User Perspective on
AM-enabled Mass Customisation Toolkits

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Abstract

Mass Customisation (MC) toolkits are powerful user interfaces (UI) that enable customers to engage in the design of their own products. This research follows a design research methodology (DRM) (integrated with a design process) to research the user perspective on additive manufacturing (AM)-enabled MC toolkits. This research proposes and validates a design framework to guide designers and software developers in designing user-centred AM-enabled MC toolkits, using digital fabrication technologies such as AM. This framework includes pre-implementation assessment, and implementation stages.

An initial literature review revealed a lack of standard or universal norms for these UIs, and a lack of consistency in their design, in which web objects such as logo, product image, prices, etc. are not shared commonly among toolkits, nor occupy a frequent position. Furthermore, optimum degrees of freedom (DoF) for MC toolkits is lacking from current design knowledge.

This research focuses on AM-enabled MC toolkits as a means to enable customers to design. A first quantitative study was conducted to compare and rank a collection of features. More detailed user requirements regarding the content and layout of MC toolkits were revealed in a workshop. As a part of the second study, four different computer aided design (CAD) systems (software programs and 3D-enabling libraries) were used to create MC toolkits. This provided an understanding of the pros and cons of each system, and demonstrated Three.js to be the best system amongst each one in terms of feasibility and application. Based on previous findings, and as a part of the UX-design process, a prototype web-based MC toolkit was constructed, utilising the Three.js library. The prototype was used for a second study as a platform to investigate the user interaction and usability of the toolkit, to validate its design as well as provide insights for its improvement.

Findings and reflections from all the studies were then visualised and communicated in an interactive design framework. A final study, conducted with professional users (N=4) assessed the usability and technicality of the framework tool and led to a number of suggested improvements.

The main contributions to knowledge are: 1- a table was produced to compare the features of four different systems, by which Three.js was identified as the most suitable among them; 2- the most important and expected features for the content were obtained from the user rankings, the most frequent location of features for the layout was identified based on the users, and user insights were reflected based on the evaluation of the prototype; 3- the UI needs to be flexible in term of DoF, in other words, each customer (novice or professional) should be able to adjust the number of options presented; 4- a framework was proposed through reviewing and adapting existing guidelines and findings from this research.

Acknowledgements

List of Publications

Yavari, H.; Abdul Kudus, S.I. and Campbell R.I. (2015), 'User Involvement in Design: A Case Study of using an AM-enabled Mass Customisation and Personalisation (MC&P) Toolkit', proceedings of the 14th Rapid Design, Prototyping & Manufacturing Conference, 15-16 Dec 2015, Loughborough, UK.

Yavari, H. (2015), 'Creating better experiences with Mass Customisation Toolkits: optimizing the degree of freedom and web-based capability', Proceedings of the 11th Student Interaction Design Research conference, 27-28 March 2015, Kolding, Denmark.

Sinclair, Matt; Campbell, Ian and Yavari, Hesam (2014), 'Specification of an Additive Manufacturing Consumer Design Toolkit for Consumer Electronics Products', Proceedings of the 19th DMI International Design Management Research Conference, 2-4 September 2014, London.

Table of Contents

x

List of Figures

List of Tables

Nomenclature

2D	Two Dimensional
3D	Three Dimensional
AM	Additive Manufacturing
API	Application Programming Interface
CAD	Computer Aided Design
CSS	Cascading Style Sheets
DoF	Degree of Freedom
FDM	Fused Deposition Modelling
GUI	Graphical User Interface(s)
MC	Mass Customisation
NPD	New Product Development
NURBS	Non-uniform Rational B-splines
SC	Sales Configurator
SL	Stereo-lithography
SLS	Selective Laser Sintering
UI	User Interface(s)
UX	User Experience

Chapter 1 :   Introduction

Designing information systems indicates new challenges for website designers (Lazar 2001), when moving from traditional development of information systems including websites to more recent approaches (Lazar 2006). The web environment is a paradigm shift, from a web developer's perception and knowledge base (used for past software developments) to those of targeted users (Lazar 2001). In fact, users are more involved in designing and developing websites as the web grows and matures (Lazar 2006). If a website is frustrating to use, it is disappointing from the users' point of view, and is wasteful from the companies' perspective (Lazar 2006). This implies that if users are involved in website design and their views are considered, they will enjoy using the website. Lynch and Horton (2008) confirm the necessity of considering users' needs by stating that: 'If you listen only to management directives, keep the process sealed tightly within the development team, and dictate to supposed users what the team imagines is best for them, be prepared for failure'.

In the early era of craft production, products were made for individuals, one by one (Davis 1987). In this paradigm, products were mostly produced by a customer referring to an artisan and asking for a product that fits exactly to his/her needs. The next era after craft production, known as mass production, was accelerated in the United States of America in 1913 by Henry Ford through introducing the assembly line (Hu 2013). In contrast to the previous era, manufacturers attempted to satisfy as many customers as possible with a single product. It can be acknowledged that the role of customers in specifying/designing the features of their products was reduced tremendously from the craft production to the mass production era.

First coined by Davis (1987), mass customisation (MC) is a paradigm shift from mass production, which

> *aims to provide customer satisfaction with increasing variety and customization without a corresponding increase in cost and lead time. It emphasizes the economies of scope, rather than the old paradigm of mass production to mass produce standardized products through economies of scale.*

> *(Tseng et al. 1996)*

MC responds to an increasing demand for more individualised products (Berger & Piller 2003). It has been suggested that digital technologies and MC are introducing a return to the values of craft production (Sinclair 2012), in which customers had an enormous involvement.

With the increased ubiquity of the internet, MC toolkits have become the touch point through which brands implement MC (Piller & Tseng 2003). Brands primarily provide these toolkits, widely known as MC toolkits, to offer MC (Piller & Tseng 2003), which

provide product varieties to customers based on the company's production capabilities (Hermans 2012). The customers communicate their needs by interacting with available options to customise the product on the toolkit. To clarify this, the customers' intended product from the company is not the toolkit, but the product that is presented on the interface of the toolkits.

The term 'user experience design' (UX design) was described in ISO 9241-210 as 'all aspects of the user's experience when interacting with the product, service, environment or facility'. It focuses on the pleasure and value of the experience as well as on performance (usability) (Stewart 2015). This contrasts with 'user-centred design', which concentrates primarily on usability, and is instead concerned with aspects such as usefulness, desirability, credibility and accessibility (Stewart 2015). This research takes a UX design approach in order to develop guidelines that are both credible and accessible from the perspective of those who will be implementing them.

1.1 Scope of the Research

Product variety or available options in MC toolkits vary, and are affected by the companies' production capabilities. There are currently over 1000 MC toolkits available on the web, based on the Configurator Database website (cyLEDGE Media 2016). Reviewed in that database, few of them provide the freedom a designer has on computer aided design (CAD) software programs, such as SolidWorks or Rhino, for customers. In other words, most of them focus on modification of lower-level attributes such as colour and surface prints (Hermans 2012). To provide the required flexibility for customers, higher-level attributes such as shape, material shape or features, etc. also need to be included in MC toolkits (Hermans 2012). This automatically shifts the manufacturing technology required to digital fabrications such as additive manufacturing (AM). Furthermore, according to Pine's definition of MC (1993), nearly everyone's desire should be met by having enough variety and customisation.

Having high flexibility (close to the experience in CAD software programs), which fulfils customers' desires more truly (close to Pine's definition of MC), the specific toolkits which are investigated here are indicated as AM-enabled MC toolkits throughout this thesis. Only by including higher level attributes, which requires AM, can true MC can be experienced. The indication may not specifically intend to say that AM is the focus, but indirectly expresses the capability of modification of higher-level attributes such as shape and surface. If a toolkit offers a high freedom of modification regarding higher level attributes, then AM is more likely to be required. AM as an enabler of this flexibility will be discussed later in this thesis (AM-enabled MC toolkits).

1.3 Aim and Objectives

The primary aim of this research is to create best practice for designers such that the experience of customers using an AM-enabled MC toolkit is optimised. A literature review was conducted in the following three areas: new product Development (NPD), CAD and AM and MC and MC toolkits. This allowed four over-arching research objectives to be identified as listed below:

I. To review the literature and find the aspects which could be explored to develop the design framework

II. To explore the solution space of an AM-enabled MC toolkit through the UX design approach

III. To utilise and compare different CAD and 3D-enabling systems for implementing MC toolkits

IV. To develop a design framework for user-centred AM-enabled MC toolkits and validate it with designers and software developers

1.4 Thesis Structure

The report is organised as follows. Chapter 2, 3, and 4 present the literature review including NPD, CAD and AM, and MC and MC toolkits. Chapter 5 presents the research questions and methodology used for this research. Chapter 6 presents the first study, which was conducted to find out about user requirements, mainly the content of the toolkits. Chapter 7 presents the workshop, which was also conducted to find out more about the user requirements, the content and mainly the layout of the toolkits. Chapter 8 includes the second study, which deals with usability testing and evaluation of user interaction with a specific AM-enabled MC toolkit. Part of this chapter also includes the comparison between different CAD and 3D-enabling systems in order to find the right one for creating a toolkit for this study. Chapter 9 explains the detail of the content of the design framework, which includes pre-implementation and implementation stages. It also contains the third and last study which intends to validate and improve the framework. Finally, chapter 10 contains the conclusions and future work.

Figure 1-1 shows that the research started with the literature review. It led to the research studies based on the gaps found in the literature. Alongside the first study, the implementation of the UI as a high-fidelity prototype was started. The implementation was amended based on the result of the first study and workshop. Next, the second study was to find out more user insights regarding the developed toolkit. This study also verified the results from the first study and workshop. Next, the design framework was developed based on the result from all previous studies and workshops as a guideline for designers and software developers to create user-

centric AM-enabled MC toolkits. The third study was formed to validate the design framework by designers and software developers.

Literature review

NPD

Chapter 2

CAD & AM

Chapter 3

MC & MC toolkits

Chapter 4

to understand the area of Mass Customisation, and identify gaps in prior knowledge

User Requirement Studies

Main Study 1
User Requirements

Chapter 6

Workshop
User Requirements

Chapter 7

to present user requirements regarding the content and layout of MC toolkits

Implementation

Toolkit Design α

Chapter 8

Toolkit Design β

Chapter 8

to create a ptotoytpe to be used to explore user's needs and desires furtherly

User Experince Study

Main Study 2
Usability Testing

Chapter 8

to present user insights obtained through evaluation of user interaction of the prototype

Final Design

Framework
Design

Chapter 9

to present the proposed framewrok, generated by existing guidelines and findings from the studies

Validation

Main Study 3
Framework
Validation

Chapter 9

to discuss the pros and cons of the framework through findings from this validating study

Figure 1-1 Phases of research and thesis structure

5

Chapter 2 :   New Product Development

2.1 Introduction

In this chapter, the design processes for products in general and UI design processes are explained. It emphasises the need for consideration of users in the centre of the design and development process of MC toolkits because of the key role they play in the design process; and introduces and defines the UX design approach.

The chapter objectives include:

1. Explaining general and modern new product design processes

2. Defining general and user-centred design processes for UI

3. Specifying required steps for exploring user involvement

2.2 Industrial Design

Design does not have a single agreed definition. Jobs (1993) suggested that if 'you' want to design an object, 'you' should not think about the design of the object, but the result of it. 'You' need to understand what it is all about (cited in Purgathofer & Baumann 2010). Terence Conran (1995) stated: '…design is 98% common sense, 2% the mystical ingredient that you might call creativity. But it's the thing that makes a perfectly decent object into something really desirable that people want as much as they might want a Picasso on the wall' (Bruce & Bessant 2002). While these are some different practical definitions of design, in a more academic sense and recognisable in the world of design, industrial design can be defined as:

> *The professional service of creating and developing concepts and specifications that optimize the function, value, and appearance of products and systems for the mutual benefit of both user and manufacturer.*

> *(IDSA 2010)*

Although, this definition contains the user and manufacturer both, users were solely considered in the research. This does not mean that manufacturers were completely ignored for the framework design, but the data from other resources other than this research were included in the framework. Furthermore, the design process involves both aesthetics and functionality, which both were considered for this research.

In order to design a product, professionals should follow a NPD. NPD can be defined as: 'The sequence of steps or activities that an enterprise employs to conceive, design and commercialize a product' (Ulrich & Eppinger 2011: p.210).

The linear product development process suggested by Ulrich and Eppinger (2011) has been depicted in Figure 2-1.
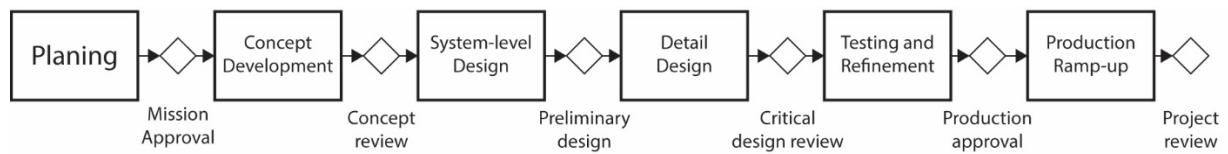
Figure 2-1 Simple NPD process (Ulrich & Eppinger 2011: p.22)

2.3 User-Centred Design

A more modern product or service design process has been introduced by the Design Council, which is referred to as Double Diamond (Design Council 2015) as shown in Figure 2-2. In this method, first, the space for lots of different ideas to be discovered and shared later is expanded. Then, by focusing on user-needs, the process assists in identifying and defining priority areas to address. Next, multiple prototype solutions based on the recognised opportunity areas are developed by designers. Finally, it is concentrates on distinct objectives and manufacturing or other constraints to deliver a final solution (Design Council 2015).
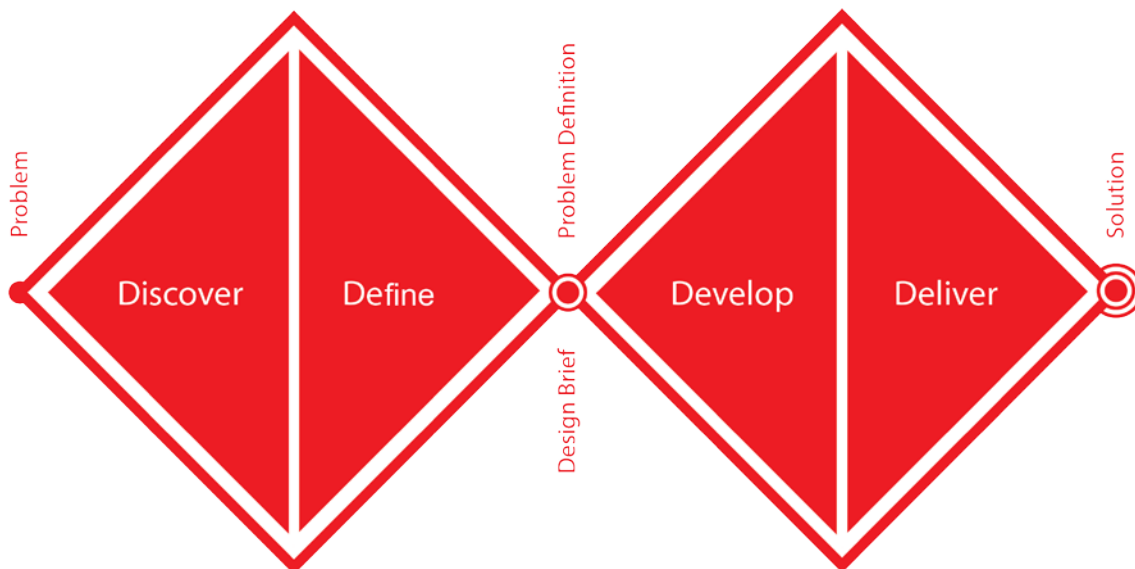
Figure 2-2 Double Diamond (Design Council 2015)

In contrast to the previous design process, this modern process involves users throughout the process to a higher extent. Although, the Design Council has not particularly specified this process as a user-centred design process, users should be involved in each stage to pursue a UX design approach. The sequential studies designed to answer the research questions in this study, or more specifically to obtain user perspective on the toolkits, follow a user-centred design approach. This provides the author with a solution as the result of the design process, which was the user-centred AM-enabled MC toolkit, but it is the design framework at the final stage

that is the outcome of this research. In other words, a user-centred design process was not used for this research, but a DRM as discussed in Chapter 5.

