COMBINING ADDITIVE MANUFACTURING WITH COMPUTER AIDED CONSUMER DESIGN

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Abstract

This paper reports an investigation into the potential for consumers designing and manufacturing their own products using a combination of "Computer Aided Consumer Design" (CaCODE) and Additive Manufacturing (AM). Recent developments in the field of AM (cheaper machines and new materials) have led to renewed interest in the manufacture of customised products and, more specifically, allowing consumers to create their own bespoke products. However, a persistent weak link in this paradigm is the inability of most consumers to create 3D models as an input for AM. Operating a conventional CAD system requires a lengthy period of specialist training and is therefore not viable in this context. Consequently, easy-to-use 3D design tools are needed to make AM more accessible to consumers. This research study investigated the suitability of such a system for enabling consumers to design their own pens for manufacture using AM. The investigation also explored the consumer acceptance of current AM capabilities when used for the production of consumer products. The results showed that careful attention must be paid to the specific needs of consumers, both in terms of their product preferences and their ability to use software. These will be used to guide the design of future CaCODE systems.

Introduction

The overall research aim of this project is to investigate the potential for consumers to actively engage in product design and manufacture. This is done regularly for aspects such as options configuration or choosing colours, but not so often for 3D shape generation. A key reason for this is the inability for ordinary consumers to create or modify 3D models. To provide an appropriate system for consumers to produce 3D models for AM, a so-called Computer Aided Consumer Design (CaCODE) approach has been employed. Consumer design refers to products whose conception, specification, design, or manufacture may occur with direct consumer input [1]. The driving philosophy of CaCODE is that it must be relatively easy to use, as it will have to be operated by the members of the general public who do not have any CAD skills.

Since the role of the CaCODE software is to generate 3D models that will ultimately be used to create actual products, this study also reviewed the current capabilities of various AM technologies when producing a consumer product (using an asymmetric pen as a case study). The pen was selected as an example of a consumer product because of its simplicity and the fact that consumers can readily identify with it. The acceptability of AM products to consumers was measured in terms of surface finish, colour quality, weight and grip.

Background

Design activity has been described as everything from "the teacher arranging desks for a discussion to the entrepreneur planning a business to the team building a rocket" [2]. In the areas of Mass Customisation (MC), personalisation or individualisation, the terms "user co-design" or "customer integration" are familiar [3]. There is also an opinion that "with user-design systems, the professional designer is replaced by the user," [4]. Research at Loughborough Design School has indicated that such wholesale replacement is not currently feasible and that collaborative consumer design is required, where part of the product design is done by the designer and the remainder by the consumer. As part of this approach, this paper will evaluate potential software and hardware systems to see how suitable they are for bringing consumers into the design process and then progress through to manufacture. The following sections review the direction of designing and manufacturing that is usually done by companies but which might, in the future, be undertaken by consumers.

The Increasing Role of the Consumer

Many industries have shifted from production-driven and market-driven approaches to consumer-driven approaches. This latter approach connects consumers' choices with the capabilities of the company and extends the philosophy of concurrent engineering to sales, marketing and end users. Thereby, it brings the voice of customers into design and manufacturing [5].

The widespread use of the personal computer and its peripherals, as well as the Internet and e-business, has affected the behaviour of many consumers [6]. Communication technologies allow easy and fast interaction between manufacturers and consumers so manufacturers can rapidly identify consumer requirements and consumers can express their particular needs [7]. In this way, consumers are becoming accustomed to conveying their requirements to manufacturers, so that the numbers of consumers who want to have personalised items has the potential to increase significantly.

Bringing Back "Craft Customisation"

In the pre-industrial era, craft customisation existed. People created products in a customised way despite the limitations of technology at the very beginning of market trade. Products were initially made one-by-one according to each individual's needs. This procedure was typically carried out by individuals or home industries. The desire to reduce production costs and time created strong influences in the increased use of Mass Production (MP). Good quality and a cheap price became very popular drivers. MP provided a low cost option that led to uniformity. This drove craft production into the realms of art and bespoke products, where higher cost and product variability were not such important issues. At some point, simplification of product variants was criticised, and consumers required industries to listen to their expectations of styles, sizes, needs or even schedules. This drives production away from pure MP towards the need to accommodate versions and options. Going beyond this, MC is a production system that enables customisation and personalisation or individualisation of products as well as services at a price comparable to MP [8].

