactured product and 20% (2/10) had no preference.

6.2.3 Group 3, did not have any intention to make and their response to AM/3D printing technologies

Group 3, the third profile, was for people who did not have an intention to make a consumer product. This group is the largest among any other group profiles with approximately 55% (22 out of 40 total participants), 68.2% (15/22) females and 31.8% (7/22) males. After they evaluated the AM/3D printed pens, 59.1% (13/22) were willing to buy the products made by those technologies, 37.8% (7/22) would prefer to buy a standard manufactured product and 9.1% (2/22) had no preference.

Regarding the result, males dominated the group of participants who have making intention (Group 1 plus Group 2) whereas most females did not have the intention. However, AM/3D printing technologies could motivate more than half the females, as nine out of 15 females (60%) said they wanted to use AM/3D printers.
6.2.4 Three groups’ acceptance of AM/3D printing comparison

If the three groups are compared, Group 1, who had used design tools before, have the highest proportion of people who wish to buy AM/3D printed products (Figure 6-2). It may be because they have hands-on experience and see AM/3D printing technologies as an easier method to use regardless of the quality of the parts.

![Figure 6-2: Participants' acceptance of AM/3D printing from each group](image)

6.3 Consumer Design and Manufacturing

Currently, there are a lot of systems to support consumers who want to design and manufacture. For the consumer design field, if configuration can be counted as design, more than 970 international web-based product configurators are available on-line (Blazek et al. 2014) whether they employ AM/3D printing or not. This can be categorised as a co-designer/co-creation because consumers only have access in the design aspect, without being offered what type of manufacturing they want to use in order to produce their design. In addition, for consumer manufacturing, where consumers have an authority to select one of the manufacturing technologies, currently, there are about 24 AM/3D printing online portals available (3diers.org 2015). Requirements of consumer design and manufacturing, especially using AM/3D printing will be discussed in the following sections.

6.3.1 Consumer design requirements

Computer programs for consumers have to be very easy, not only to operate but also to access the software. Laypersons would not bother if the system required them to do installation of the software. The viable options to achieve this are by employing cloud based software or web-based applications where both are operated through a
web-browser. As a consequence, the system relies on the Internet. This will not be a problem in the near future with the increasing use of the Internet worldwide, and a United Nations Human Rights Council report in 2011 examined the important question of whether internet access is a human right (Human Rights Council 2011). In fact, currently there are more than 3,222,562,000 internet users or around 40% of the world population. It has increased tenfold from 1999 to 2013. An "Internet User" is defined as an individual who can access the internet, via computer or mobile device, within the place where the individual lives (Internet Live Stats 2015).

There are some user-friendly CAD packages available on the internet (3DTin, Tinkercad, Onshape), which consumers can use freely without any installation. CAD can provide a very easy way to create a 3D model, but with the analogy that everybody may have access to a pencil and pen, but only artists can produce a beautiful picture. Consumers prefer creating a 3D model with a template, not from scratch (Yavari 2015). With a template of a specific product the general public can modify, add or remove features.

The concept of creating the CaCODE system in this research is shown in Figure 6-3: Consumer design software, from CAD to CaCODE below. Designers create a basic product (Sinclair 2012) using Rhinoceros 3D CAD. All of the aspects of engineering, hard points, limitations have to be included in the 3D model. The approach is that the product has to be safe whatever consumers do with the parameter. This means it can be produced using AM/3D printing, maintaining the function and safety.

![Figure 6-3: Consumer design software, from CAD to CaCODE](image)

Based on the observations during the usability test, literature and existing CAD review here is the refinement of CaCODE:
Figure 6-4: Improved PenCAD, conceptual layout based on consumer acceptance survey

1. **Product selection**: allowing users to select a product through categories.

2. **Views**: has options: one views isometric, or two views (front and isometric), three views (front, side and isometric) and four views (front, side, top and isometric); full scale view.

3. **Sliders**: number of sliders depending on the products, showing number, and allowing users to input number.

4. **Drag points**: number of drag points depending on the products.

5. **Product accessories**: depending on the products, and accessories provided by designers.

6. **Save and compare**: allowing users to keep several designs and compare later.

7. **Undo and redo**: allowing users to undo and redo steps.

8. **Colour options**: colours choices need to be followed by material, process and post processing options.

9. **Material option**: system assesses the shape and offers material available for the shape.

10. **Real time volume, build envelope (length x width x depth), weight and estimation price**: this information will follow in every step, change taken; price based on average cost on the market, so it is not the final price.
11. **AM/3D printed preview**: allowing the consumer to see the surface roughness based on the build orientation options; also showing support structure, which needs to be broken/cut away (for those techniques which need support structure).

12. **Post-processing**: offering users an additional processing.