2.4 Development Cycle for User Interface

This section explains and compares the design of UI using traditional, generic design processes versus a specific, a user experience process.

2.4.1 Generic process

The concentration is on the development cycle of UI. It contains a series of stages that together form the classic 'design cycle'. Since the UI of MC toolkits only includes one page of a whole website of a company, then these steps were simplified accordingly. The simplified steps are as follows (Lynch & Horton 2008):

1. Requirements: the users themselves are the most productive source for requirements. This involves formal market and user research, a focus group of current or prospective users, and formal usability testing. In smaller projects, it is usually done by having a form of team meetings with users, project stockholders, and project sponsors, to come up with a list of requirements.

2. Design: the requirements are transformed into concrete form, first as rough layouts and then as page wireframes, navigation interfaces, and site diagrams. Detailed graphics need to be saved for later stages, and the concentration is on the fundamental structure and functionality of the website.

3. Development: The actual webpages are created through coding of any associated web applications, such as HTML, JavaScript, CSS, etc. The detailed graphics (detail coding) of the website also need to be taken later until all major issues of design are settled. HTML is the standard markup language for creating web pages. CSS works as the style on the HTML webpage to decorate and add visualisation. JavaScript counts as the interaction tool with the HTML webpage such as interacting with buttons, boxes, etc.

4. Testing: functional testing, browser compatibility issues, link checks, cross-platform issues and editorial quality testing are all done last.
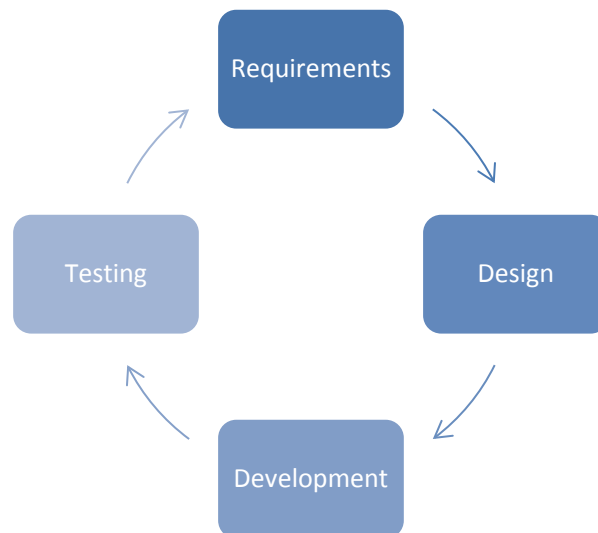
Figure 2-3 The development cycle for user interfaces (Lynch & Horton 2008)

Prototyping, which is an essential part, is required at the development stage. In this context, a prototype is a set of rough-sketched webpages to simulate a functional application, which users interact with to test it (Lynch & Horton 2008). Prototyping is useful for two reasons; first, it is the best way to extract user behaviour such as website navigation, at the early stages of development and design. In other words, with a prototype, an environment is created for walking a user thorough a task to identify problems, difficulties, and points of confusion. Second, a prototype allows graphic designers to check the flexibility between the website's look and navigation (Lynch & Horton 2008).

2.4.2 User experience approach

As previously mentioned, the term 'user experience' (UX) was described in ISO 9241-210 as 'all aspects of the user's experience when interacting with the product, service, environment or facility'(Stewart 2015). It focuses on the pleasure and value as well as on performance (usability). The UX is concerned with aspects, such as: usefulness, desirability, credibility, and acceptability (Lazar 2006). By considering UX for this research, AM-enabled MC toolkits were examined based on its users. According to Garrett (2002), the 5 plane-strategy, scope, structure, skeleton, and surface provide the framework (Figure 2-4) for dealing with UX problems, and the tools to be used to solve them. The basis of each UI is comprised of those different layers and elements that need to be decided on. This does not describe a development process; it seeks to define the key considerations that go into the development of UX on the web today (Garrett 2002).
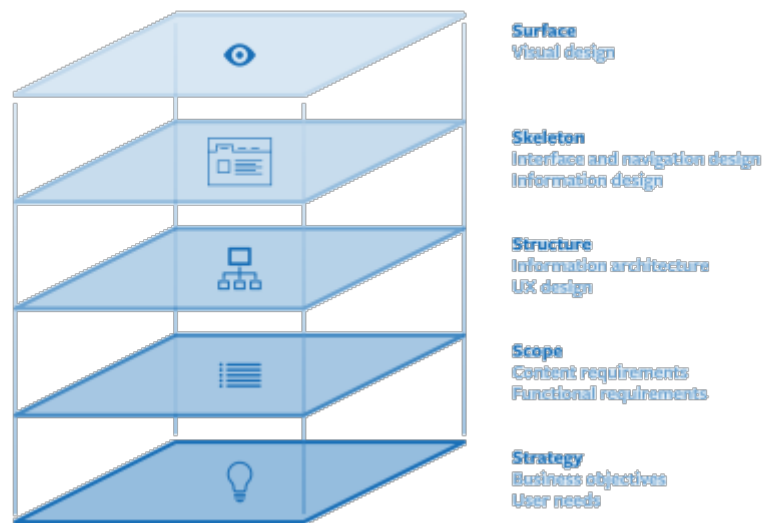
Figure 2-4 Elements of the user interface and user experience (Garrett 2002)

The strategy determines what users want to get out of the site by using it (the strategy of the site). The scope of the website defines the features and functions of the site. The structure layer represents the user interaction design of the website. The skeleton deals with optimizing the arrangement of these elements for maximum effectiveness and efficiency, representing UI design. Finally, the surface plane is about illumination, and visualisation of the website elements, representing visual design (Garrett 2002).

The strategy, although very important, is being covered by adjacent research at the Design School at Loughborough University (henceforth the Design School). Issues related to the surface plane are also beyond the scope of this research. The concentration of this thesis is on the scope, the structure, and the skeleton of the UI. These three areas were merged into two main aspects of: user requirements for the content, and user requirements for the layout, other than doing them separately, which required a huge amount of time, due to the iterative nature of the design process. This framework also indicates that the structure and the skeleton of a UI come after the scope, which is the same as the order of the studies performed in this research.

2.5 User Involvement in Design

As the implication of user involvement for the AM-enabled MC toolkit was the main investigation of this research, it was explored in more detail. The design of a product is sometimes not done solely by the designer, but also by customers who take on roles in different steps of NPD (Hermans 2011). The product, in this case, is a graphical UI (GUI). GUI allows human interaction with what is inside computer. In

other words, the GUI is the graphical representation of what the underlying program contains, and is the 'frontier' of the computer.

The GUI should involve user-centred design, not system-centred design. It should be designed to match the skills, experience and expectations of its anticipated users. Therefore, measuring customers' attitude toward platforms outweighs measuring the platform's performance in this research. However, the adaptation requires more time and contains complexity for system developers, both the GUI designer, and the GUI programmer. Therefore, as explained previously in Chapter 1, users need to be involved through the development cycle of the UI. User involvement is especially helpful in two major stages of development: requirements gathering and usability testing (Lazar 2006).

2.6 User Requirements

One of the minimum levels of user involvement in website design is to gather user requirements. There are varieties of requirements a design team may consider that help in designing the webpage. The user requirements, as an example, may include the following questions (Lazar 2006):

'What are the technological characteristics of the users?'

'What content and information are they interested in?'

'What features would encourage them to revisit your websites and what elements would keep them away?'

After determining what kind of information needs to be gathered, collecting them is the next step. A number of different techniques are available to gather the requirements, including surveys, focus group, interviews, etc. (Lazar 2001).

2.7 Usability Testing

The most important characteristic of GUI is usability, but because it is not achievable through routine methods, it is difficult to be defined in a framework for designers to deal with. Another term that is used for an easy and pleasant GUI is 'user-friendly', but again it is not easily defined, and it is a difficult design object to reach. Usability is used as the design objective for GUI in this thesis, because its meaning is clearer and it is a more appropriate concept (Redmond-Pyle & Moore 1995).

Usability aims to adapt the system to the user, rather than the user to the system, to provide convenient interaction, leading to user effectiveness and productivity (Redmond-Pyle & Moore 1995). Usability is defined in Part II of the ISO 9241 standard (BSI 1998) as 'the extent to which a product can be used by specified users to achieve specified goals with effectiveness, efficiency, and satisfaction in a specified context of use'.

Usability has four main aspects (Shackel 1990):

- Effectiveness: how effectively can the tasks be done using the interface for a specified range of tasks? Alternatively, how fast can the user perform the tasks (referred to as productivity)?

- Learnability: how long does it take the users to be effective with the system? How much practice do users need before becoming effective with the interface?

- Flexibility: how easily can the users perform their task if the environment of task has changed?

- Attitude: do users experience tiredness and frustration when using the system, or is it rewarding to use, and do they feel satisfied with the system?

According to Redmond-Pyle & Moore (1995), two common approaches to measure usability are as follows:

- Performance tests, where users use the system and perform a task, and they are tested in terms of speed and accuracy.

- Attitude surveys, where user satisfaction and perception are measured through an interview or questionnaire.

The usability aspects, which were considered for assessment of this toolkit are effectiveness and attitude. Learnability requires testing the user during a period of time, and flexibility demands changing the environment, both of which are out of the scope of this thesis, due to time limitation. The two common approaches mentioned above were considered for this research to assess the two aspects of usability; effectiveness and Attitude.

2.8 Summary

In this chapter, two practical and academic definitions of design were given and both general and modern NPD processes were explained (objective 1). The generic cycle of UI design was defined. This cycle, from the user centric point of view, was then presented as the development cycle of UI by Garrett (2002) (objective 2). As a requirement for the second study, the toolkit would be created with the similar approach as the development cycle for UI by Garrett. Three stages of that framework by Garrett were merged into two main areas of content and layout of toolkits (the selection of a UX design approach development cycle will be later justified using design research methodology (DRM) as the methodology of this research.

Two minimum stages of user involvement were explained and considered (objective 3): user requirement and usability testing. User requirements were gathered to understand the user needs that, when addressed, will lead to a successful product,

and attitude testing was considered to assess the usability of the toolkit. It was also explained why other aspects of usability were not considered.

AM is one of the key enabling factors of involving customers in the design and development of a product, and is essential for developing parametric MC toolkits. The manufacturing of the outcome of the MC toolkits has become easier with AM due to there being no need for tooling, cost effectiveness and flexibility. In order for user involvement and implementation of AM-enabled MC toolkits respectively, both CAD software/3D-enabling systems and AM act as enabler technologies. The next chapter deals with this topic.

Chapter 3 : Computer Aided Design and Additive Manufacturing

3.1 Introduction

The focus of this thesis is AM-enabled MC toolkits where design of the shape, size, and form of the products must be available in the toolkits. This capability can be provided through different existing methods such as CAD software programs, 3D-enabling libraries, etc. Investigation of the user perspective on AM-enabled MC toolkits can be achieved through acquiring the user requirements and usability evaluation, as indicated in the previous chapter (Chapter 2). In order to perform the latter and test the understanding of the user needs, a working prototype is required. This chapter covers the potential platforms for AM-enabled MC toolkits, which were later tested to find the best solution among them to create the working prototype. Furthermore, due to the selection of AM for the production of MC toolkit outcomes, the main principles of this technology are also covered. Therefore, this chapter deals with the potential platforms for implementation of AM-enabled MC toolkits, and also AM technology.

The chapter objectives are to:

1- give a brief history of CAD

2- explain 3D modelling in general and consumer-oriented 3D modelling as a requirement for MC toolkits

3- explain parametric modelling algorithms in CAD software programs

4- explore CAD software programs' application programming interface (API) as offline tools for AM-enabled MC toolkits

5- explore 3D-enabling libraries as web-based tools for AM-enabled MC toolkits

6- explain the use of AM technology for AM-enabled MC toolkits

3.2 CAD History

In 1957, CAD was developed as today's definition (Sanders 2008, CADAZZ 2004), and can be defined as the:

> use of computers in industrial-design work, computer-aided design (CAD), with their use in manufacturing operations, computer-aided manufacturing (CAM). This integrated process is commonly called CAD/CAM. CAD systems generally consist of a computer with one or more terminals featuring video monitors and interactive graphics-input devices; they can be used to design such things as machine[s]…

(Britannica 2014)

14

Pronto was the first commercial Numerical Control (NC) programming system, which was created by Dr Patrick J. Hanratty, so most often referred to as 'the father of CAD/CAM'. After that, Ivan Sutherland created Sketchpad. This application uses a smart pen to create its drawing and sketches on a monitor, so it was unique in its era. The first application of CAD software was 2D and due to the high cost of the production and design process, it was only used by car and aircraft production companies. In 1970, manufacturers in conjunction with universities started to develop CAD further (Sanders 2008, CADAZZ 2004). Many automotive companies as in 1960, started to use CAD software programs. The first 3D solid modelling program was introduced in 1972 by Magi (Mathematics Application Group Inc.). It was called Synthavision. Many other new CAD software programs were also introduced and released in this period. In 1980, 3D rendering emerged from new generation UNIX workstations and it shifted the CAD software market to 3D and solid modelling further. By 1990, most licenses were sold to users for 3D CAD software until that time, and it was more than any time before that. It was 1993 when a small company with not a tremendous budget began to do business in the CAD software area. In 2000, companies began to focus on web-based CAD software, which enabled users to do the work without installation. Examples include Clara.io and Tinkercad. In the 2000s, there was less energy to move the industry forward than in the 70s and 80s (Sanders 2008, CADAZZ 2004).

MC toolkits can be designed through different software programs or 3D-enabling libraries, e.g. Flash (Adobe Flash), Java (Oracle Java), SolidWorks API (Dassault System SolidWorks), Grasshopper (McNeel), Three.js (mrdoob), etc. In section 3.5 it is specifically explained why CAD and 3D-enabling libraries have been researched for implementation of MC toolkits.

3.3 3D Modelling

There are several approaches that are available for the display of 3D information in 3D digital scenes. Two standard methods of producing images of 3D solid objects are ray tracing and polygon scan conversion. The great advantage of ray tracing is that it can produce realistic looking images. This technique allows implementation of a wide variety of lightening effects. However, its drawback is that the range of primitive shapes is limited by the ability of the programmer to write an algorithm to intersect a ray with the shape. It is considered by many to be the natural or obvious way to render 3D objects (Dodgson 2012).