AM technology can move the method of customisation away from the conventional means, such as product modularity, towards bespoke production. AM capabilities can serve consumers as individuals in the same way craft customisation can, but employing different forms of communication and interaction. In addition, with this relatively simple type of manufacturing (no tools, little set-up) the manufacturing can be undertaken by SMEs or even individuals. In some ways, this shows similarity to the manufacturing conditions of the pre-industrialisation era. According to Davis, similar events to those in the past will happen in the future regardless of how or what form they will take [9]. Hence, the use of AM could be portrayed as a means of completing the circular pattern of production technologies shown in Figure 1.

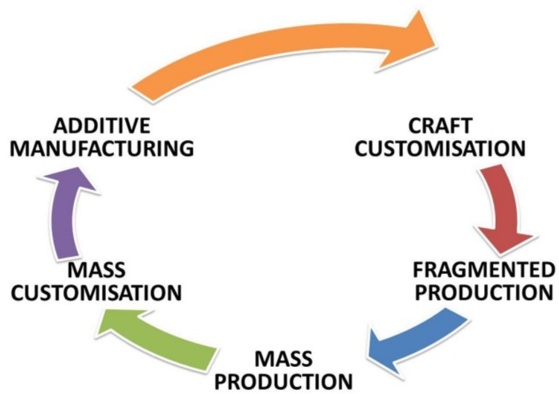

Figure 1: Production Technology cycle: from craft customisation to AM customisation

Alongside the movement of AM into smaller organisations, CAD has already progressed in a similar direction. Historically, CAD was first developed for large scale manufacturing companies, such as those found in the automotive and aerospace sectors. Early computer aided design tools were not easy to operate, even for well-trained design engineers. With further developments, CAD has taken many steps to become an industrial design tool also. With regards to opening up AM advantages to more people and to bringing manufacturing closer to consumers, this research focuses on extending the use of CAD to consumers. If feasible, then consumers themselves could modify digital models without the need for extensive CAD experience. Consequently, this would place a new design tool on the market for consumers (Figure 2).

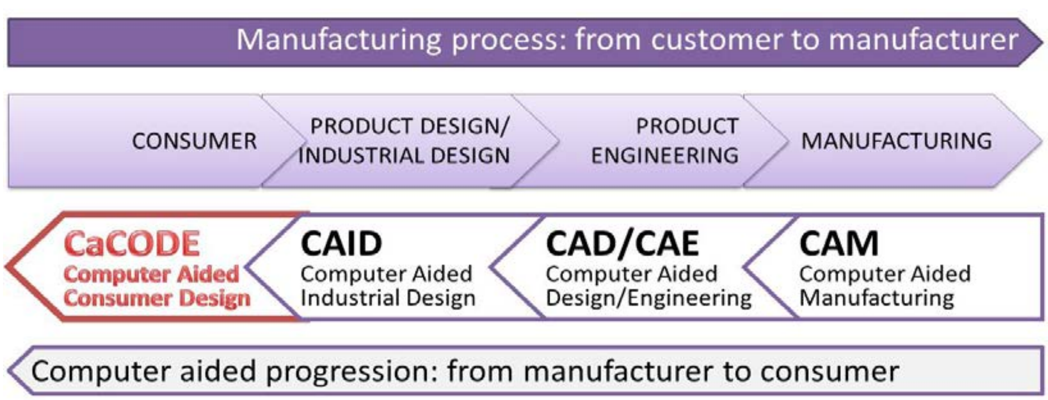

Figure 2: The progression of CAD towards the consumer

Consumer innovation, personalisation and sustainability

For four decades, several studies have observed consumers' innovative buying behaviour. These studies focused on consumption values to explain why consumers choose to buy or not to buy certain products, as well as the relations between consumers and products. As a result, four types of motivation underlying consumer innovativeness were identified, namely functional, hedonic, social and cognitive motivation as shown in Table 1 [10]. The anticipated advantages of CaCODE combined with AM are to enhance the motivation for consumer innovation.