13. **Print it and final price**: allowing users to select: print by themselves, send to a company or find a local maker.

14. **Help**: using context-sensitive approach on a tooltip; the help text appears when a cursor is positioned over a button; based on the current/previous stage of operation.

### 6.3.2 Consumer manufacturing requirements

From the AM/3D printed evaluation, this research can offer recommendations based on participants’ perceptions of quality. The AM/3D printed pens represented different type of technologies and post-processing. The scenario is suggested by this research based on the literature review and participants’ feedback (page 141).

**6.3.2.1 Current performance**

Based on the research result, consumers still expected injection moulding part quality. It might be difficult to achieve even with the current post-processing system available. In this research case, the number one rank is the pen with the metallization. Metallization required 600 grit smoothness, which in the pen’s case cannot be done using tumbling. It has to be done manually and patiently.

Tumbling as post processing can increase the performance. With the same process and material, the ‘powder bed fusion SLS polyamide white pen’ jumped up the ranking from 12 (out of 13) to 5. It also happened with the ‘material jetting Polyjet ABS white’, it moved up from ranking 10 to ranking 7 after being tumbled. However, the tumbled pen did not always give a better performance, for example, in the case of the dyed pen, because it made the colour fade. The ‘powder bed fusion SLS dyed purple pen’ was degraded from ranking 4 to ranking 8 after being tumbled.
In the case of the AM/3D printed pen, high quality surface at injection mould level is not always the solution for mixed materials and colours. The ‘material jetting Polyjet mixed-materials and colours pen’ was evaluated straight out from the machine without any post-processing, and ranked at number two.

6.3.2.2 Scenario

After the prosumers create their own design, they can go through features 8 to 12 of CaCODE as those steps are part of the ‘consumer manufacturing’ activity. There are three viable options to do consumer manufacturing at the moment. Firstly, for the consumer who can afford to buy an AM/3D printer, they can just simply print it and use it or iterate their design. Secondly, using their own 3D printer, they can produce a product prototype before they order from the manufacturer to print the final one. Thirdly, for consumers who do not have an AM/3D printer machine at home, they can ask the community such as 3D hubs, or upload it to an e-manufacturing portal e.g. Shapeways, Ponoko, Kraftwurx and iMaterialise.

6.4 Consumer design adds sustainability value

Product personality was investigated as a means to influence this self-expression and this can cause people to postpone replacing their product for non-technical reasons. Clearly, the longer consumers keep the products the better for the environment (Mugge et al., 2009). This study confirmed that if people could design and/or print products for themselves, they would like to use the product longer than previous standard products that they have used (88% or 30/34 participants).

It is believed that the effect of the effort invested during the design process by customers on the emotional bond with the product is more self-expression of a person’s unique identity (Kiesler and Kiesler 2004; o. Blom and Monk 2003). Previous research on personalised products by users concluded that by personalising products in such a way they can distinguish themselves from others and can communicate a personal identity. Moreover, people who undertake a creative task on a product may enhance their sense of identity (Dahl and Moreau 2007).
Chapter 6 Discussion

The trend resulted from this study is also in line with two of five values of the theory of consumption. First is functional value, which is measured on a profile of attributes preferences about functional aspects. Second is emotional value, which is defined as a profile feeling associated with an alternative capacity to arouse feelings when the product is associated with something else (Sheth et al. 1991).

6.5 Willingness to pay and actual cost of AM/3D printed pens

The findings indicated that the participants’ willingness to pay was far lower than the actual cost that can be achieved by AM/3D printing. The lowest gap was three times and the highest was 11 times. These may be because participants did not design the product by themselves, it was purely based on the perceived quality of the pen samples. This suggests to AM/3D printing manufacturers that participants still value the product with ones that can be done by mass production.

Based on the Configurator Database Report 2014, there are 970 company websites that enable customers to personalise their own individual customised product, which manufacturers can produce once the order has been confirmed (Blazek et al. 2014). To date, there are three factors of the economic value of self-designed products using mass customisation toolkits: 1) preference fit achieved, which should be as high as possible; 2) design effort, which should be as low as possible; and 3) the awareness of being the creator of the product design (Franke et al. 2010). Regarding these factors, it is important for companies to develop mass customisation toolkits to generate value for the consumer. Therefore, the user-friendly interface, innovation and design of the co-design system should be good enough to gain customer satisfaction to lead to consumers’ willingness to pay. Feelings of accomplishment with regard to the self-design is also important in order to increase willingness to pay effect (Randall et al. 2007).