One or more rays from the eye point are fired through each pixel to figure out its colour and illumination. This process happens repeatedly in the intersection point until determining its exact illumination (and hence colour). Reflection, refraction, and shadowing are also handled with ease with these secondary rays. The biggest disadvantage of ray tracing is that it is slow. However, the result is of high quality in comparison to polygon scan conversion (Dodgson 2012).

Polygon scan conversion encompasses a range of algorithms where polygons are rendered, one at a time, into a frame buffer. The great advantage of polygon scan conversion is that it is fast. Its algorithms are essential in places where interactivity is important, such as computer games, flight simulators, and other applications. In order to give a human the illusion that they are interacting with a 3D model in real time, they need to be presented with animation running at 10 frames per second or faster for passive viewing on a monitor, TV, or movie screen. The basic algorithms in polygon scan conversion support only simplistic lighting models, so images do not necessarily look realistic. Furthermore, it only has a single primitive, which causes everything to be made up of flat surfaces. Polygon scan conversion is used in almost all applications of computer graphics (Dodgson 2012).

In order to do polygon scan conversion, it is necessary to know how to handle polygon meshes. For each polygon mesh, its vertices and normal should be identified. The direction of the normal tells which side is the front of the polygon and which is the back. Most hardware implementations use only triangle drawing, and polygons with more vertices are simply split into triangles; therefore, this is not a serious drawback (Dodgson 2012).

While polygons are good for rendering, a better way of generating curved surfaces is needed. A designer typically needs to manipulate, directly, the millions of polygons that comprise the rendered model. A general way to specify arbitrary curved surfaces is needed, which can then be converted to polygons for rendering. Ideally, a mechanism is needed, which allows any smooth curved surface desired, to be specified. The problem of designing smooth aeroplanes and cars was first faced in 1960s. There are two solutions regarding this issue: non-uniform rational B-splines (NURBS) and subdivision. The CAD industry uses NURBS surfaces as its standard definition mechanism. The visual effects industry uses both NURBS surfaces and subdivision surfaces (Dodgson 2012).

3.3.1 Topologies and surface representation

Topology is a term that is used by mathematicians and in many branches of science. Topology is sometimes referred to as 'the mathematics of continuity'. In a view, more related to this research, it is 'the study of those properties of geometric forms that remain invariant under certain transformations, such as bending or stretching' (Wayne University 2000). In topology, any continuous change is allowable as long as it can be continuously undone. For example, a circle has the same topology as a triangle or a square since the outline can be pulled to three sides to make a triangle and then pulled again to 4 sides to make a square (Wayne University 2000).

From the early applications of CAD in industry, there was no standardised representation for freeform curves and surfaces, which made it difficult to transfer designs between different systems. NURBS were therefore created to bring a wide range of freeform surfaces together in a standard representation (University of

Cambridge 2010, Rogers 2001). An example of a NURBS with its control points is shown in the Figure 3-1.

Another type of surface representation is a polygon. Polygons are straight-sided shapes defined by three-dimensional points (vertices) and straight lines that connect them (edges) (Botsch et al. 2007, Meade & Arima 2004). An example of a polygon model with its vertices is shown in Figure 3-1 below. While trimming a NURBS will keep the original surface data, in polygon modelling, the polygon is adjusted with more surfaces after trimming and does not keep the original surface data.
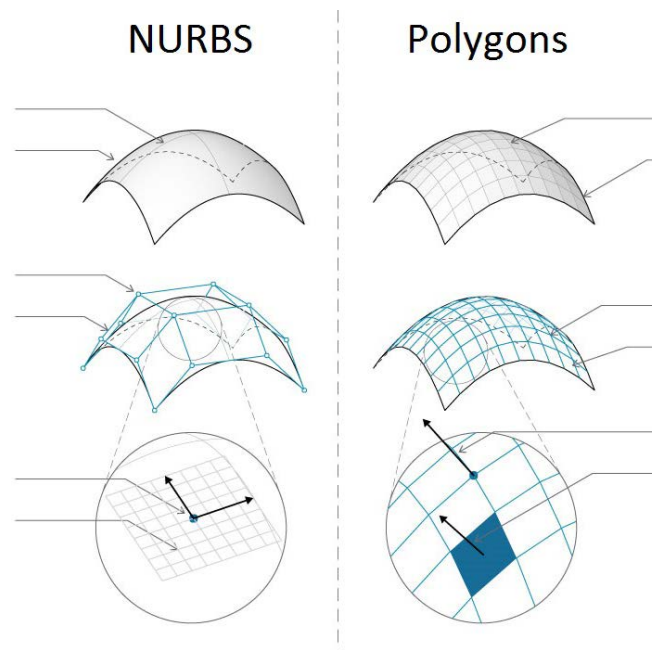
Figure 3-1 A NURBS with its control points vs Polygons with its vertices (Dynamo 2015)

3.3.2 Surface vs solid modelling

A surface modeler creates an object boundary with geometrical descriptions, focused on external aspects of an object. However, a solid modeler creates a 3D solid object with mathematical principles in a more detailed and thorough way (Sederberg & Parry 1986, Indovance 2016). In other words, solid modelling represents a solid object as if it is a 'watertight' model. Surface modelling on the other hand, emphasises the external aspects of the object, and if it were cut, it would be seen to be hollow. Going back to revise models that have been created with surface modelling is not easy, since they are not parametric. However, in solid models, the commands used to create the design are available so it is easy to make changes to the parametric model (Choi 1991, Indovance 2016).

3.4 Consumer-Oriented CAD

The design practice needs to be transferred into a level that helps consumers to contribute to the design process directly. This relates to consumer design and co-design. Consumer design refers to the products whose conception, specification, design, or manufacture may occur with direct consumer input (Sinclair & Campbell 2014). Co-design is also about the designers' and consumers' work in collaboration with each other in the design process of the product. The degree of involvement, however, is not exactly the same. Sinclair (2012) identified that consumers in the consumer-design process have more direct deliberate influence over the form of the product than in co-design. Ariadi (2012) similarly introduces a new topic, which is focused on Computer Aided Consumer Design (CACODE) to develop a design interface for consumers to interact with, in a clever, easy and direct way. It means not only are they free to change the product shape, but also, they can deliberately and intelligently do it by themselves without designer correction or refinement. Therefore, for customers to interact in the process of production, CAD needs to be consumer-oriented.

3.5 Parametric Modelling Algorithm

As explained in the previous section, CAD software programs should be consumer oriented to enable customers easily use the system, which justifies the use of automatic capabilities, such as parametric modelling algorithms. CAD software programs can be used as tools to produce geometrical objects with the help of parameters, which are dimensions and constraints. In this case, parameters allow the size of the model to be defined, which can be manipulated by users to generate an object, or in other words, parametric modelling. If there is a representation (a parameter) for each dimension, and the parameters are put together into formulas, then it creates a bigger image, which represents an algorithm. An algorithm allows to a product to be generated repeatedly just by running its code. Therefore, an algorithm allows the system to generate different versions of a product continuously by entering different parameters as inputs. As it is obvious, each algorithm has input(s) and therefore processes the input data and then generates output(s), which is a combination of forms, in this case. The specific steps used in order to generate a model by defined parameters through using an algorithm are called parametric modelling algorithms.

An example of parametric modelling in Grasshopper, which is a graphical algorithm editor (Grasshopper 2014), is shown in Figure 3-1. In this example, it is obvious that by changing three groups of parameters; height of pyramids (1), number of segments in x and y directions (2), and inclination of pyramids (3) in design tree, the final product is modifiable. This object is modelled following an example in the book *Parametric Architecture with Grasshopper* (Tedeschi 2011).

For an AM-enabled MC toolkit in which a representation of a physical product is customised parametrically, this pre-supposes the use of CAD programs or 3D-enabling libraries. Also, CAD software programs and 3D-enabling libraries have been considered for this research due to the choice of topic: Production by AM, and because they allow freedom to create or change the shape of the 3D model.

First, production by AM (Hippel 2001) will be discussed. While creating a product on an interface, it would be better to input the outcome easily to a 3D printer after the customisation process, and take advantage of a very large solution space (Hippel 2001). However, although very common among MC toolkits, providing an online interface to access the toolkit easily anywhere for online purchasing is obstructive. Rhino (McNeel Rhinoceros) and SolidWorks (*Dassault Systems SolidWorks),* although powerful, are not very appropriate since they are not cloud or web-based. This is where 3D-enabling libraries pave the way to create an online MC toolkit.

Second, there is more freedom regarding creating and changing the shape of a 3D model to fulfil heterogeneous needs of customers; one of the downsides of most current MC toolkits is the lack of shape modification. The current customisations are either mostly cosmetic or apparent (such as adding text and colour selection). CAD enables radical changes to base products due to the tools and features available in its graphical interface. This is also true about 3D-enabling libraries.
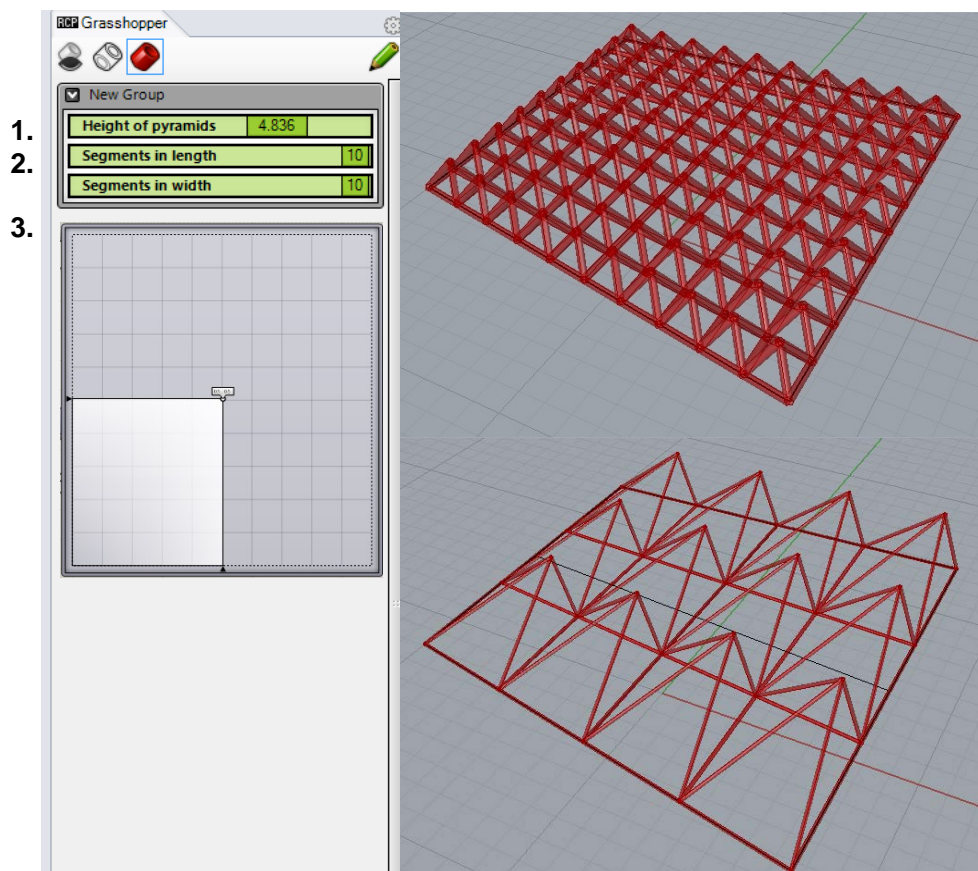
Figure 3-2 A demonstration of parametric modelling in Grasshopper

As mentioned before, the 3D model of objects is intended to be modifiable with AM-enabled MC toolkits. This necessitates the use of CAD software programs or 3D-enabling libraries through parametric modelling algorithms available with them.

3.5.1 Offline software programs (CAD Programs)

To take advantage of parametric algorithm in CAD software programs, programmers have access to pre-defined common functions, known as a library. In other words, in order to develop an application, a library as a collection of resources can be used for programming by software developers (Simsek 2004). API is a set of symbols and commands exported and available from a software with which users can write custom programs. In programming, libraries are sources or references in order to use specific commands, syntax, etc. The design of applications is highly affected by the design of the APIs; therefore, they are the most critical part of the design of libraries (Blanchette 2008). In simple words, repetitive modelling tasks can be programmed by users through using APIs. This allows them to use the library without the need to rewrite them. API contains hundreds of functions that can be called from different programming languages, such as visual basic, or C++ to get direct access to CAD software functionality such as creating a line, inserting an existing part into a part document, or verifying the parameters of a surface (SolidWorks 2015).

There are two types of APIs that were selected and discussed here; SolidWorks API, and Rhino visual programming (known as Grasshopper). SolidWorks API was chosen since it is one of the most powerful CAD software programs, so its API should also be. Furthermore, the author was familiar with the software and its API programming language. The selection of Grasshopper was due to using graphical API, for which it is not primarily known as though. In other words, in this API, blocks can be connected to each other graphically to create a parametric algorithm.

3.5.1.1 SolidWorks API

SolidWorks API (Dassault Systems SolidWorks) allows for parametric modelling, which can be used for customisation of products. SolidWorks API takes advantage of using Visual Basic for Application, which allows connection between different software programs that use the same programming language, such as Office Word (Microsoft Office Word) and Office Excel (Microsoft Office Excel). Another advantage of SolidWorks API is its 'userform'. Userform can be used to generate a GUI for customers to generate their product based on their parameter(s); otherwise, the algorithm creates the same object repeatedly without taking any input. Therefore, the userform allows for getting input(s) from the customer and providing the output(s), which is its geometry. An example of parametric modelling in SolidWorks API is shown in Figure 3-2, in which the userfrom is shown on the left, and the model, is shown on the right.

The downsides of using SolidWorks API are the inability to update the model after first input(s) (real-time update) (without the need for heavy programming), and difficulty of coding for radical shape modifications. For example, for the top face of a keyboard's keys, if a curved surface is desired, it is very hard to program that in the SolidWorks API. However, simple modifications such as chamfers or fillets are easily implementable in comparison to Grasshopper.