Functional	Hedonic	Social	Cognitive
Usefulness, handiness, compatibility, efficiency, comfort, ease, quality, reliability.	Pleasure, fun, sensation, excitement, enjoyment, tension, desire, an escape from the daily round.	Being different and unique, status, standing, prestige, distinction, opinion leadership, manipulation, visibility, social rewards, trendiness, symbolism, demonstrating one's success, sense of belonging, image.	Knowledge, information, intelligence, wisdom, eagerness to learn, logical thinking, insight and understanding, reason, brainpower, mental stimulation.

Table 1: Examples of four consumer innovation motivations

Product personalisation refers to a process that defines or changes the appearance or functionality of a product to increase its personal relevance to an individual [11]. Consumers need to invest mental effort in a product to configure choices of shapes and colours. As a result, the effect of the effort invested during the customisation process generates an emotional bond with the product. It has been shown that users will extend the period of time spent with the product [12]. This can postpone people's tendency to replace products for non-technical reasons and the longer consumers keep products the better it is for the environment, in terms of product disposal or the energy going into recycling. In this way, it is anticipated that greater consumer involvement in design will lead to improved product sustainability.

Research Design

This research study employs quantitative and qualitative methods integrated through participant surveys, in which the participants will be asked to evaluate the use of a CaCODE tool and assess the appearance of AM products. Both types of data will likely provide useful information such as user acceptance of the method and products. It will also help to narrow down possible directions for follow-up research as well as improvements to future CaCODE systems. The authors developed a CaCODE pen design tool for this survey and built pen samples using several AM systems, coupled with different finishing techniques. Non-designers from a variety of backgrounds were asked to design their own pens using the tool and then to evaluate the AM products as if they were the results of their design input. Consumers were then asked to evaluate the software's user-friendliness and their acceptance of the sample products.

Developing CaCODE:Pen

One type of consumer design tool available today is design configuration programs. These programs are also called co-design tools and defined as software applications that create particular products where consumers can build a certain version by choosing some of its 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.

Recently, web-based "easy CAD" tools have been released, which consumers can access through the Internet with no installation required. These are 3D CAD systems and 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 [13], [14]. 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 reach 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 printing AM products (Figure 3).

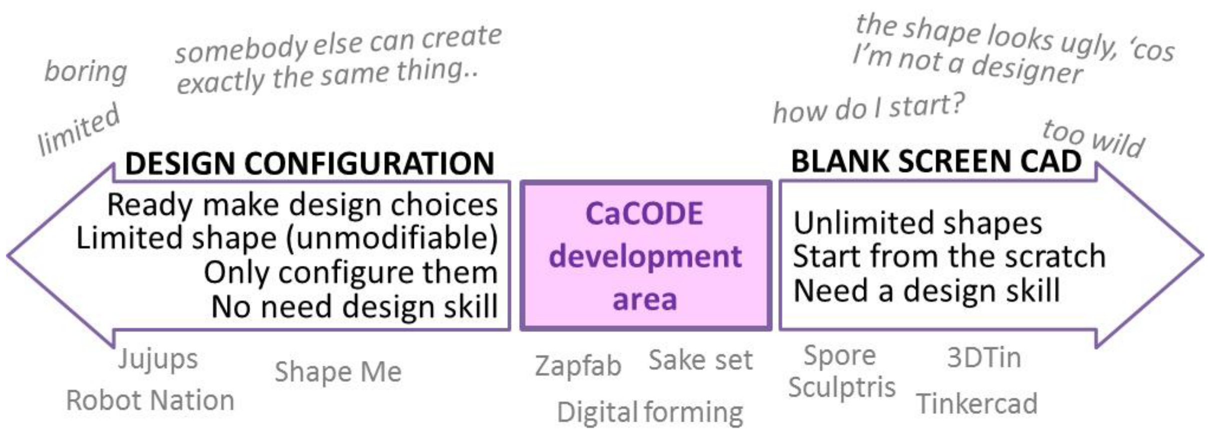

Figure 3: Filling the gap between design configuration tools and blank screen CAD

To simplify the operation of CaCODE, it has been developed to cater for one particular product or similar shapes at a time. CaCODE should be easy enough to use so that it requires no prior CAD skills. For this reason, the first version of CaCODE was developed for pen design and was used to run trials in which members of the general public were asked to comment on whether or not it was easy to operate.