6.6 Research evaluation

The findings of this thesis indicate initial ideas on the potential of the general public to designing their own products and be accepting of the quality of AM/3D printed products. However, this research is seen as a beginning and needs to be investigated
further. For instance, the willingness to design, make and willingness to pay only demonstrated the profile based on generation and gender as it was limited to two aspects of generation and gender. Other aspects influencing personal factors such as stage of life, education, computer literacy and socioeconomic class (Tanner and Raymond 2012) were not considered by this research.

As the consumer product used in this research was a pen, the findings can be generalised to the products that have similar characteristics, such as products that people use by touching, holding, lifting by hand. Examples are mobile phone covers, toys, cutlery and mugs. An example of a product that cannot be generalised from this is a lampshade as it does need to be touched or lifted by hand, so the weight and surface finish for comfort to touch are not important. The most important aspect is how it lets the light through the shade. Another example is a mechanical part, where strength of material and precision and fatigue strength are more important than any other physical properties. Hence, these kinds of products would not be appropriate for this study.

The CaCODE system used in this research was an offline version. Respondents could only participate in the survey on a specific computer. Although all of the questionnaires were online, the offline design software was limited to a number of participants because the situation was reliant on the availability of both participant and researcher. While the PhD was in its final stages, Platypus became available to put Rhinoceros + Grasshopper online. With this capability, it could widen the participant profiles such as culture, country because it can be accessed worldwide.

If this research was to be repeated, the design process by participants would be run online. They would not need to meet the researcher, so it would be necessary to refine the CaCODE system to make it easier to operate without the need of a facilitator to train and explain how to use it. Using context-sensitive help for guidance and a very short and simple video tutorial as the back-up would help just in case the participants had a time and willingness to learn more. This would also test the user-friendliness of the software. With the online system, the number of participants could
be increased then the study could also expand the demographic data on socioeconomic classes for certain generations.
CHAPTER 7  Conclusion and Recommendation

This research has attempted to predict how AM/3D printing technologies and design software development could impact the offerings of industries and the way people consume a product. For that reason, this study focuses on developing a system to support consumers who would like to design their own products. The aim and objectives were developed in the field of consumer-led design prior to manufacture of the product using AM/3D printing. After the study was conducted, an original contribution to knowledge was made and this PhD research has met the aims and objectives, which will be summarised on the following sections.

7.1 Conclusions

Research aim: To investigate the potential of consumers to actively engage in product design and lead the product creation process to manufacture via AM/3D printing technologies.

For the significant contribution to the knowledge in the field of industrial design and product development, it is proven by the survey that there is a potential for consumers to design a product using user-friendly design tools. Although, as a software prototype, CaCODE still has some limitations, its influence to motivate the general public to use it is quite promising.
**Objective 1:** To identify the state of the art in consumer design tool development software and AM/3D printing with capacity to facilitate this.

This research identified the availability of software technologies that could be used to develop a tool to support consumer design and manufacturing, particularly using AM/3D printing methods. There were five basic alternatives available for the development platform: 1) develop a completely new system from scratch using a standard kernel such as CGM, ACIS or Parasolid, 2) use a conventional CAD package with its own API, 3) use visual programming language such as JavaScript Three.js, 4) use a specially developed “easyCAD” system, i.e. Digital Forming, 5) use a conventional CAD package with a special user-interface application, for example Rhinoceros and Grasshopper. The NURBS geometry CAD Rhinoceros was selected as the best option considering the skill of the researcher. The add-on Grasshopper enables the 3D model from Rhinoceros to be manipulated by a layperson without a CAD background. Platypus can be used as an interface of Rhinoceros CAD and Grasshopper plug-in for consumers through a web-browser, without the need for software installation.

The availability of AM/3D printing to produce a pen in plastic and metal as a consumer product was examined. For the plastic product, material extrusion could be used regardless of the stair-stepping effect as it is widely employed by low cost AM/3D printers. Material jetting Polyjet and powder bed fusion SLS were also used as they are widely utilised by companies who serve personalisation. Material jetting Polyjet with a multi-materials feature would be a good option as it is offered by standard manufacturing techniques, but with AM/3D printing technologies no assembly processes are needed. For the metal product, powder bed fusion SLM is the closest viable option for consumer manufacturing. Different post-processing methods were reviewed. Manual finishing, tumbling, painting, dyeing and metallization could be used to improve the appearance.
Objective 2: To determine the viability and parameters of 3D computer modelling software for consumer uses.

Based on the literature review, this research identified the movement of CAD from industries to consumers. One of the reasons is mass customisation where companies allow their customers to personalise their own products using a user-friendly 3D computer modelling program. Researchers have attempted to explore these areas. Herd (2012) developed conceptual models and design tools for mass customisation focussing on co-design experience, as an important part of the mass customisation journey. Sinclair (2012) suggested a specification of consumer design toolkits. Guido (2015) developed a working prototype for a consumer design tool that was tested by participants. This research enriched the previous research by developing a system for building consumer design software and offering two options in 3D manipulation, direct and indirect.