SolidWorks is capable of doing simulation based on the finite element analysis (FEA) method. SolidWorks simulation helps to optimise the designs by predicting their responses to various working conditions that the user defines. Using its API, it is possible to perform a range of analyses, and process the results (SolidWorks 2015).
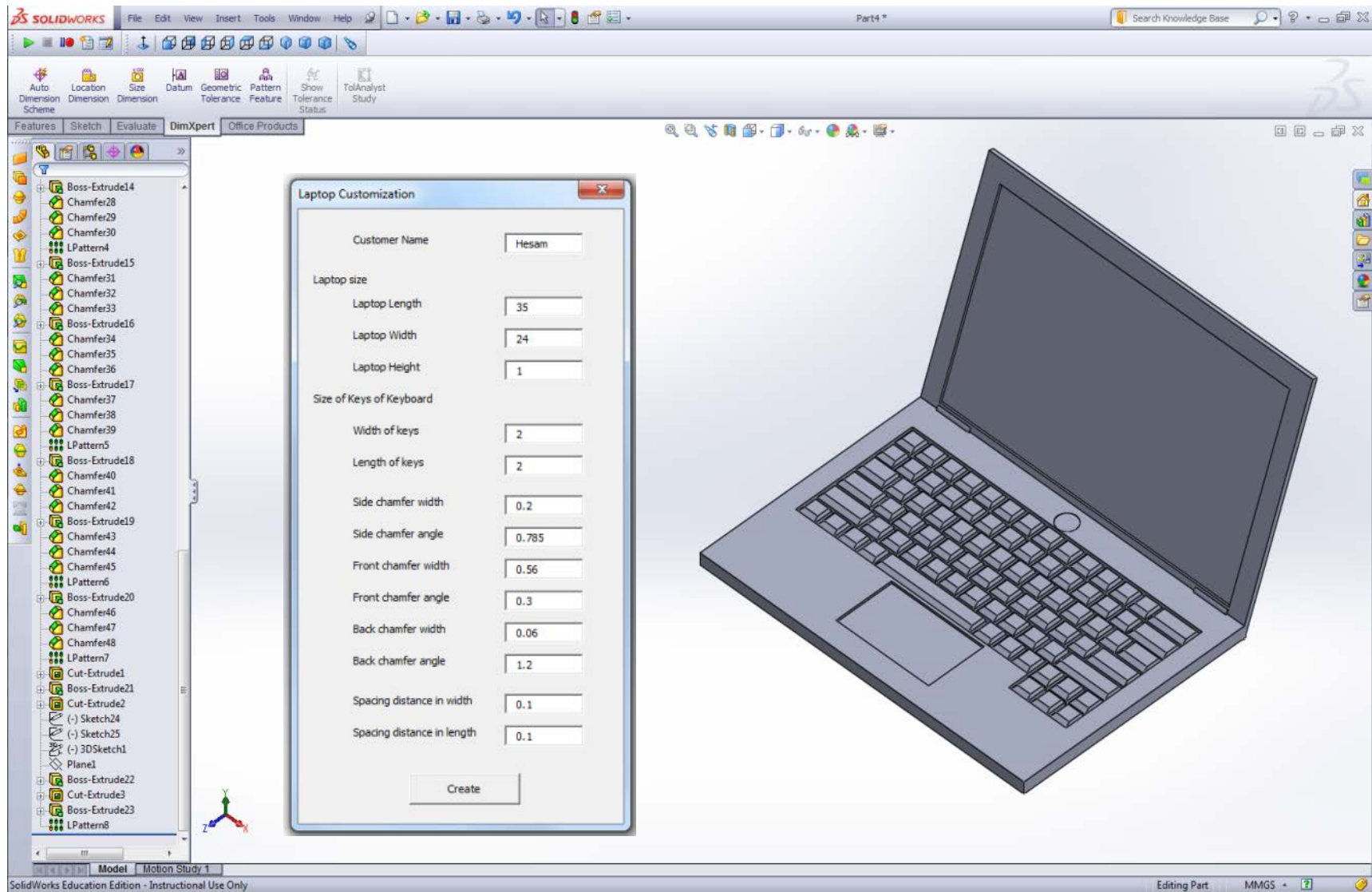
Figure 3-3 A parametric modelling in SolidWorks API for Mass Customisation

3.5.1.2 Grasshopper

Grasshopper is an interface whose characteristic to automate the process of product creation can be readily extended to MC toolkit application. Its website introduces it as: 'a graphical algorithm editor tightly integrated with Rhino's 3D modelling tools' (Grasshopper 2014). It makes the scripting easy by visualizing the algorithm through using components, therefore it can be perceived as a graphical API, although not specifically known for this though. It allows for parameters in the form of sliders, menus, etc., so it facilitates parametric modelling for customers. In Grasshopper, with the use of modules and connections, an algorithm can be created to result in an output which is a 3D model. This automates the process of creating the model, which is intended in this research to result in an output. Although Grasshopper does not have the userform, it takes advantage of a similar component, the 'control panel'. With the aid of this, the user concentrates on the design task, and also is not interfered with Grasshopper window any more. An example of this interface is shown below:
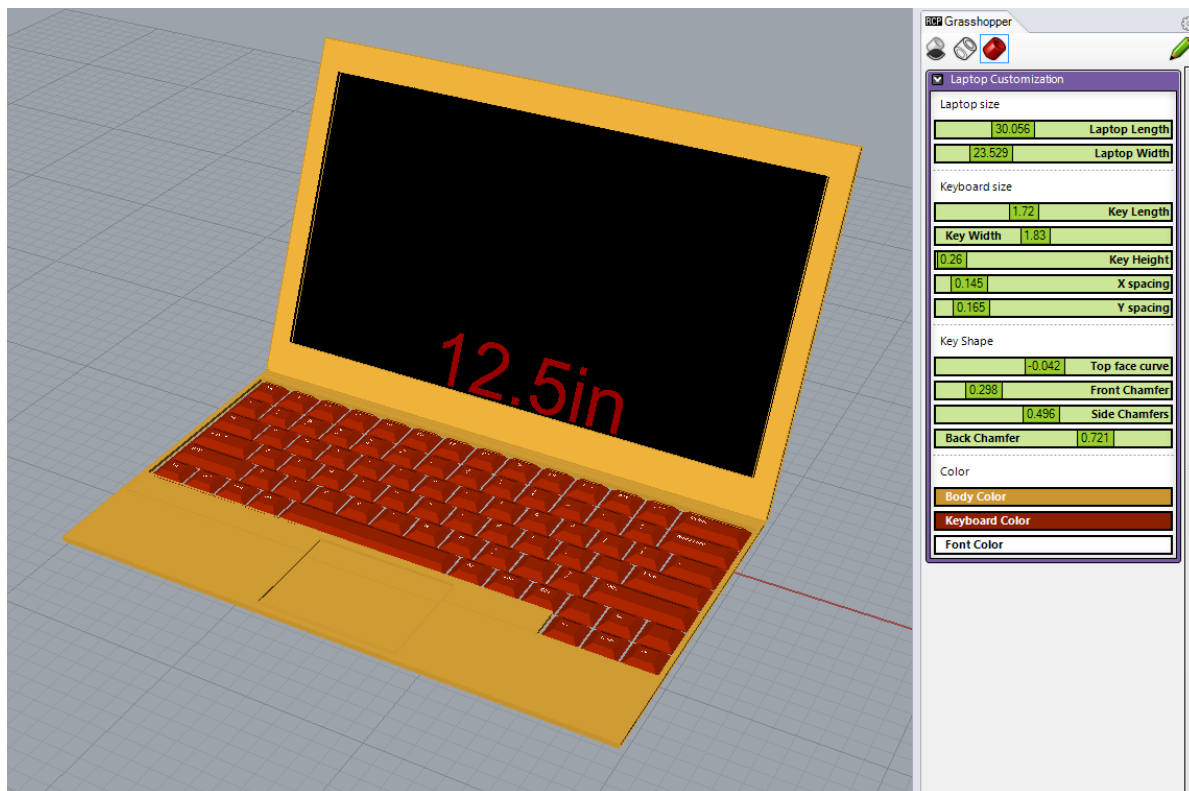
Figure 3-4 An example of Grasshopper interface, specifically to show control panel (on the right)

A simple example to describe how Grasshopper works is now described. In order to create a line, two points are needed; therefore, two 'point' elements are added to the screen (figure 3-4). These points need an actual representation in the Rhino model. Therefore, two points need to be created in Rhino and linked to the point elements (figure 3-5). Next, these two points can form a line by connecting them to a 'line' element (figure3-6). This results in an actual line being drawn in the Rhino model

23

(figure 3-7). Now, if the line element is connected to a pipe element, then the output is a cylinder. The pipe element not only accepts input from the line element, but also inputs such as a radius (figure 3-8). By using a slider element and connecting it to the pipe element, the pipe radius can be manipulated through the user (figure 3-9). This process shows how changing the dimensions in a Rhino model can be done easily by using Grasshopper elements.
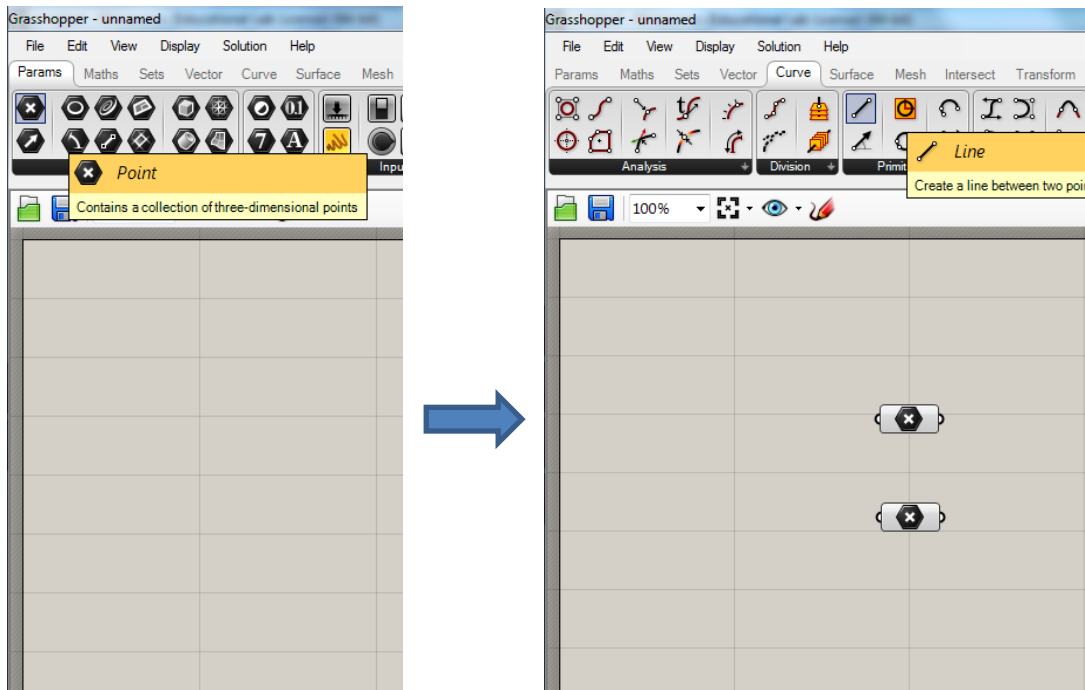
Figure 3-5 Inserting two point components into the grasshopper screen
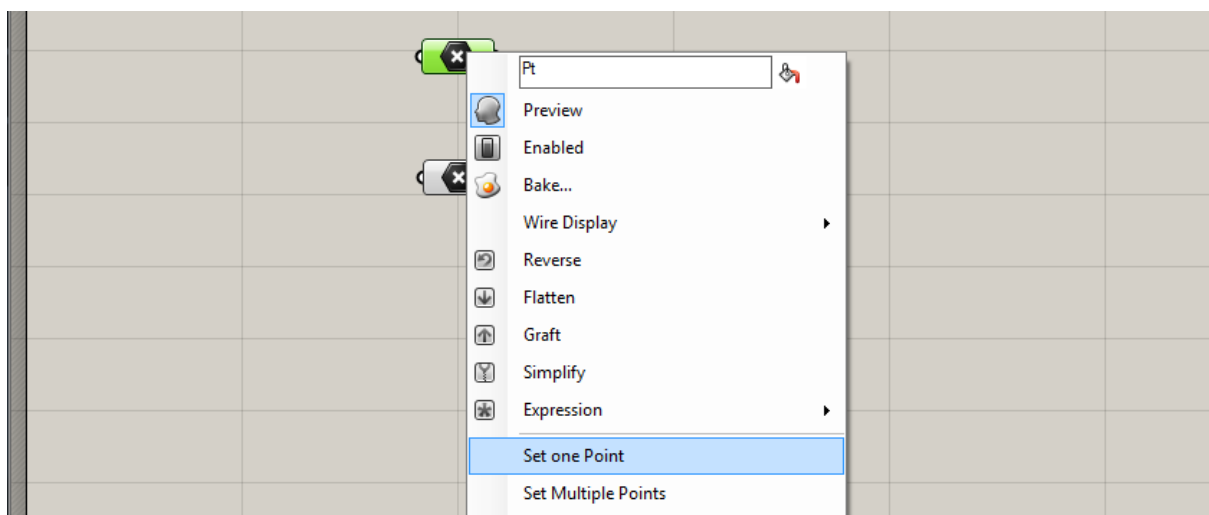
Figure 3-6 Connecting each point element on Grasshopper to an actual point in the Rhino model
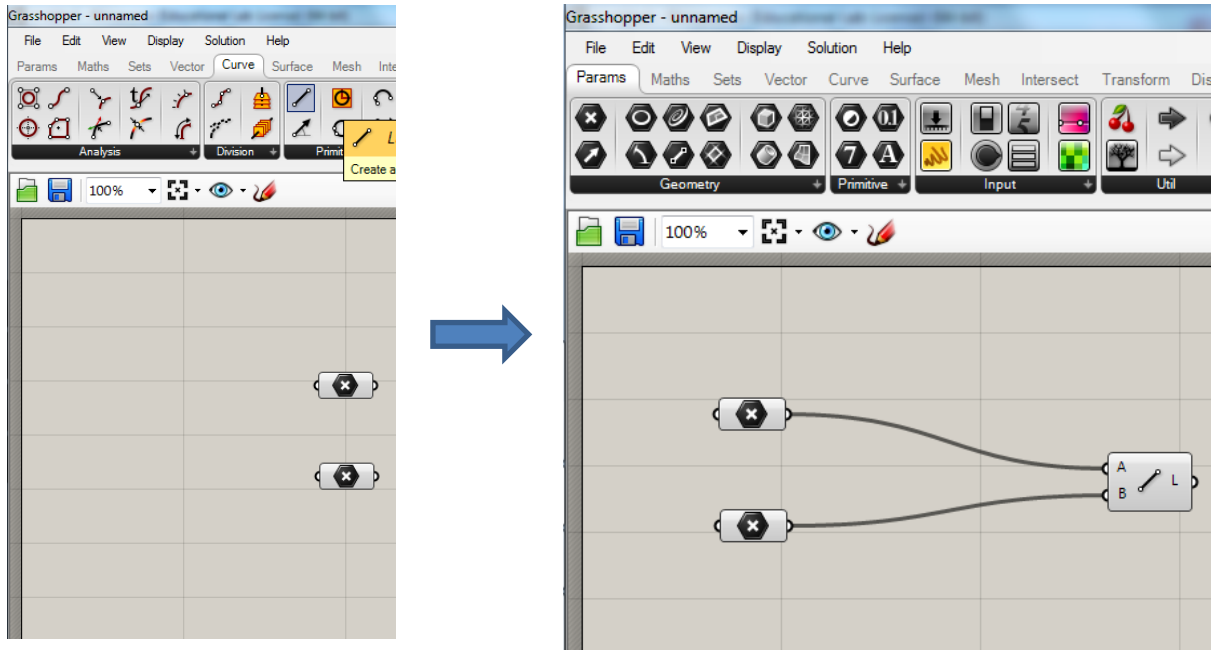
Figure 3-7 Inserting the line element and connecting point elements to it
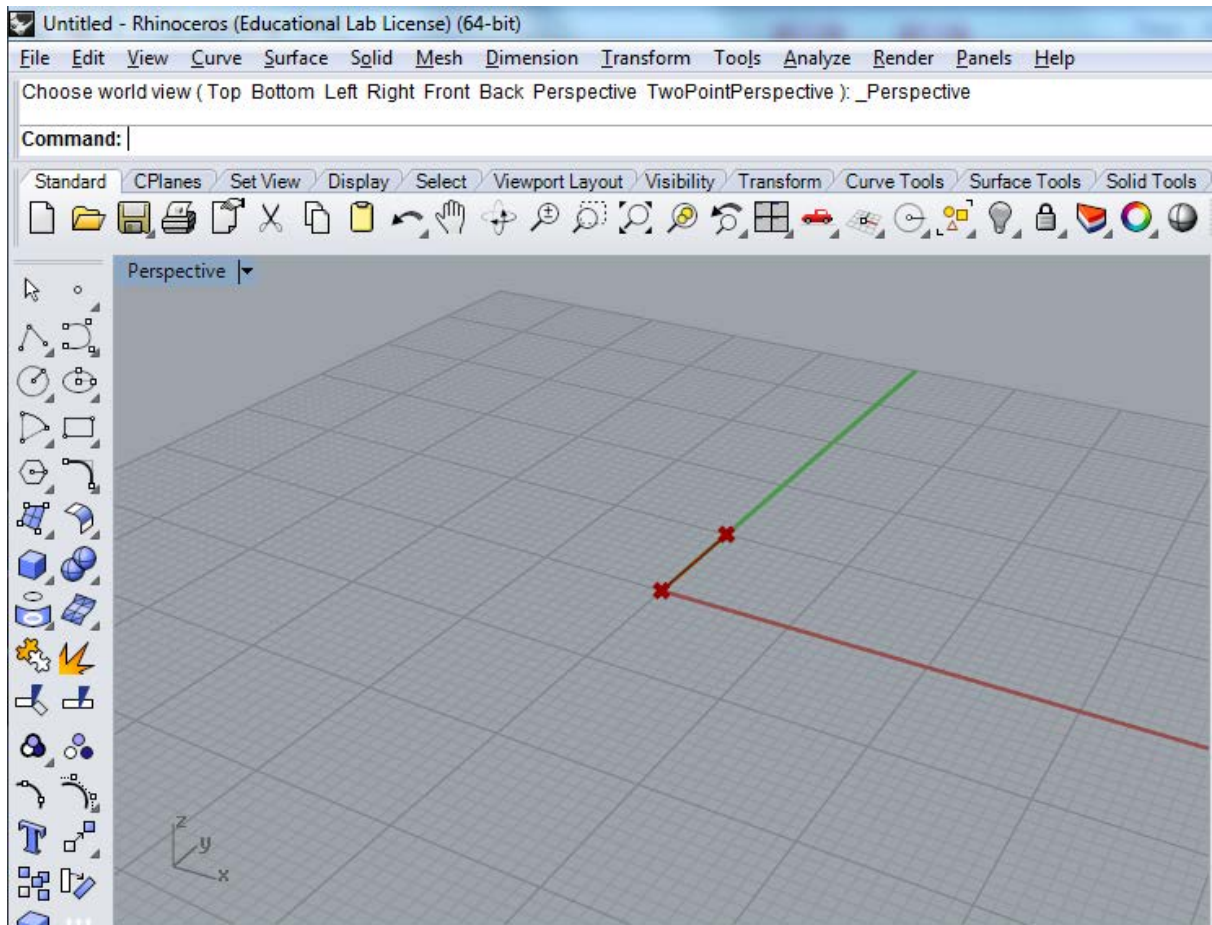
Figure 3-8 A line is formed automatically in the Rhino model