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

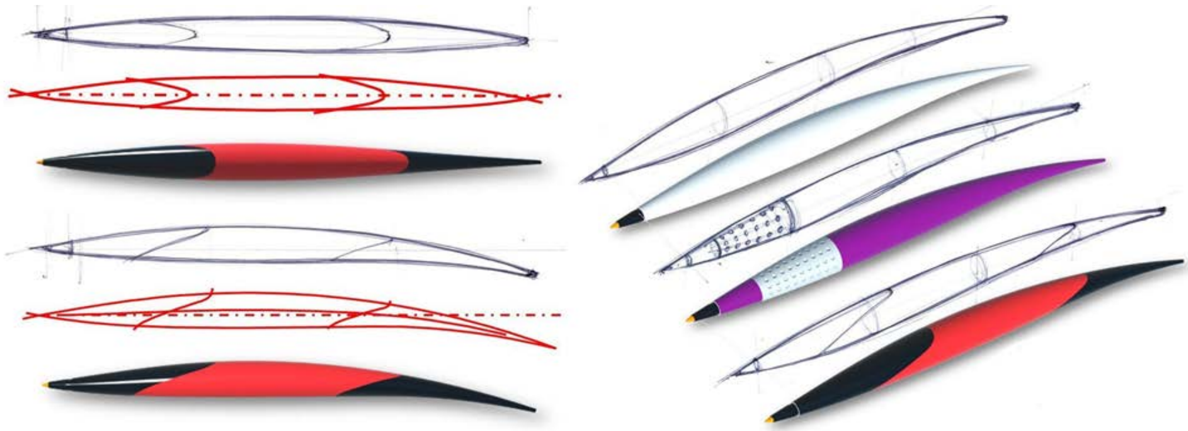

Figure 4: 2D sketches of the starting point pen design

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 5). The profile curves 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.

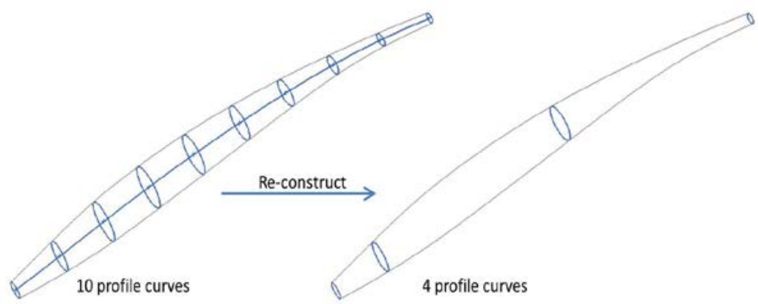

Figure 5: Simplifying the profile curves used for CAD construction

Building the CaCODE:Pen system

CaCODE:Pen 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 [15]. 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.

Figure 6 shows how the CaCODE:Pen tool was generated from the Grasshopper software. Basically, the pen is built by four sections of circles where the top and middle circle positions are movable and the diameter of each circle is changeable. Also, by using another parameter, the circles can be modified to become ellipses. The bottom and end circles are fixed, because they are related to 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 thus creates the surface of the pen.