In order to answer objective 2, CaCODE was developed as a consumer design tool. The basic product was built by an experienced CAD user, using Rhinoceros, then with Grasshopper and Platypus the shape of Rhinoceros models can be easily modified using sliders (indirect) and drag points (direct). This allows anyone to make geometric variations of the product.

Objective 3: To employ the findings from Objective 2 to explore how consumers would respond to a consumer design tool.

The design software prototype was developed with two different options of design manipulation in order to uncover consumer preferences and to provide the best system for the general public. The first option was indirect manipulation using sliders and the second option was direct manipulation using drag points. Although with both options participants could easily learn and operate CaCODE; the majority of users found clicking on an object using drag points (direct manipulation) to change its shape and size more easily and quicker to produce a 3D model than using sliders (indirect manipulation). In general, CaCODE can enhance participants’ design intentions. Before they experienced the consumer design software only 47.5% (19/40) had design intentions and only 20% (8/40) went on to actually design, whereas after they
operated CaCODE, 75% (30/40) said they would like to use design software for designing their own product. The improved CaCODE concept was built based on the study and feedback from participants, which could be used for further development.

**Objective 4: To examine AM/3D printing capabilities in terms of materials, colours and surface finish by creating a sample of consumer products.**

This study assessed AM/3D printing technologies and selected the appropriate systems to produce a consumer product. For the plastic product, the consumer product in this research, pens, were built using material extrusion FDM, material jetting Polyjet and powder bed fusion SLS. For the metal product, powder bed fusion SLM was used. Apart from the powder bed fusion SLS plastic pen and vertical build material extrusion FDM pen, all of the processes required post-processing. The material jetting Polyjet plastic pen support structure could be removed easily using sprayed water, but for the horizontal build FDM plastic pen and SLM metal pen needed a special tool (i.e. a plier) was needed. This has to be considered for the consumer before they select the process. This research also examined the available additional post-processing which can improve the appearance. Different post-processing methods were undertaken: manual finishing, tumbling, painting, dyeing and metallization methods.

**Objective 5: To examine the level in which consumer will accept the material and production properties of AM/3D printing.**

A range of pens printed using different AM/3D printing methods were evaluated by participants. The result clearly identified participants’ preferences on perceived quality and they expected high surface quality at the same level as injection moulded products. However, AM/3D printing has advantages that standard manufacturing techniques do not have, for instance multi-materials from the material jetting method. Therefore AM/3D printing related businesses should exploit the advantages and embed these into customisable product designs. To improve the performance of AM/3D printing products, post processing tumbling and dyeing can be applied for material jetting Polyjet and powder based fusion SLM. For entry-level AM/3D printing machines, which mostly employ material extrusion FDM processes, the ‘stair-
stepping’ effect resulted in participants placing the product as the last choice. However, the texture can be a benefit for some products, in this research case, to add a grip effect for the pen.

### 7.2 Contribution to knowledge

This research made a number of original contributions to knowledge, as listed below:

1. The findings provided greater understanding of the level of consumers’ preference to designing their own products. These results could help development in areas of consumer design, customisation, personalisation, mass customisation, CAD development, AM/3D printing and business related areas.
   a. Based on the research, an initial software prototype was made to enable the general public to develop custom geometric variations. The prototype was tested on participants to understand user-friendliness. Based on findings, the improved consumer design tool concept was created as a reference for future development.
   b. The results of usability-test on the consumer design software identified that most participants prefer to use direct manipulation rather than indirect manipulation as this causes the users to ‘touch’ the digital model in a more intuitive and natural way. Also, it was easy to learn and faster to use.
   c. The study clearly indicated that the consumer design software could motivate the general public to design their own product and help them in developing a customised product to be manufactured using AM/3D printing fabrication.

2. Knowledge gained from this research contributes towards better understanding of consumer perception of quality in accepting AM/3D printed products. These could be beneficial to AM/3D printing developers. The research examined the number of AM/3D printing methods for producing consumer products. It also identified that the material jetting method with multi-materials has potential to be accepted in the same way as injection-
moulded product, because it offers a unique feature that standard manufacturing does not. Post-processing such as metallisation, dyeing and tumbling could also increase the participants’ acceptance level.