25
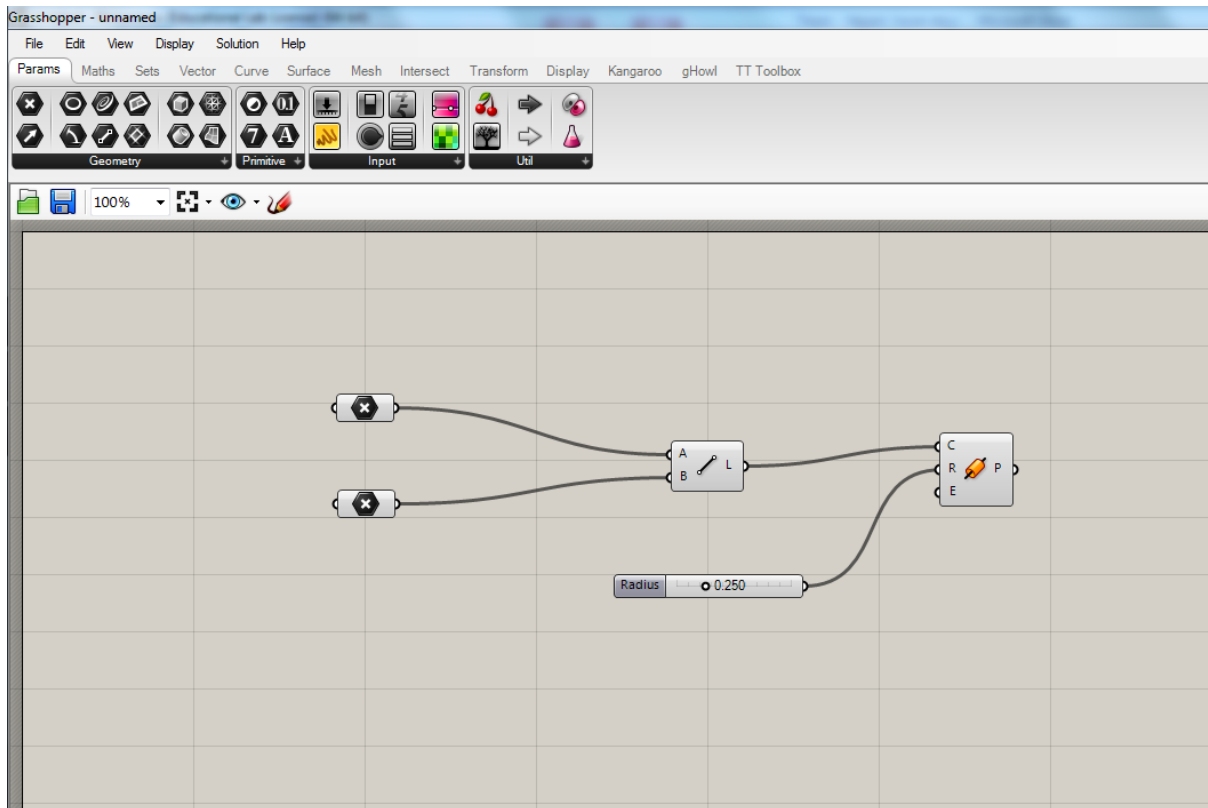
Figure 3-9 Inserting a pipe element and connecting line and slider elements to it
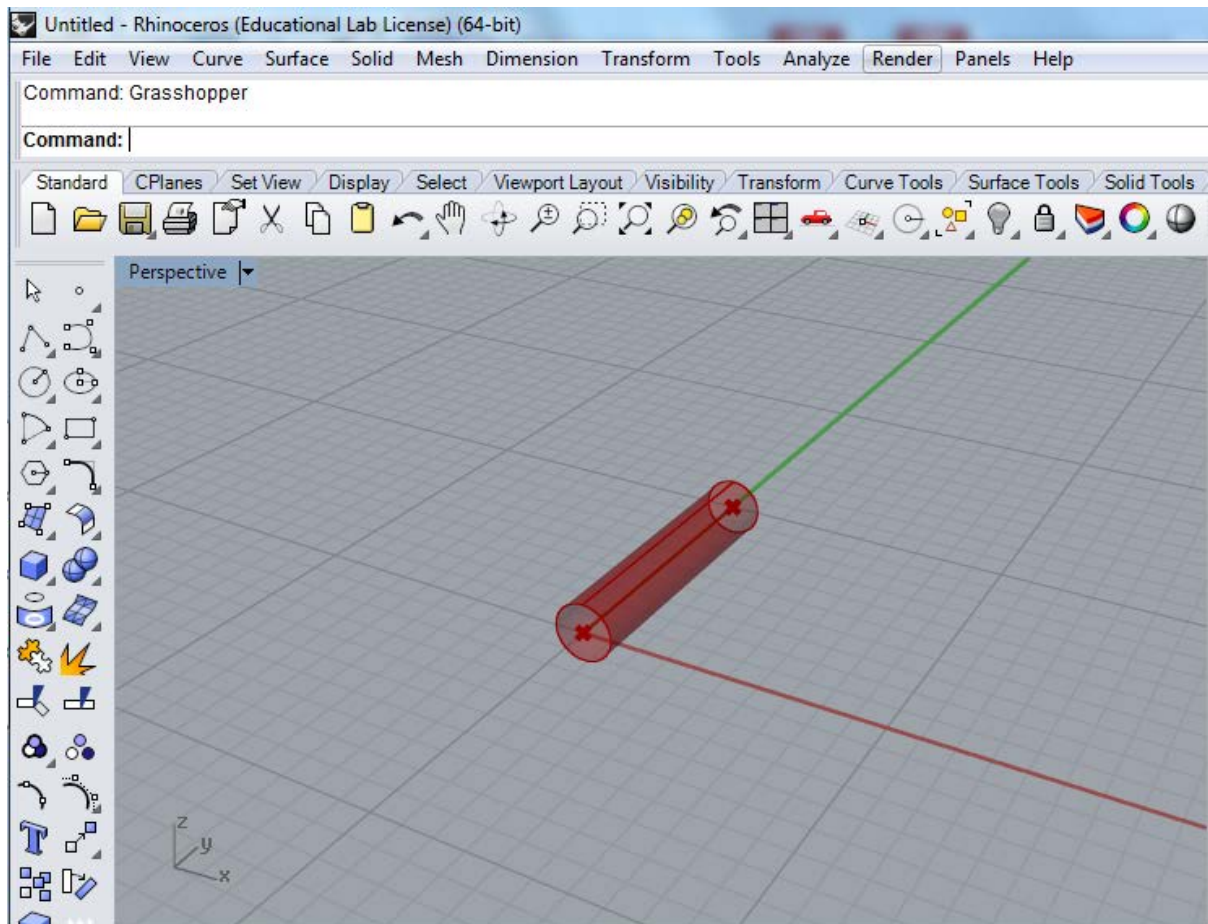
Figure 3-10 A cylinder formed automatically whose radius can be changed readily by a slider

26

Grasshopper also has different add-ons, similar to SolidWorks having the Simulation add-on. Two related and useful add-ons for MC toolkits are Platypus and Kangaroo. Platypus allows streaming of the geometry from Grasshopper on the 'http://3dplatyp.us/' website (CORE Studio 2015). The website provides a session ID, with which the grasshopper content can be linked to the website. However, this requires that grasshopper to be already running, and it does not work independently.

Kangaroo is another add-on that provides a solver library. Based on the definition from the website: 'Kangaroo is a live physics engine for interactive simulation, form-finding, optimisation and constraint solving' (Daniel Piker 2017). Therefore, with this add-on the physics of the product could be shown to the customer through the toolkit.

3.5.2 Online software programs with 3D-enabling Libraries

One of the characteristics of MC toolkits that is rather important, and nowadays due to the advent of the internet, is considered for this section is the potential capability of them being web-based. In fact, a significant number are web-based nowadays (Abbasi et al. 2013) so the customer can access and manipulate his/her data easily and conveniently. If the internet is taken advantage of and utilised (which is one of the enablers of MC (Piller et al. 2004)), then a web-based MC toolkit can be created. In order to do so, it has to be based on a 3D-enabling library, due to the very limited on-line acceptability of CAD software programs.

A library is a collection of numerous items (or commands) in order to ease programming in a specific language. For example, many 3D-enabling libraries, such as WebGL (Khronos Group), Three.js (mrdoob 2014), Processing (Processing Foundation 2016)ease the programming for creating 3D models. The advantage of using these libraries is that there is no need to install any programme(s)/add-in(s) to show the 3D graphics on the screen, where Flash (Adobe) has some limitations in this case. WebGL, which stands for web graphical language, enables programmers to render 3D objects on the web. WebGL makes use of a new element of HTML5 called Canvas. Many libraries have appeared since the appearance of WebGL to make the task of programming in WebGL easy. Three.js (mrdoob 2014) is the easy version of WebGL, and is recommended for novice programmers. It is a library, which contains numerous items (or commands) in order to build the 3D space with OpenGL rendering. An advantage of Three.js is that it has a good documentation on different cameras (prospective camera, orthographic camera), lights (e.g. point light, area light) and geometries (e.g. cylinder geometry, box geometry), which are the main aspects of a scene. The Three.js library is accessible through its documentation on the Threejs website (mrdoob 2014). The process of programming in Three.js is explained later in detail (3.6 Considerations for Programming in Three.js).

The goal of this section is to give a brief introduction to three.js. We will start by setting up a scene, with a spinning cube. A working example is provided at the bottom of the page in case you get stuck and need help.

Before we start

Before you can use three.js, you need somewhere to display it. Save the following HTML to a file on your computer, along with a copy of three.js in the js/ directory, and open it in your browser.

```html
<!DOCTYPE html>
<html>
    <head>
        <meta charset=utf-8>
        <title>My first three.js app</title>
        <style>
            body { margin: 0; }
            canvas { width: 100%; height: 100% }
        </style>
    </head>
    <body>
        <script src="js/three.js"></script>
        <script>
            // Our Javascript will go here.
        </script>
    </body>
</html>
```

That's all. All the code below goes into the empty <script> tag.

Figure 3-11 Documentation of Three.js to access its library

Based on Three.js programming, the physics of the product could be simulated from scratch using maths and physics equations; however, there are libraries/engines that facilitate this type of simulation. The libraries known as Cannon.js and physic.js are two that the author came across during this research.

Another program that enables 3D graphics on the web is 'Processing'. Processing is an open source software program that has two ways of rendering as the same as WebGL and Three.js, 2D and 3D. Again, like WebGL and Three.js, the content of Processing can be shown on HTML with the help of Canvas.

To briefly explain the process for Processing, the file has two parts of code: setup (for initial setup and default values), draw (for doing repetitive drawing jobs on canvas). The Processing file then can be read by a HTML file which can contain any JavaScript or/and Stylesheets, including text formats. The Processing file is read with the help of the Processing.min.js file used in the HTML file.

While several experiments were conducted to implement different AM-enabled MC toolkits within existing CAD software programs, the necessity for Web-based capability convinced the author to experiment with 3D-enabling libraries as well.

3.6 The Promising Way for Implementing MC Toolkits

The importance of visualisation and real representation of the product in 3D for customers who engage in customisation of their products has been increasingly emphasised. Regardless of having web-based capability, 3D-enabling libraries such as Three.js were incorporated in recent parametric MC toolkits. At the early stages of this research, few toolkits were found that used Three.js to represent their product in 3D on the web (e.g. CellCycle from Nervous System). At the later stages of this research, more toolkits were added to this list (e.g. Shapeshifter.io (Autodesk) (Figure 3-11) and Platypus (CORE studio)).

The Shapeshifter.io explains itself as

> *a project which is a free technology preview by Autodesk. It provides an easy way to create complex 3D printable models in your web browser. With a simple tweak of sliders, you can control the object's shape and select a 3D pattern that wraps around it.*

(Autodesk 2013)

The advantage of this system is that it compromises of many options for customisation of the product, such as surface, shape, and pattern modifications. The customer may prefer this system to other systems with fewer options. The representation of the options also makes it easy to interact with the system. However, direct manipulation (DM), which is absent in this system, could have made it a lot more interactive, and user-friendly. Its disadvantage is that it does not work as a MC

toolkit since it was not designed for customers who want to readily order a product online.