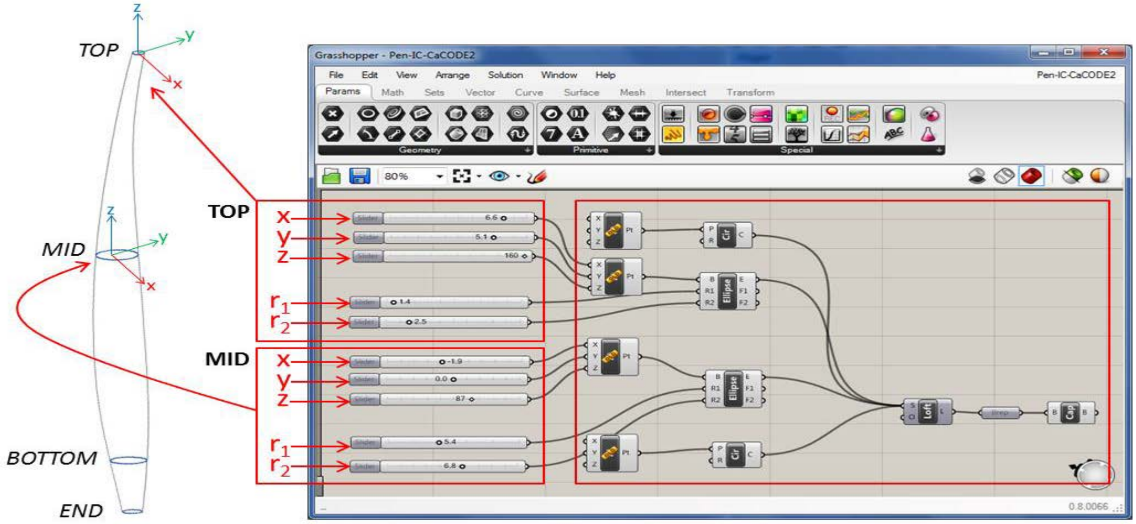

Figure 6: Grasshopper: Building a script for the CaCODE:Pen tool

Figure 7 shows how the CaCODE:Pen interface appeared to the users. There is a control panel on the right and by using the mouse users can change the pen by sliding the small buttons on the sliders. In addition, the interface has 3 display views, front, right and isometric, to evaluate the appearance of the pen that they are designing.