7.3 Recommendations for Future Work

To provide a sophisticated consumer design software, there are some aspect that need to be developed further. This recommendation focuses on technology and consumer perspectives:

1. Technology aspect
   a. For design, HCI and visualisation, design tools for consumers should be easy to operate. Hence, besides developing software, in which utilising conventional HCI (i.e. mouse, touch screen and scree), combining haptic and VR headset may help the general public easily interact with digital models. As this research indicates that the more naturally people interact with digital objects, the easier they find it to use.
   b. For the AM/3D printing technologies, surface smoothness is still desired. Use of the product directly from the machine without any post-processing is the best but post-processing can still be an option. Cost-effective surface smoothing techniques (e.g. using an acetone vapour chamber) need to be investigated further.
   c. Multicolour plastic AM/3D printing technologies have not been included in this research due to on-going development while this study was taking place. This option needs to be explored further as it may give a positive impact for consumer preferences.
   d. In terms of CAD progression at the consumer level, companies may need to consider developing computer-aids related to design for AM/3D printing, such as computer-aided engineering (CAE) for virtually testing the product before it is made, and computer-aided manufacture (CAM) for manufacturing. It may be useful for consumers to have access to a user-friendly CAE and CAM system. This would
enable them to avoid the failure of the product in terms of function and/or strength, or failure due to the manufacturing process.

2. Consumer aspect
   a. The degree of customisation may increase enjoyment and lead to product attachment. Consumer design software may help the general public by simplifying the step of manipulating the 3D model; hence the levels of simplification need to be defined. To accurately develop the software, it may be useful to measure to what degree a program would allow consumers to modify or create a system that can be adjusted to match consumer skill.
   b. Consumer designers are not trained to conceive how products look in the real world. Although the design software provides a 3D virtual model, there might be a gap between what consumers expect on the screen and what they actually obtain. Therefore, the future research may need to extend the usability test of the software by manufacturing the consumer designs and exploring whether there is a gap between consumers’ expectation during designing and the reality of a printed product.
   c. This research has limitations in picturing the market from a more complete demographic view. A comprehensive approach using the theory of consumer buying behaviours (personal, psychological, culture/societal and physical/situational factors) may be useful to explore further the details of the AM/3D printing market.
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References


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Appendices
Appendix A – Pen development

Refill pen drawing – hard points
Appendix A – Pen development

- Rubber material is not in finger grip position
- Looks square
- Too soft
- No black material available

- Cut at this position for the next printing
- The pimpls are too high

193
Appendix B – Grasshopper script

PenCAD1 – Asymmetry - Sliders
PenCAD2 – Symmetry – Drag points
Appendix C – Cost for manufacturing a pen in PA and metal material by AM/3D printing manufacturers

i.materialise
Appendix C – Cost for manufacturing a pen in PA and metal

kraftwurx
Appendix C – Cost for manufacturing a pen in PA and metal

Ponoko
sculpteo
Appendix C – Cost for manufacturing a pen in PA and metal

shapeways
Appendix D - Pilot Study questionnaire

Research: Computer Aided Consumer Design for Additive Manufacturing / 3D Printing Products

Participant Information Sheet

Research performed by:
This research is being conducted by Yudhi Ariadi (Y.Ariadi@lboro.ac.uk, 01509-216966) and supervised by Dr. Mark Evans (M.A.Evans@lboro.ac.uk, 01509-222656) and Dr. Ian Campbell (I.Campbell@lboro.ac.uk, 01509-228312) from Design School, Loughborough University.

What is the purpose of the study?
The purpose of this study is to understand the acceptability of consumer design software and AM/3D printing printed products. The result will be used for further development.

What will I be asked to do? How long will it take?
The participants are required to fill a questionnaire, use software and assess sample products. This session should take no longer than 20 minutes.

What personal information will be required from me? Will my taking part in this study be kept confidential?
The data we collect do not contain any personal information about you except your age group and your job. The age group is needed to see the generation you are and the job is to see how familiar participants with the research purpose. All the information you give us will be confidential and used for the purposes of this study only.

Are there any risks in participating? No risks anticipated

Once I take part, can I change my mind?
Agreed text: Yes! After you have read this information and asked any questions you may have we will ask you to complete an Informed Consent Form, however if at any time, before, during or after the sessions you wish to withdraw from the study please just contact the main investigator. You can withdraw at any time, for any reason and you will not be asked to explain your reasons for withdrawing.

What if I am not happy with how the research was conducted?
The University has a policy relating to the Research Misconduct and Whistle Blowing which is available online at http://www.lboro.ac.uk/admin/committees/ethics/Whistleblowing(2).html.