The other one is Platypus (CORE studio 2015), which is defined by its website as allowing 'Grasshopper authors to stream geometry to the web in real time. It works like a chatroom for parametric geometry, and allows for on-the-fly 3D model mashups in the web browser'. From another perspective, this interface, therefore, is very similar to ShapeShifter.io, which is a readily available website for a number of templates, e.g. ring, vase, bowl, etc., but in Platypus, the user can provide this website for any design in Grasshopper by connecting the sliders to a specific component in Grasshopper. Therefore, the website may represent any product that is designed in Grasshopper, and it is limitless in comparison to Shapeshifter.io. The disadvantage of Platypus is that it still lacks components, such as price and side-by-side comparison, etc., for a proper MC experience.

These two examples in the area of manipulating 3D models on a website especially with 3D-enabling libraries, such as Three.js, show right path of the research.

3.7 Considerations for Programming in Three.js

The necessity of doing online CAD modelling has been considered by CAD developers and program language coders, and therefore a new way for doing this was available since WebGL has come into existence. However, WebGL programmers confront difficulties because it is a low-level library since it needs to communicate with Graphics Processing Unit (GPU) of the system.

Three.js, created by mrdoob, is a library that makes WebGL easier. This library makes the process of programming for 3D graphics, such as WebGL, a lot easier in terms of the three main elements of the scene: camera, object, and light, which should be created and added to the scene in order to show an object on a website (and the web). The process in the Three.js is straightforward; the three scene elements are created by commands with the same name as the elements, and then added to the scene, the renderer is created and attached to an HTML element, and finally the scene is rendered. The documentation of Three.js has been improved over years and the latest version of Three.js (r84) was released in January 2017.

As explained previously, most applications of computer graphics use polygon scan conversion for rendering, so does Three.js. It means that each surface or volume consists of small triangles or squares, whichever is preferred. For each kind of surface or volume, a considerable calculation is needed to create it out of small triangles. However, in Three.js, there are some default geometries available, such as circle, cube, cylinder, sphere, etc.
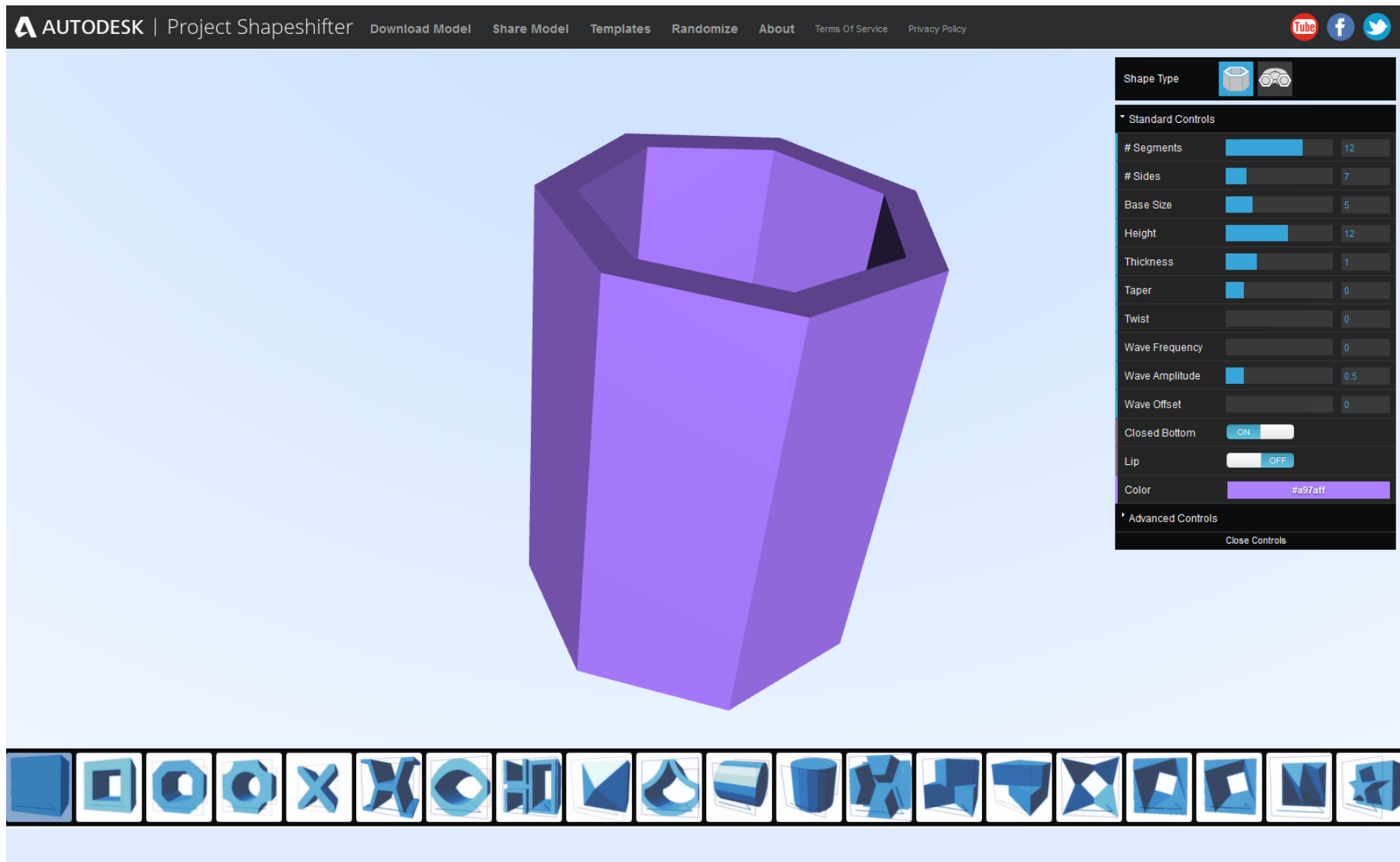
31

The coordinate system for Three.js is different from that in HTML. In Three.js, the x and y-axis are parallel to the screen. The positive direction of the x-axis is horizontal from left to right, and the y-axis vertical from bottom to top. The positive direction of the z-axis comes out from the screen. The coordinate system for Three.js is depicted in Figure 3-12 as explained. It is important to keep in mind that in HTML the direction is different. Therefore, transferring these two directions (HTML to Three.js and vice versa) has to be done in order for the system to work properly.
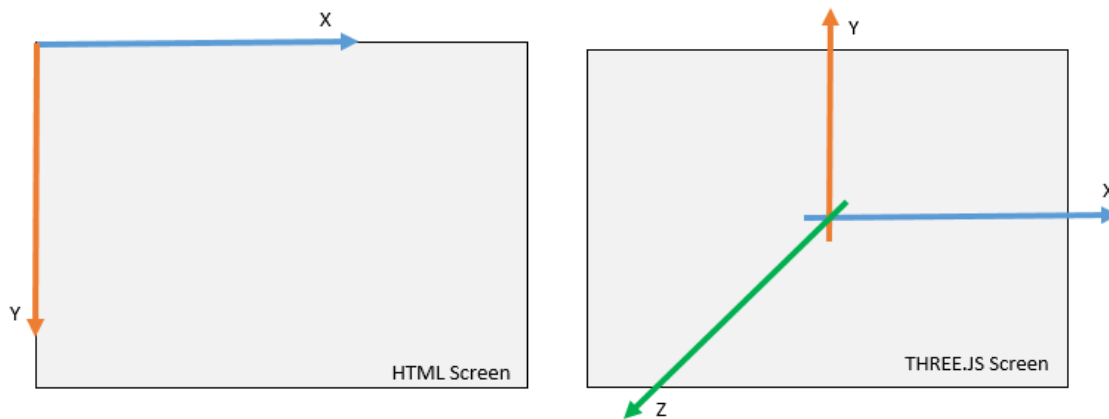
Figure 3-13 The coordinate system, used in Three.js and HTML, shown on user's screen (Three.js on right, HTML on left)

Another benefit of using Three.js and WebGL is that DM is achievable. DM allows customers to manipulate 3D objects on the screen with dragging and moving the vertices of its surface directly (Stone 2005). DM has been regarded by researchers as the way these toolkits should really be (Sinclair 2012, Stone 2005). In other words, one of the findings in memory research is that it is easier to recognize information than to recall it. DM interfaces exist in many application areas, such as word processing, desktop publishing, CAD, flight simulation, and video games (Stone 2005).

3.8 Additive Manufacturing

Pine (1993) defined mass customised products as ''having enough variety and customisation that nearly everyone finds exactly what they want'. However, not only did internet technology enable MC, but also advances in manufacturing methods, namely, AM did too. AM allows more freedom in terms of number of options for these toolkits. AM-enabled toolkits generally enable users to manipulate the surface, form and shape of the product (Sinclair et al. 2014), which is nearly impossible with traditional methods of manufacturing. In other words, AM-enabled MC toolkits are similar to CAD software programs, but are almost always located on the web, and facilitate parametric manipulations of 3D models, available on CAD software programs, but with ease so that customers can take part. Not only, should it inheritance the tools available on CAD software programs for manipulation/design of a 3D object, but web elements are required to demonstrate options/tools in a user-

friendly way, as well as to enable customers to make an on-line purchase. Apart from this, the outcome of the manipulation through AM-enabled MC toolkits is a product that is very likely to be manufacturable only with AM, as the name indicates.

AM can be defined as a process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies (ASTM International 2012). As users are involved in the process of creating their own products, and are given the ability to change the product geometry, AM has become a promise to deliver the service. AM supports a 'batch size of one' manufacturing paradigm, allowing that the outcome of the toolkit, either the product or part of the product, to be manufactured in a way not possible with conventional manufacturing. Due to high product surface manipulation and variation in MC toolkits, the output has to be manufactured by using new manufacturing methods, such as AM, in most cases. However, not all toolkits will use AM (SketchChair 2011). The MC toolkit can additionally become a design interface or software for novice customers to produce their products with personal 3D printers.

By using AM to facilitate MC, customers are not limited to having a standard product choice anymore; in theory, they can have almost the exact product they want. Consumer orientation is not the only requirement for the companies who pursue MC toolkits. Companies, in order to catch up with that, they also need to revolutionize their manufacturing. In order to let every customer, have their desired products, it requires manufacturing in batch sizes of one of each product individually. Therefore, it is necessary to do this while trying to keep the cost of manufacturing to a reasonable level. Again, AM can allow the production of a range of different product designs within the same build. However, the outcome may not satisfy the customer due to low resolution and roughness. As in personal 3D printers, the colour of the product is also limited most of the time. Nevertheless, the advances in AM are very promising as the speed of process, smoothness of the surface finish, and material selectivity have improved in recent years (Carbon3D 2015).

AM allows not only manufacturing of products with complex shapes, but also customers to be more involved and have more control of the design. Therefore, this research considers AM for the production of the outcome of the toolkit, and as mainly indicated, AM-enabled toolkits are the focus.

Figure 3-13 shows that to help keep manufacturing costs down, AM can be used for producing one or few products. The cost of the mould in injection moulding is distributed across the production volume, which causes the cost to decrease as the number of parts increases. However, the curve of the laser sintering (LS) method as an AM process stays constant since indirect costs are charged on every single part. This diagram is valid for high production volumes and manufacturing copies of the same product (Ruffo & Hague 2007).
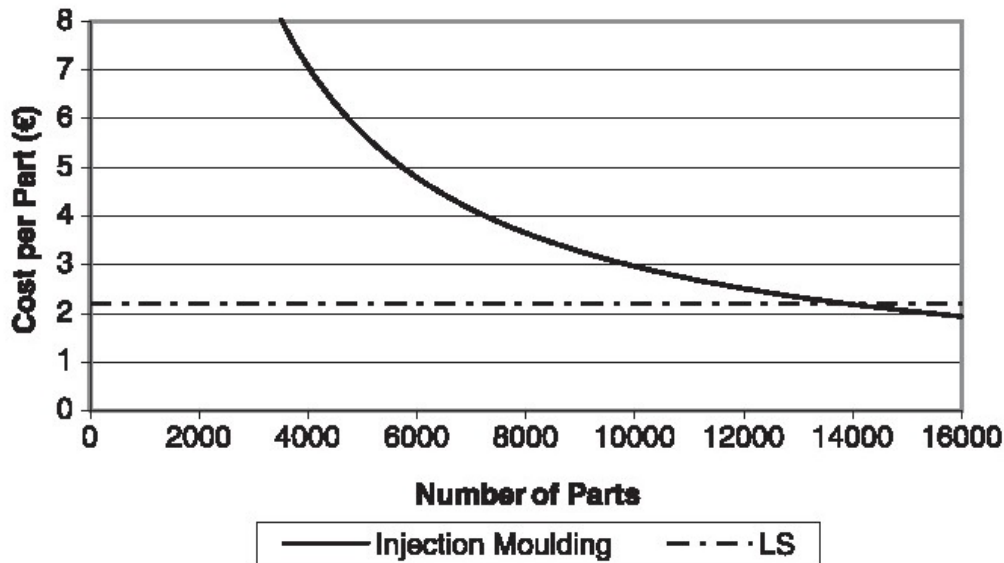
Figure 3-14 Example of break-even analysis comparing laser sintering (LS) with injection moulding (IM) (Ruffo & Hague 2007)

3.9 Different Systems and Processes of Additive Manufacturing

Considering there are over twenty different processes for rapid prototyping, not all of them are suitable for AM. This is because not all are useful for applications beyond visualisation (Hopkinson et al. 2006).

Commonly used and recently developed AM technologies are described below. They have been divided into three main categories according to the raw material used in the process (ASTM International 2012, Hopkinson et al. 2006, Carbon 2015, Loughborough University N/A, Mansour & Hague 2003, Upcraft & Fletcher 2003):

1. Liquid-based systems

Vat Photopolymerisation: This technology, typified by the stereolithography process, uses an ultraviolet light-source to cure and solidify a layer of a resin of photopolymer liquid. Each solidified layer is covered with a fresh layer of liquid before the light-source selectively cures the next layer. Layers are bonded together and finally form the object desired (Hopkinson et al. 2006). There is usually a need for supports since the part is essentially built up inside a liquid vat (Mansour & Hague 2003).

Material Jetting: This technology works similarly to two-dimensional ink jet printers. The material is deposited either continuously or with a drop on demand approach. The model is built up layer by layer and hardened using ultraviolet light or allowed to solidify through cooling. Materials need to be deposited as liquid drops and therefore the range of materials available for this method is limited. Among them, waxes and polymers are widely used for their ability to form drops easily (ASTM International 2012, Loughborough University N/A).

34

Continuous Liquid Interface Production (CLIP): This is a relatively new photochemical process that harnesses light and oxygen to build objects continuously from a pool of resin. Various materials can be used including polyurethane and cyanate. The resolution is very precise and surface finish is of high quality in this process, comparable to injection-moulded plastics (Carbon3D 2015).

2. Powder-based systems

Powder Bed Fusion: In this technology, typified by the LS process, each two-dimensional solid layer is created using powdered raw material instead of liquid material as in stereolithography (Hopkinson et al. 2006). The surface of a powder bed is selectively scanned by a laser or electron-beam, fusing the powder particles together. The process continues layer-by-layer until the object reaches its final three-dimensional shape. When using polymer materials, the bed is usually heated during the process to bring the temperature of the powder to a level a few degrees below the melting temperature (Mansour & Hague 2003).