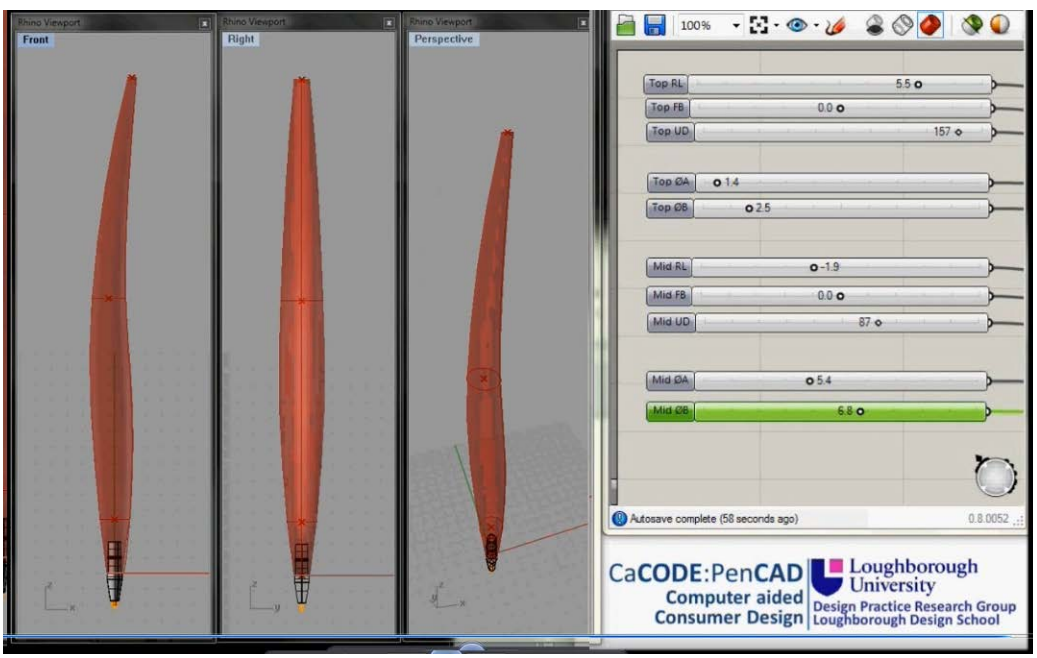

Figure 7: The user interface of the CaCODE:Pen: tool

Creating a range of AM samples

This second part of this research was aimed at assessing how consumers would respond to the materials, surface finish, and colours of consumer products made using AM. To this end, 14 pen samples were built based on three varying parameters: different AM technologies and build materials, different colouring techniques and different finishing techniques (Figure 8). The AM technologies selected for this study were laser sintering/melting, polyjet printing, polymer extrusion and ink-jet printing onto powder. Suitable post processing techniques were used to achieve better surface finish and colour quality, including tumbling, painting, dying and metallisation. Two of the pens were hand-finished and painted to provide injection moulded quality, both gloss and matt finish, so that they could act as datums against which the quality of the other pens would be evaluated.

Figure 8: AM pen samples used for the study

User Trials

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, eight of whom had never used CAD before. 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 design of pen. They were then asked to evaluate their experience by completing a questionnaire. Research participants were also asked to evaluate the appearance of the range of AM made pens. A summary of the questions asked in the questionnaire is as follows:

- Have you ever wanted to design a product, if not, why not?
- Have you ever actually designed a product, if not, why not?

- If yes, give an example of a product that you have designed and state how you designed it.
- Have you ever wanted to create/modify a product, if not, why not?
- Have you ever actually created/modified a product by yourself, if not, why not?
- If yes, how did you create it?
- Having now used PenCAD as consumer design software, how do you rate its usability?
- Are there are any feature(s) of PenCAD that you feel are inconvenient?
- Are there any feature(s) you would like added to PenCAD?
- 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.
- When considering which pen you would like to buy, how important is function, surface finish and colour quality?
- Having now used consumer design software, how much would you like to design a pen?
- Having now seen pens built using 3D printing, how much would you like to buy one?
- 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?
- From your 5 favourite pens, please say what price would you pay for each of them?

Many of the 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”. The values given by the participants are shown as colour-coded bars in Figure 9, where each horizontal bar represents the ten answers. The most important results to note are that sliders were seen as the most useful interaction tool, that functionality and surface finish were more important than the colour quality, that downloading a ready-to-print design was slightly more desirable than designing one using PenCAD and that most of the participants thought they would keep a customised AM pen longer than a standard design. There is a tension between these last two results which will need to be investigated further.