Loughborough University

Computer Aided Consumer Design for AM/3D Printing products
Researcher: Yudhi Ariadi – Y.Ariadi@lboro.ac.uk
Appendix D – Pilot Study questionnaire

DEMographic

PARTICIPANT NO

A1- Age

☐ 18 - 25  ☐ 36 - 40  ☐ 51 - 55
☐ 26 - 30  ☐ 41 - 45  ☐ 56 - 60
☐ 31 - 35  ☐ 46 - 50  ☐ 61 - 65

DESIRE FOR DESIGNING (DRAWING, SKETCHING) PRODUCTS

B1- Have you ever wanted to design a product?
☐ Yes (please continue to B2)
☐ No. Why not? (please choose from the following possible answers, then continue to C1)
☐ I cannot design
☐ I never thought about it, it is outside my area.
☐ Other, please explain:

B2- Have you ever actually designed a product?
☐ Yes (please continue to B3)
☐ No. Why not? (please choose from the following possible answers, then continue to C1)
☐ My design ability is very low.
☐ Other, please explain:

B3- Give (an) example(s) of product(s) that you have designed (Please continue overleaf if necessary):

B4- How did you design it/them?
☐ Hand sketching
☐ 2D design software (e.g. MS-Paint, Photoshop, Coreldraw, GIMP or other__________). 
☐ Other, please explain (Please continue overleaf if necessary):

Design School
Computer Aided Consumer Design for AM/3D Printing products
Researcher: Yusuf Aradi – Y.Aradi@lboro.ac.uk

Loughborough University
Appendix D – Pilot Study questionnaire

DESIRED FOR MAKING (OR MODIFYING) PRODUCTS

C1- Have you ever wanted to create/modify a product?
- Yes (please continue to C2)
- No. Why not? (please choose from the following possible answers, then continue to D1)
  - I am too busy.
  - It is expensive and needs investment.
  - I do not have the skills to hand make things.
  - I do not have the facilities/tools.

C2- Have you ever actually created/modified a product by yourself?
- Yes (please continue to C3)
- No. Why not? (please choose from the following possible answers, then continue to D1)
  - I am too busy.
  - It is expensive and needs investment.
  - As a handicraft, I do not they have a skill.

C3- How did you create a product?
- By hand
- Using (computer) machine tools
- Used an expert/technician/service
- Other, please explain:

3D PRINTED PENS EVALUATION

E1- Could you please select your 5 preferred options for surface finish/colour and rank them in order.
(No. 1 is better than no. 2)

When considering which product you would like to buy:

E3- The function of the product is important
E4- The surface finish of the product is important
E5- The colour quality of the product is important
**APPENDIX D – PENCIL EVALUATION**

Having now used PenCAD as consumer design software, would you say:

<table>
<thead>
<tr>
<th></th>
<th>strongly disagree</th>
<th>disagree</th>
<th>neutral</th>
<th>agree</th>
<th>Strongly agree</th>
</tr>
</thead>
<tbody>
<tr>
<td>D1</td>
<td>I found it is easy to change the shape using sliders.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>D2</td>
<td>I found it is easy to change the shape using click &amp; drag.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>D3</td>
<td>Using a ruler is helpful to change the shape.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>D4</td>
<td>Are there any feature(s) of PenCAD that you feel are inconvenient?</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>D5</td>
<td>Are there any feature(s) you would like added to PenCAD?</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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**DESIRE FOR USING CONSUMER DESIGN SOFTWARE**

3D data for making a product using 3D printing can be obtained by:
- Creating/designing your own product (using consumer design software, e.g. PenCAD), or
- Downloading a ready-to-print pen from an on-line shop

Having now used consumer design software:

<table>
<thead>
<tr>
<th></th>
<th>strongly disagree</th>
<th>disagree</th>
<th>neutral</th>
<th>agree</th>
<th>Strongly agree</th>
</tr>
</thead>
<tbody>
<tr>
<td>F1</td>
<td>I would like to design my own product using consumer design software (e.g., PenCAD)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>F2</td>
<td>I would like to download a ready-to-print product design</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**DESIRE FOR USING A 3D PRINTER**

Your chosen product design could be made by:
- Having your own 3D printer and printing it yourself,
- Sending the file or uploading 3D data to a 3D printing manufacturer.

Having now seen products built using 3D printing:

<table>
<thead>
<tr>
<th></th>
<th>strongly disagree</th>
<th>disagree</th>
<th>neutral</th>
<th>agree</th>
<th>Strongly agree</th>
</tr>
</thead>
<tbody>
<tr>
<td>F3</td>
<td>I would like to buy my own product made from a 3D printer</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>F4</td>
<td>I would still prefer to buy a standard product (available on the market)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Appendix D – Pilot Study questionnaire

KEEPING YOUR OWN DESIGNED AND PRINTED PRODUCTS LONGER
If I could design and/or print products for myself, strong agree disagree neutral agree strongly agree
G1- I would keep/use/maintain them longer than previous standard products that I have used.

WILLINGNESS TO BUY
H1- From your 5 favourite pens and please say what price would you pay for each of them?