Directed Energy Deposition: In this technology, an A4 or 5 axis arm moves around a fixed object, and deposits melted material on a specified surface. This movement can also be reversed, and the object moves and the axis be fixed. The melting happens by a laser or electron beam. The material is usually metal in the form of powder or wire, but ceramics or polymers are also used. This process is usually used to add material to or repair an existing object (ASTM International 2012, Loughborough University N/A).

Binder Jetting: This technology is similar to LS, but instead of using a laser to join powder particles together, it uses an ink-jet printing head to print a liquid binder onto successive layers. As an example of this technology, the ' 3D printing' process that was invented at MIT, was licensed to Z-Corporation for prototyping applications, and to ProMetal for metal tooling (Mansour & Hague 2003).

High Speed Sintering (HSS): This process is a mix between LS and binder jetting. It selectively prints heat-absorbing ink on top of powder before a heat source fuses it together to form a solid layer. It is quoted as being up to 100 times faster than competing powder-bed technologies. The heat applied through an infrared lamp melts the powder faster than using a scanning laser, as with LS (Loughborough University N/A).

3. Solid-based systems

Material Extrusion: In this technology, typified by the fused deposition modeling process, a filament of polymer or wax is heated and extruded through a nozzle. Successive layers are built on top of each other until the final thermoplastic part is formed (Mansour & Hague 2003). This process forms the basis for many of the low-cost 'concept modellers' used by product development teams as a fast and clean

route to create parts for gross error checking and as communication tools (Upcraft & Fletcher 2003).

Sheet Lamination: In this technology, sheets of material are cut and bonded together using adhesive to form the object. The objects are typically used for aesthetic purposes, and are not suitable for structural use. Materials are limited for this process, and internal unused material is difficult to remove (ASTM International 2012, Loughborough University N/A).

Considering the requirements for consumer product design, material extrusion and binder jetting were not considered for the rest of the research due to their poor surface finish. Various forms of vat photopolymerisation and sheet lamination were also eliminated due to the small range of available materials. HSS was considered not to be cost effective. LS allows a good range of materials to be used with a reasonable price and quality for customers. Since this research is based on the user's perspective, the outcome of the toolkit had to be reasonable in terms of cost and quality (surface finish) for customers. Therefore, LS was selected as the target AM process. It also satisfies businesses' needs due to the ease of component nesting, and the lack of the need for the removal of support structures.

3.10 Summary

A brief history of CAD was given (objective 1). 3D modelling in general and specifically for consumer-orientation was discussed (objective 2). The parametric modelling approach was described, and it was specified that the use of CAD software programs can be eased for customers by using this capability. CAD software programs need to evolve further for novice users to interact with them in the form of MC toolkits, which can be done with the use of APIs (objective 3). As an offline method for providing AM-enabled MC toolkits, a parametric modelling approach was used in two CAD software programs: SolidWorks API and Grasshopper, and the pros and cons of each API were identified (objective 4). The CAD software programs were very limited in terms of web-based capability, which directed the author to use 3D-enabling libraries. Therefore, two more systems were examined as the basis of an online method of representation for AM-enabled MC toolkits (objective 5).

The recent implementation of Three.js in two AM-enabled applications was mentioned, which verifies the use of 3D-enabling libraries, specially Three.js (considering that there were not many AM-enabled toolkits found at the time of this research). Some hints regarding programming in Three.js and processing were also conveyed.

The use of AM, which supports the flexibility of product geometry required for MC toolkits, was justified in the first chapter, and was covered in more depth here

(objective 6). The next chapter deals with the main topic of this thesis, which is the development of MC toolkits.

Chapter 4 :   Mass Customisation and MC Toolkits

4.1 Introduction

In this chapter, MC is introduced, with particular regard to MC toolkits.

This chapter includes:

1- A discussion of the MC paradigm; including benefits, consequences, technology drivers, success factors, etc.
2- A description of MC toolkits in general; including advantages, types, solution space.
3- A Specific exploration of MC toolkits in term of elements, features, and DoF
4- An overview of available guidelines for MC toolkits

4.2 Manufacturing Trend

In the craft production era, every product was made for an individual, one by one (Davis 1987). In this paradigm, products are mostly produced by an artisan for a customer requiring a product that fits exactly his/her needs. The Industrial Revolution, firstly in Great Britain and later in the USA, enabled the development of mass production and, in its developed state, assembly line production (Hu 2013). In contrast to craft production, mass production manufacturers attempt to satisfy as many consumers as possible with a single product. This reduces the cost of the final product, but introduces uniformity at the expense of neglecting individuals' specific needs.

The next era, which takes advantage of the techniques in mass production to amend the cost, whilst introducing a return to the values of craft production, is MC. It has been suggested that digital technologies and the MC paradigm enable a return to the values of craft production (Sinclair 2012), commerce and culture, and that 'MC will be as important to business in the twenty-first century as mass production was in [the] twentieth' (Gilmore & Pine 2000). It was first coined by Davis (1987), and the idea became popular with Pine's (1993) book: *Mass Customisation: The new frontier in business competition.* Figure 4-1 (adapted from Lin, 2012) illustrates this shift.
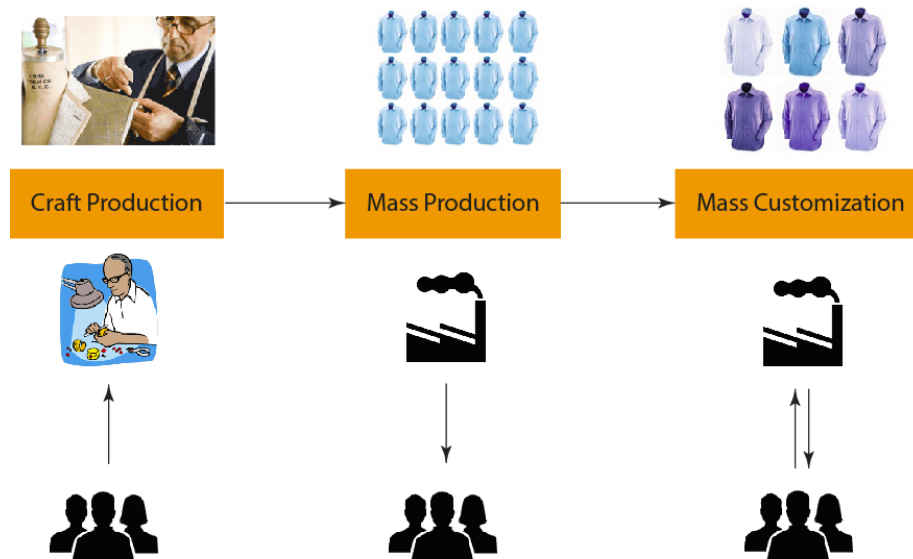
4.3 Mass Customisation

Listening and understanding the voice of customers is beneficial for both companies and customers (Berger & Piller 2003). Listening carefully to what customers want is necessary in producing a successful product (Thomke & von Hippel 2002). However, customer needs and desires are not easy to obtain, since customers themselves have not consciously prepared their needs and how to achieve them (Ciccantelli & Magidson 1993). This becomes even more problematic when customers are limited in what is available to them, and are not given a chance to express new desires and concepts. In MC, the trade-off between variety and productivity is decreased, and customers become co-designers (Franke & Piller 2003). MC is defined as a paradigm shift to fulfil customer needs and desires as precisely as possible, with an efficiency as close as possible to that achieved in mass production (Tseng & Jiao 2001). This is a win-win situation for companies and customers where companies get direct access to customer trends and consequently increase sales, and customers benefit from having their voices heard (Berger & Piller 2003).

From another perspective, consumers with increasing purchasing power - the power to choose between different items (heterogeneous needs) (Franke & Hippel 2003), and have their product crafted - are increasingly trying to make their product choices based on fitting their functional and psychological needs (Hu 2013, Berger & Piller 2003). People increasingly would like to customise their products (Piller 2008), which motivates companies to pursue MC, which in reverse creates competitive advantages for them (Hippel 2001, Mugge et al. 2009, Pine 1993, Dai et al. 2006) (for more benefits of MC see '4.4 MC Benefits').

MC responds to increasing demand for more individualised products (Berger & Piller 2003). The primary indicator of the paradigm shift from mass production to MC is

39

market turbulence within a firm and industry. In current markets, turbulence is caused by increasing complexity of consumers' preferences and desires, which is more difficult to forecast (Kincade 2007; Hart 1995). By allowing the postponement of production until after the customer has placed his/her order, MC reduces this turbulence, while simultaneously allowing the reduction of stock levels and the introduction of just-in-time logistics (Kincade 2007, Berger & Piller 2003).

4.4 MC Benefits

Previous research has identified a number of benefits of MC to the user and the manufacturer:

Preference Fit (Franke & Schreier 2010): refers to the size, colour, material, shape, etc. of a product. Increased preference fit through MC has been shown to lead to increased willingness-to-pay in a number of product and market sectors.

Leading innovation management by producing successful MC-tested innovative technologies or solutions (Berger & Piller 2003): Innovative technologies or product solutions can be tested first on a MC platform, and then brought to market as mass manufactured off-the-shelf products if approved by customers.

Encourage sustainability (Mugge et al. 2009): Increased preference fit encourages longer lasting relationships between user and the product, by postponing disposal and replacement; this encourages sustainability.

Streamline and trending products (Gateway3D 2015)**:** MC enables the customers to design and create a product according to his/her needs and desire. Through the observation of what is purchased and designed, companies can get ideas of what is trending.

Finally, other advantages of MC toolkits are: increasing cash flow by postponing the production; preventing risk of market turbulence by keeping up-to-date need-related information about the customers; and taking advantage of user customised preferences to create mass produced options that go with today's market demand (Berger & Piller 2003).

4.5 Mass Customisation Consequences

Although companies try to make the cost of mass customised products as low as mass produced ones, and as Tseng and Jiao's definition (Tseng & Jiao 2001) says MC products should be at near mass production efficiency, MC usually comes with premium prices. Furthermore, the efforts that customers usually need to make to customise a product is not always enjoyable (Franke & Schreier 2010), so the process experience of self-customising a product has been counted as a disincentive impacting the customer's willingness to pay and not finishing the customisation

(Franke et al. 2010). Furthermore, not only is the customisation process time consuming, but also there are usually longer waiting times for orders.

Numerous possible iterations are needed to find the perfect product due to the trial and error process in MC toolkits. These cause some difficulty for customers as well (Huffman & Kahn 1998, Hippel 2001), which may lead to them not finishing the customisation process, and postponing or abandoning the purchase (Hermans 2012). However, this is in contrast to the claim that customers enjoy the experience, and the effort made by them goes toward strengthening the emotional bonding with the product. Another consequence of MC could be the spoiling of the product's brand, due to too much modification of its appearance (Mugge et al. 2009).

Therefore, one of the important tasks of the supplier is keeping the cost of the process as low as possible while the perceived value of the customisation process is as high as possible (Franke & Piller 2003, Berger & Piller 2003, Piller 2003).

4.6 MC Implementation and Technology Drivers

The technology that makes the delivery of customised/personalised products possible is divided into three categories: product technology, public technology adoption and software/browser evolution (Gateway3D 2015).

Production Technology: Digital printing allows printing on hundreds of products, such as T-Shirts, promotional pens or greeting cards. 3D printing allows 3D objects with a variety of shapes and surfaces to be created.

Public Technology Adoption: increased acceptance of e-commerce ensures that it is convenient for people to order online and enjoy fun applications such as those that enable you to create your own products.

Software and Browser Evolution: It is now easier for companies to use HTML and modern browsers to present their toolkit. Most web browsers now support HTML5, so it is easier to create web-based enjoyable applications.

4.7 Success Factors of Mass Customisation

The success of MC systems depends on a number of internal and external factors, which justify the use of MC as a competitive strategy. They are mainly customer, product, market, industry, and organisational factors. The success factors are primarily (Silveira et al. 2001):

- Customer demand for variety and customisation must exist. The success of MC depends on the existence of a market for product variety and customisation. The balance between the potential sacrifice that customers make for MC products (time and cost), and the company's ability to produce and deliver individualised products within time and cost frame is essential.

- Market condition must be appropriate. The success of MC depends not only on the existence of the market for customised products but also on the timing of entering the market. In other words, a company can be well rooted in the MC position if it is the first to develop a MC system over the competitors. This will also lead to customers seeing the company as an innovative and customer-driven one.

- Value chain should be ready. The readiness of supply providers, retailers, and distributors is essential in MC. The suppliers should be close enough to the company to deliver raw material efficiently. Not only willingness and readiness is important but also the communication and information network between them needs to be improved in MC.

- Technology must be available. The development of a MC system is dependent on implementation of advanced manufacturing technologies. Two important technologies that enable MC are information technology and AM (Piller et al. 2004).

- Products should be customisable. A modular product is composed of independent units that can be assembled into different forms. Successful MC products need to be versatile, modularised and constantly renewed. Modularity enables low-cost and simpler manufacturing of products if compared to true customisation (where products are manufactured individually); however, it is not counted as the fundamental characteristic of MC implementation.

- Knowledge must be shared. As explained previously, the communication between suppliers, retailers, and distributors should happen readily. The new customer demands should be translated into new products and services in the MC system. This requires the development of a dynamic network.

Other than the success factors above, another factor for MC success are that marketing must provide up to date information about what customers need or desire, this is known as the elicitation process (Berger & Piller 2003). This success factor can be hard for marketing because collecting information about each customer is not an easy task. Those factors show that MC is not every companies' best strategy. Furthermore, it shows that MC implementation is not easy and involves complexity.

4.8 Product Factor (Choosing the Right Product)

The product factor, which plays an important role in MC implementation, can be divided into smaller factors (Broekhuizen & Alsem 2000):

1- Purchasing frequency, which enables companies to build learning a relationship with customers, which leads to enhancement of customer loyalty.

Companies can be educated with the options with which their customers are satisfied.

2- Luxury level products: the more luxurious a product is, the higher price, distinctiveness, and uniqueness it has. These kinds of products are more likely to be customised by customers than the products related to basic needs, such as commodities. Since MC products provoke the feelings of fun and pleasure, luxury products tend to be more suited for MC. Not only should the product should be luxurious, but the interface should be pleasurable.

3- The visibility of the product: products that are displayed publicly are the ones that are more self-expressive. These kinds of products, which express customers' lifestyles easier, are more suitable for MC because of their high observability.

4- The product adaptability: the cost of performing MC influences its success. It is easier to customise a service than a product, and a modular product than a non-modular one. In general, MC is less costly when the customer needs can be met with easier product manipulation.