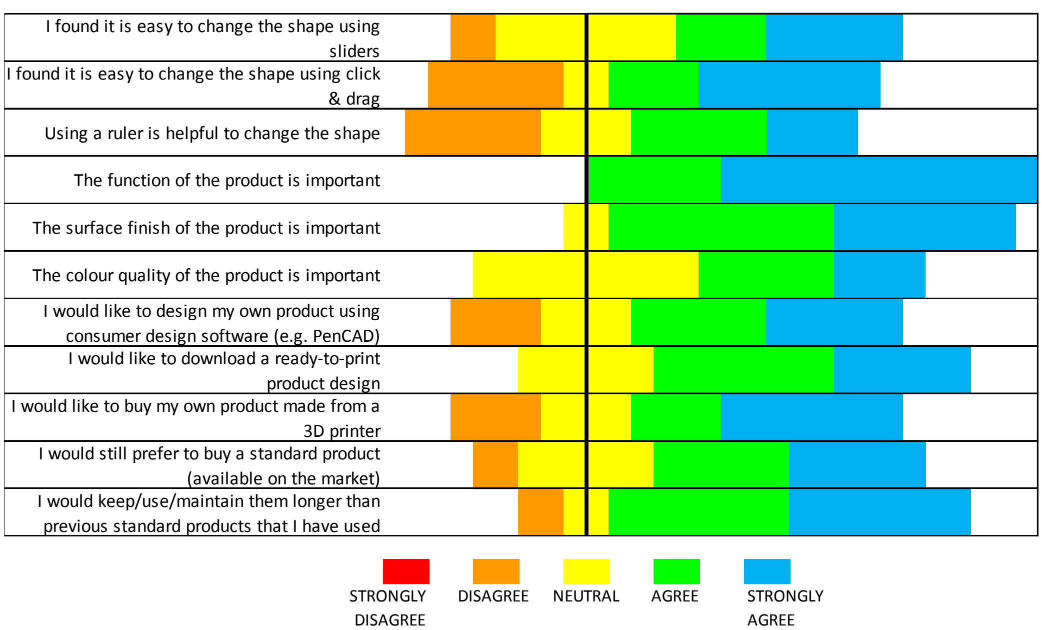

Figure 9: Results of Likert scale questions.

The participants' pen ranking values were inverted to give each pen a score out of 10 (i.e. a top ranked pen was given a score of 10 and a bottom ranked pen was given a score of 1) and used to calculate the total score given to each pen by the 10 participants. These scores are shown in Figure 10 next to a brief description of each pen, i.e. how it was made and finished. Not surprisingly, the two injection moulding quality pens came out top but several of the AM made and finished pens came quite close, specifically 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 come out worst. The only pen made in metal received the lowest score with several participants commenting that it was too heavy. In terms of the price that consumers said they would pay for personalised pens, almost all the pens were valued at between 1 and 5 GBP. 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.

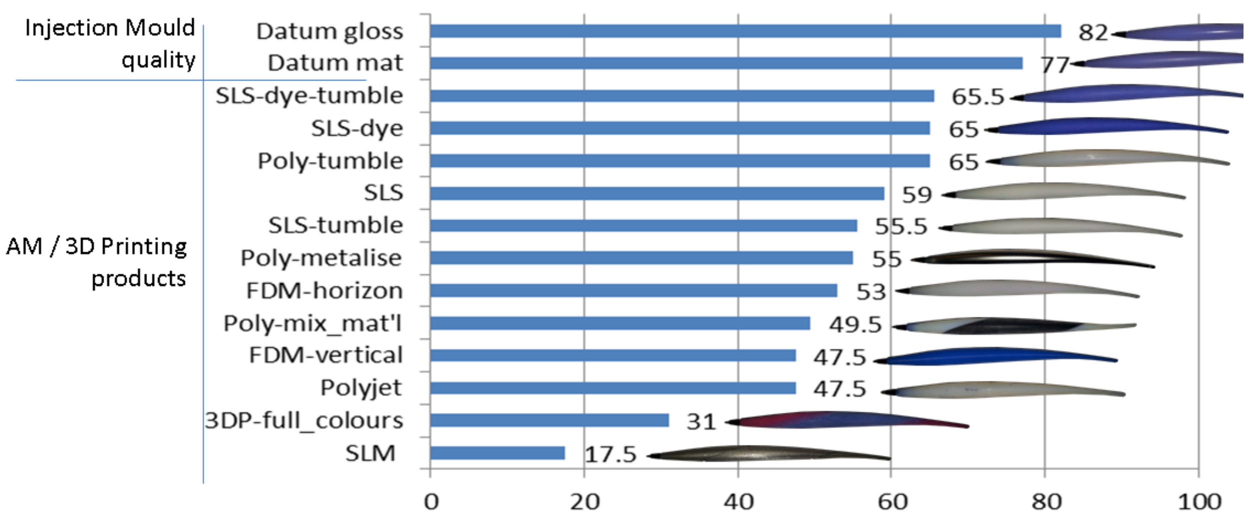

Figure 10: Scores out of 100 for the range of pens.

<u>Conclusions and Future Work</u>

The research has identified the potential for simplifying the interfaces of 3D CAD systems to a level where they can be used by non-expert users. The user of slider buttons was a particularly effective way of simplifying the modelling process. The general reaction to CaCODE:Pen was favourable although some consumers felt restricted by the shape of the starting pen design that was used. A possible solution to this would be to create a starting design that was built from sketches drawn by the consumer. This method has been used previously at Loughborough [16] but suffered from two drawbacks. Firstly, it was time consuming for the designer and secondly, some consumers felt uncomfortable with sketching. An alternative is to use software that will automatically generate a range of potential designs, from which the consumer can select a starting point. Such a system is "evoShape" (also developed at Loughborough University), which is an interactive evolutionary design (IED) tool that generates shapes through the use of the Genetic Algorithm [17]. Figure 11 shows an example of evoShape output where one design has been selected by the user for further development. Future work will investigate how IED tools can best support consumer design.