Pen No.  | Price (£)
---------|---------
         |         
         |         
         |         
         |         
         |         

PARTICIPANT CONSENT FORM

Title of the project: Computer Aided Consumer Design for Additive Manufacturing / 3D Printing Products
Researcher’s contact details: Yudhi Ariadi E: Y.Ariadi@lboro.ac.uk T: 01509-226966

- I agree to take part in the above research. I have read the Participant Information Sheet, which is attached to this form. I understand what my role will be in this research, and all my questions have been answered to my satisfaction.
- I understand that I am free to withdraw from the research at any time, for any reason and without prejudice.
- I have been informed that the confidentiality of the information I provide will be safeguarded.
- I am free to ask any questions at any time before and during the study.
- I have been provided with a copy of this form and the Participant Information Sheet.

Data Protection: I agree to the University processing personal data that I have supplied. I agree to the processing of such data for any purposes connected with the Research Project as outlined to me.

Name of participant (print): __________________________
Signed: __________________________
Date: __________________________

Design School
Computer Aided Consumer Design for AM/3D Printing products
Researcher: Yudhi Ariadi – Y.Ariadi@lboro.ac.uk
Appendix E – Main study questionnaire

Computer Aided Consumer Design for Additive Manufacturing / 3D Printing Products V7

Welcome

Researcher:
This research is being conducted by Yudhi Ariadi (Y.Ariadi@lboro.ac.uk, 01509-226966) and supervised by Dr. Mark Evans (M.A.Evans@lboro.ac.uk, 01509-222656) and Dr. Ian Campbell (R.I.Campbell@lboro.ac.uk, 01509-228312) from Design School, Loughborough University.

What is the purpose of the study?
The purpose of this study is to understand the acceptability of consumer design software and AM/3D printing printed products. The result will be used for further development in those areas.

What will I be asked to do? How long will it take?
The participants are required to complete a questionnaire, use some software and assess sample products. This session should take no longer than 45 minutes.

What personal information will be required from me? Will my taking part in this study be kept confidential?
The data we collect will not contain any personal information about you, except your age group. The age groups are needed to see what generation you are in and indicate that the research covers all of the generations. Information provided by you will be kept confidential and be used for the purpose of this study only.

Are there any risks in participating?
There are no risks associated in participating.

Once I take part, can I change my mind?
Yes! After you have read this information and asked any questions you may have, we will ask you to complete an Informed Consent Form. However if at any time, before, during or after the sessions you wish to withdraw from the study please just contact the main investigator. You can withdraw at any time, for any reason and will not be asked to explain your withdrawal reasons.

What if I am not happy with how the research was conducted?
The University has a policy related to Research Misconduct and Whistle Blowing where you can express your dissatisfaction here or at http://www.lboro.ac.uk/admin/committees/ethical/Whistleblowing(2).htm.

Click the NEXT button below to start your participation...
About you

1) Are you?
   - Female
   - Male

2) Please select your age group
   - 5-9
   - 10-14
   - 15-19
   - 20-24
   - 25-29
   - 30-34
   - 35-39
   - 40-44
   - 45-49
   - 50-54
   - 55-59
   - 60-64
Your desire to design a consumer product

In the next few questions you will be asked about "designing and making a consumer product" where in this research consumer products mean: solid physical objects that have three dimensions; common ready to use objects such as; kitchenware, tableware, toys, jewellery, decoration, tools, or devices, accessories and components for other consumer products.

3) Have you ever wanted to design a consumer product?
   - Yes
   - No

4) Please write the desired consumer product

5) Did you go on to design the consumer product?
   - Yes
   - No

6) How did you design the consumer product?
   (Select all that apply, you can choose more than one)
   - Hand-sketching
   - 2D design software/program, please specify:
   - 3D design software/program, please specify:
   - Other, please specify:

7) Why not?
   - I cannot design
   - I never thought about it, it is outside my area of expertise
   - Other, please specify:
Appendix E – Main Study questionnaire

PAGE 2 OF 9
Desire to make a product

8) Have you ever wanted to make a product
   - Yes
   - No

Logic: Dynamically shown if "Have you ever wanted to make a consumer product" = Yes

9) Please write the desired product

Logic: Dynamically shown if "Have you ever wanted to make a consumer product" = Yes

10) Did you actually make the product?
   - Yes
   - No

Logic: Dynamically shown if "Did you actually make the consumer product?" = Yes

11) How did you make the product?
   - By hand
   - Using (computer) machine tools
   - Used an expert / a technician / a service
   - Other, please specify:

Logic: Dynamically shown if "Have you ever wanted to make a product" = No or "Did you actually make the product?" = No

12) Why not?
   - I was too busy
   - I did not have the skill to make it
   - It was too expensive and needed investment
   - I did not have the facilities/tools
   - Other, please specify:
PenCAD evaluation

You will be asked to evaluate/review an example of consumer product design software: PenCAD, a design software for creating a pen.

PenCAD-type1, changing a pen shape using slider buttons:

PenCAD-type2, changing a pen shape using drag-&-drop control points of a curve:
Having now used PenCAD as consumer design software, would you say:

13) I found it is easy to change the shape using sliders (PenCAD-type1)
   - Strongly disagree  - Disagree  - Neutral  - Agree  - Strongly agree

14) I found it is easy to change the shape using click & drag (PenCAD-type2).
   - Strongly disagree  - Disagree  - Neutral  - Agree  - Strongly agree

15) Using a 'ruler' is helpful when changing the shape
   - Strongly disagree  - Disagree  - Neutral  - Agree  - Strongly agree

16) Are there any feature(s) of PenCAD that are difficult to use?

17) Are there any feature(s) you would like added to PenCAD?
Having now seen the 3D printed products, please consider the surface finish and colours:

18) Could you please rank them in order based on your preferred options for finish/colour:

- Pen 1
- Pen 2
- Pen 3
- Pen 4
- Pen 5
- Pen 6
- Pen 7
- Pen 8
- Pen 9
- Pen 10
- Pen 11
- Pen 12
19) Why do you like it (the best one)?
(Select all that apply, you can choose more than one)
☐ Surface finish
☐ Surface texture
☐ Rubbery
☐ Shiny
☐ Matt
☐ Colour
☐ Weight
☐ Other, please specify::

20) Why do you NOT like it (the worst one)?
(Select all that apply, you can choose more than one)
☐ Surface finish
☐ Surface texture
☐ Rubbery
☐ Shiny
☐ Matt
☐ Colour
☐ Weight
☐ Other, please specify::
Desire for using Computer-aided Consumer Design

3D data for making a product using 3D printing can be obtained by:
Creating/designing your own pen (using consumer design software, e.g. using PenCAD) (see below)

Downloading a ready-to-print pen design from one of the available websites:

24) If you want to manufacture your desired product, would you prefer to:
   - design my own product using consumer design software.
   - download a ready-to-print product file.
   - no preference
Desire for using Additive Manufacturing machines / 3D Printers

Your chosen product design could be made by:
- Having your own 3D printer and printing it yourself, or
- Sending the file or uploading 3D data to a 3D printing manufacturer.

For more information what is 3D Printing, please watch the video below:

25) Having now seen the quality of the 3D printed pens (EXCLUDING Pen 3, 12 and Pen 13); and the benefits of 3D printing which allow you to customise a product. Would you prefer to:

- buy your own customised product made using a 3D printer
- buy a standard manufactured product.
- no preference
26) If you could design and/or print products for yourself, would you like to use them longer than previous standard products that you have used?

☐ Yes

☐ No

☐ I do not know

Logic: Dynamically shown if "If you could design and/or print products for yourself, would you like to use them longer than previous standard products that you have used?" = Yes

28) Why do you want to use them longer?

<table>
<thead>
<tr>
<th></th>
<th>Strongly disagree</th>
<th>Disagree</th>
<th>Neutral</th>
<th>Agree</th>
<th>Strongly agree</th>
</tr>
</thead>
<tbody>
<tr>
<td>I have designed it myself</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>The product I designed expresses my identity</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>I have a bond with the product I designed</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
</tbody>
</table>
Appendix E – Main Study questionnaire

Willingness to pay

27) What price would you be prepared to pay for your top 3 pens?

For the Rank 1: I would pay £:

For the Rank 2: I would pay £:

For the Rank 3: I would pay £:

For the Rank 4: I would pay £:

For the Rank 5: I would pay £:

For the Rank 6: I would pay £:

Thank you

Hidden Value: Participant data
Value: Populates with the length of time since the survey taker started the survey

Thank You!

Thank you very much for completing our survey. Your response is very important to us.
Thank you.
Appendix F – Pen designs by consumers

PenCAD1 – Asymmetry - Sliders

Age group 5-14
Appendix F – Pen designs by consumers

Age group 15-24
Appendix F – Pen designs by consumers

Age group 25-34
Appendix F – Pen designs by consumers

Age group 35–44
Age group 45-54
Appendix F – Pen designs by consumers

PenCAD2 – Symmetry – Drag points

**Age group 5-14**
Appendix F – Pen designs by consumers

Age group 15-24
Appendix F – Pen designs by consumers

Age group 25-34
Appendix F – Pen designs by consumers

Age group 35-44

[Diagram of pen designs for age group 35-44]
Age group 45-54
Age group 55-64