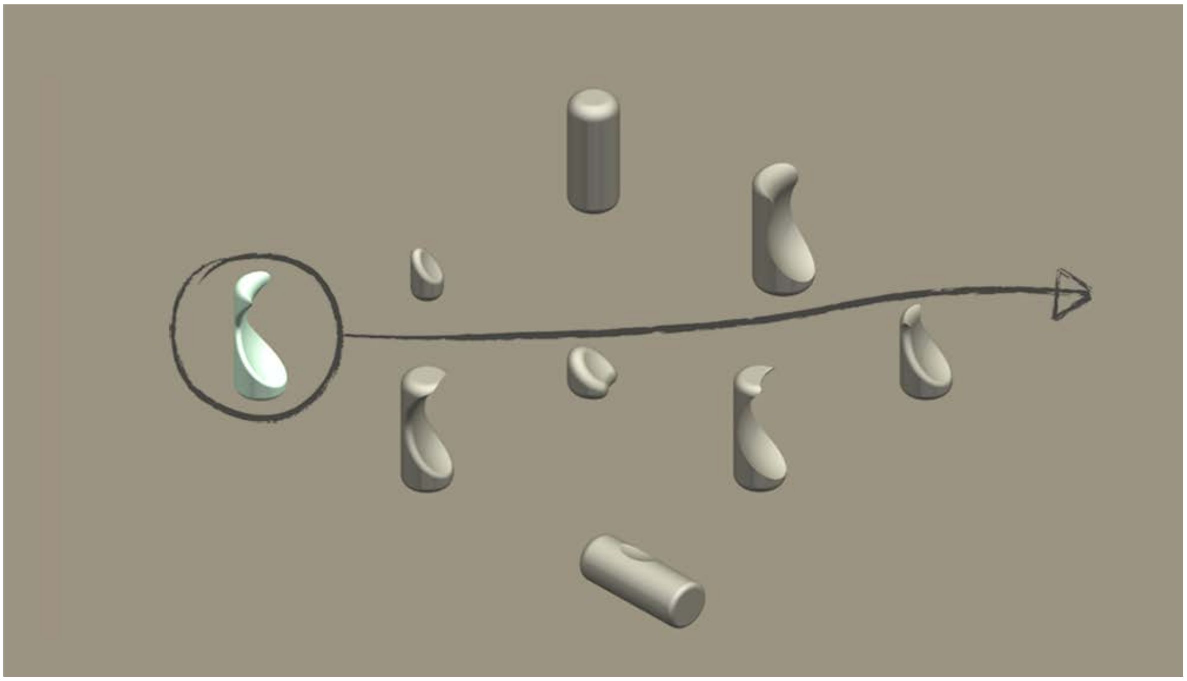

Figure 11: Automatically generated designs in the evoShape system

The research has also identified several AM systems and post-processing combinations that might be suitable for the manufacture of consumer products. In general, many of the AM parts evaluated were found lacking in some way by the consumers. However, laser sintering and polyjet technologies show good promise with participants in the trial scoring tumbled versions of these pens close to injection mould quality pens. It was encouraging to note that most of the participants believed they would keep a personalised pen design longer than a standard design. This could be a route towards improved sustainability and away from the "throw away" society. However, the range of prices that consumers said they would pay for the pens was not high enough to justify the use of high-end AM systems, at least for this product. This could possibly be remedied in future by the use of entry-level 3D printers. Although the quality of parts from these machines is improving, previous research has shown that they are not yet capable of consistently producing high quality parts [18]. Future research work will look at build strategies and finishing techniques that can be applied to entry-level 3D printers with a view to making them suitable for manufacturing of consumer designed products.

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