Apart from the product factors explained above, trend statistics from current 3D printing products demonstrate the tendency towards particular product categories. The first diagram (Figure 4-2) shows the average order value of different product categories, and the second one (Figure 4-3) shows the popularity of each one (3D hubs 2015).
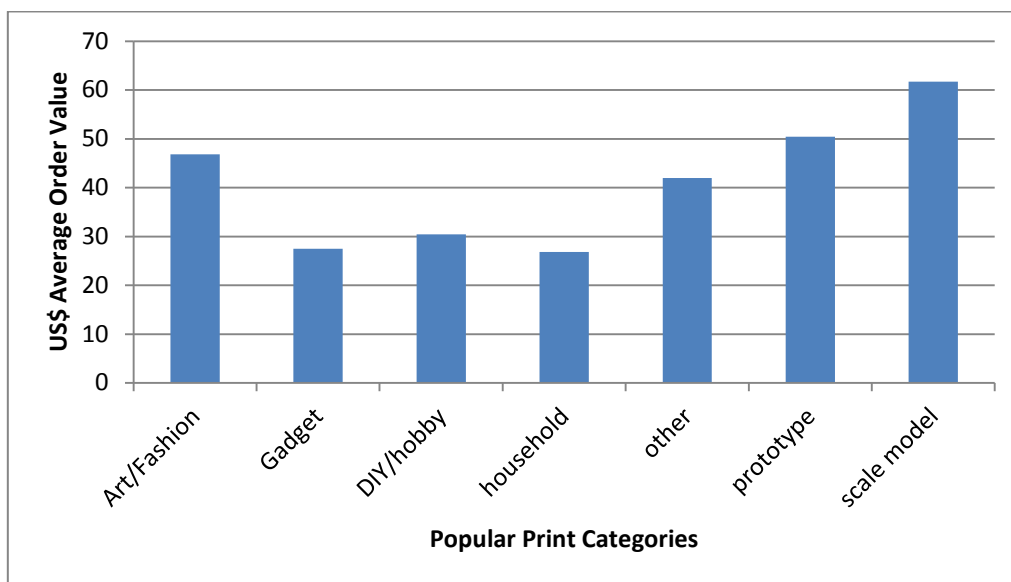
Figure 4-2 Average order value per category of 3D printed products (3D hubs 2015)
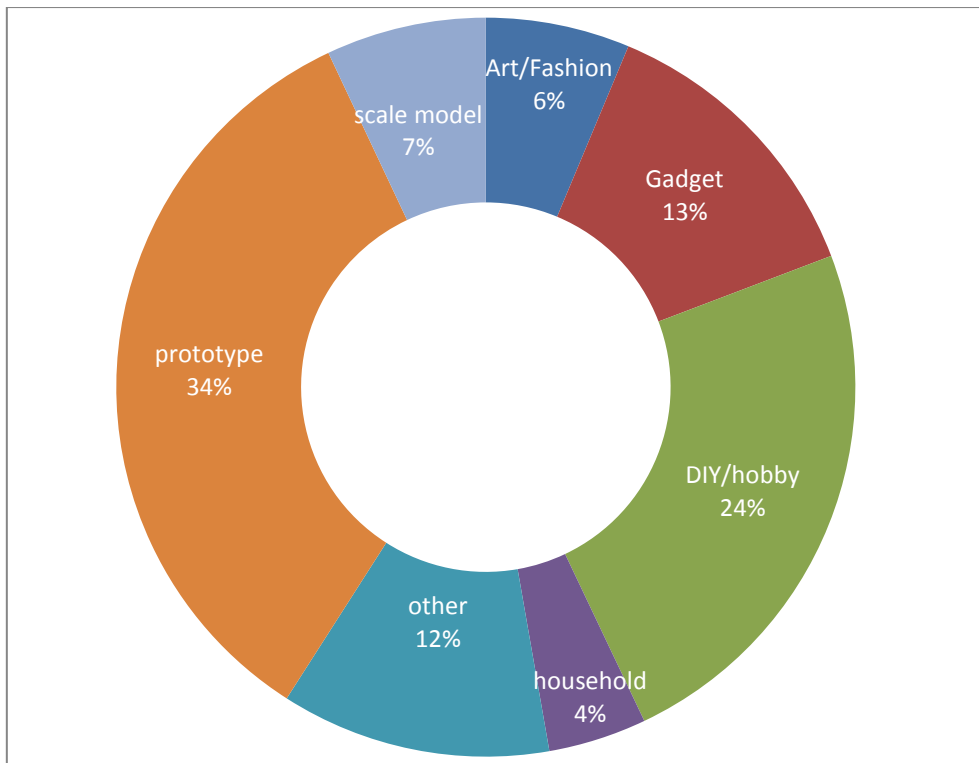
Figure 4-3 Popular print categories of 3D printed products (3D hubs 2015)

As for the main material of the second study, a product needs to be chosen for the AM-enabled MC toolkit. Considering the product factors, the selected product was a lampshade, due to it meeting at least two of the factors: being a luxury item, and visibility. It also involves both aesthetic and functional aspects, whichever customers want to customise. However, it belongs to the household category, which is not considered very trendy according to Figure 4-2 and Figure 4-3. However, for the purpose of the study, a lampshade would be acceptable, since the commercial aspect of the toolkit is not very important in this research.

4.9 Mass Customisation versus Personalisation

Personalisation is the era that has come after MC, according to Hu (2013). The difference between personalisation and MC is that MC is about designing or modifying product components or whole products based on a person's specific needs and desires, but personalisation is about selecting or filtering information (Kaplan & Haenlein 2006). It is also concerned with aspects of the product's specification that match with a person's personality, and this makes the product unique and relevant to customers. MC is the offering of a variety of options for a product as far as it is feasible for the company (this may not directly reflect personal desires or needs, but just the potential of the company), while in personalisation, a company tries to meet the person's needs and desires more accurately. In other words, the industrial aspects still affect MC, however, personalisation dives deeper into people's desires and needs.

While MC and personalisation do not have the same meaning, it can be inferred that MC and personalisation overlap at some points. In personalisation, the customers are completely involved in designing their products (Mugge et al. 2009). It is not always the case in MC, but there is a face of MC, called collaborative customisation, that necessitates the involvement of customer in designing their products. Therefore, in the author's opinion, personalisation may be counted as closer to collaborative customisation.

4.10 Customer Involvement in MC

Since one of the drivers to conducting research about MC toolkits is to help the customer in the first place to create their favourite products, then it was investigated whether the customer necessarily has to be involved in the design or not. In MC, customers' needs have to be acquired in some way or another (Hermans 2011, Broekhuizen & Alsem 2000) in order to produce their individualised products. In addition, Franke & Piller (2003) stated, 'The idea of integrating users in the design and production process is a promising strategy for companies being forced to react to the growing individualization of demand'. However, it is not in the definition of MC to involve the customers themselves in the process of extracting their need-related information (elicitation process). This can be achieved with the aid of customers themselves.

There are four faces of MC: collaborative customisation, adaptive customisation, cosmetic customisation, and transparent customisation (Gilmore & Pine II 1997). In only one of them, is the customer included in the process of extracting their own needs: collaborative customisation, which is of interest in this thesis. Contrary to other faces of MC other than collaborative customisation, Broekhuizen & Alsem (2000) stated,

> with MC, customers must first interact with the producer, the retailer or the product (i.e., adaptive products) to configure their product. In other words, they must be involved in specifying characteristics of the product during design, fabrication, assembly, or use.

It is to some extent obvious that in order to find out each individual's desire as precisely as possible, customers need to be involved in the design process in MC in some way or another, even if the definition of MC may not suggest this. Some writers have addressed it as part of MC, as Hermans (2012) says, 'MC involves consumers in the design process by enabling them to customise a product through the use of a toolkit'. Some did not, as interpreted by numbers of MC faces. In MC, customers gain some authority to design (i.e. the customer has increased autonomy) and become active in the design process; in reverse, the authority of the designer is reduced. In other words, the customer becomes a 'prosumer' (Toffler 1970), producer plus consumer, the co-creator of the product.

Therefore, in contrast to doing a focus group or survey to acquire users' needs implicitly, users can be explicitly involved in designing their own product in MC. The point of customer involvement reveals the configuration of processes and technologies that must be used to manufacture mass customised products (Chandra, Charu, Kamrani & Ali K., 2004). Five different strategies have arisen based on levels of customer involvement (see Figure 4-4).
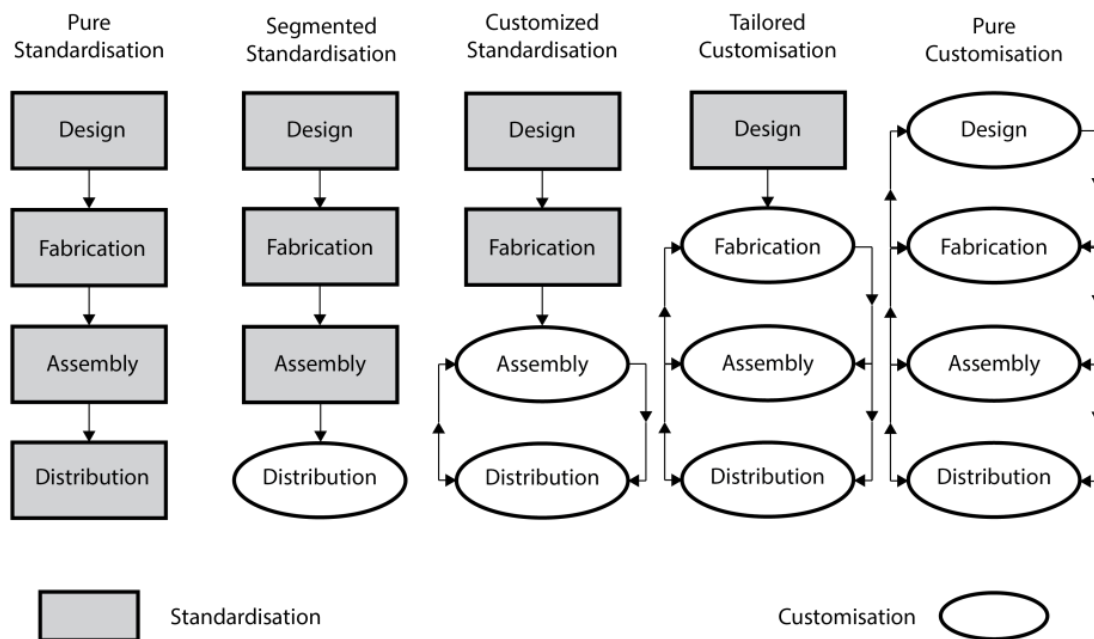
Figure 4-4 A continuum of strategies between aggregation and individualisation (Lampel & Mintzberg 1996)

Products are made to order based on a high to low degree of customer engagements. Only pure customisation was relevant to this research due to the inclusion of customisation of design and fabrication stages by the customers.

In order to involve customers and gain their need-related information, they are required to attend some design sessions, for which the monetary and non-monetary costs are not small (Lagrosen 2005). To enable different levels of customer involvement: weak, through e.g. focus groups or hearing customers' voices; moderate, through advanced user interaction; and strong, through a toolkit, such as an interface, the MC toolkit, is needed (Jeppesen 2005). In this method, the need-related information is acquired based on a space that is provided at the location of the customer. Therefore, it does not cost as much as the conventional methods (Jeppesen 2005), and it is faster. Whether users are required to be involved in MC or not, MC toolkits enable this capability.

While inputting the data and customer involvement can be directly done by the customer themselves, the data sometimes concerns 3D scanning a part or even customer's body (e.g. with a laser scanner), which could be done by a specialist or

technician. 3D Scanning is typically used to capture complex 3D geometry of physical artefacts so they can be used in a virtual context for design, analysis, or evaluation. Although, this constitutes an interesting area of research, particularly for medical purposes, it is out of scope of this research, and the emphasis of this research is on the customer as the main manipulator of the toolkit.

4.11 MC Toolkit

MC toolkits emerged in the high-tech field of custom integrated circuits in 1980 (von Hippel & Katz 2002). They have increasingly received attention by researchers and practitioners since then (Fogliatto et al. 2012). There are currently over 1000 MC toolkits available on the web based on the Configurator Database website (cyLEDGE Media 2016).

MC toolkits have been defined as a set of user-friendly design tools that allow trial and error experimentation processes, and deliver immediate simulated feedback on the outcome of design ideas (Franke et al. 2008). There are different definitions for MC toolkits. In addition to the definition above, MC toolkits count as 'knowledge-based software applications that support a potential customer, or a sales-person interacting with the customer, in completely and correctly specifying a product solution within a company's product offer' (Trentin et al. 2014). A MC toolkit is also known as a (sales) configurator (Grosso et al. 2016), design system (Franke & Piller 2003), choice board (Franke & Piller 2003), co-design platform (Franke & Piller 2003), user toolkit for innovation (Hippel 2001), collaborative design toolkit (Head & Porter 2011), or toolkit for user innovation (von Hippel & Katz 2002).

4.12 MC Toolkit Advantages

By enabling customer involvement in product design and development through MC toolkits, some of the benefits are explained below:

Learning by doing at the location of customers (trial and error at the location of customers) (Hippel 2001): Purchases by customers involve learning by doing. The customer, at first, does not exactly know what he/she needs, and by using and buying the product, he/she realises the reality, and tries to purchase another one with new specifications that fulfil new needs. After using the new product, again some problems occur that are due to the difference between the product and reality. Finally, after iterations, the final product is closer to what the customer needs. A MC toolkit allows this iteration to happen virtually at the place of the customer. That is, the customer can iterate quickly as many as they desire to reach a final design before purchasing the product.

Enjoyment of process: While Franke & Schereier (2010) argued that it might not always be preferable, due to burdensome nature of many trial and errors, some articles stated that the process of customising a product, known as flow experience

(Piller 2003), is enjoyable (Mugge et al. 2009, Franke & Schreier 2010). The customisation experience may be perceived as enjoyable because it is entertaining like a game (Merle & Chandon 2010), and because it provides a visualisation feedback, every time customers change the options (Kamis et al. 2008). Another reason that self-customisation of a product can be enjoyable is that the autonomy of customers regarding the product creation, according to self-determination theory, is often appreciated (Franke & Schreier 2010).

4.13 MC Toolkit Types

MC toolkits are categorised into three types according to the kind of customising or personalising which is done to the products (Gateway3D 2015). Customisable products are created either by adding one's own design/images/text or by changing the product configuration. A subset of configuration is print-on-demand, where the user creates a product, which is then produced via AM. Therefore, the toolkits can be divided into three types as shown below:

Figure 4-5 Different types of MC toolkits

The focus of this research is on the 'print on demand' type, which allows the highest amount of manipulation by the customer compared to others. The toolkit to be created, used and tested for the second study (Chapter 8) allows modification of higher level attributes, such as surface, shape, and size as well as lower level attributes such as colour.

4.14 Solution Space

Customer autonomy can be defined as 'the capability to act on the basis of one's own decisions; to be guided by one's own reasons, desires, and goals.' (Friedman & Nissenbaum 2015). Adjusting customer autonomy with some predefined options to control brand image, manufacturability, satisfaction etc. by designers solves the task of solution space of MC toolkits. While the design space is infinite in general, in MC it is narrowed down to a finite and constrained one, known as the solution space (Hermans 2012). In other words, a solution space is for extracting the need-related information from the customer ('the sticky information') (von Hippel & Katz 2002). The smaller the solution space is, the easier the interaction is with it; in addition, the solution space links a company's strategy with its manufacturing capabilities (Hermans 2012).

4.15 Degree of Freedom

The solution space of a MC toolkit consists of an area for showing available product options (predefined options); which encompasses all the possible designs, a toolkit is capable of creating (Hermans 2012). The 'options' indicate some freedom, which gives some autonomy to customers. However, the term 'predefined' emphasizes the authority of the designer. Therefore, a balance is required between these two, which makes the solution space important and interesting. This balance can be determined by and is related to degree of freedom (DoF), which is defined by the number and variety of options (Hermans 2012). Furthermore, counting the varying parameters can be a good scale for DoF (Franke & Piller 2003). However, additional studies are needed to identify if there is an optimum DoF for a toolkit, and how specifically it is defined, considering the available options.

Previous research has examined the extent to which DoF is preferred by users. Schwartz (2009), for example, found that students asked to rank varieties of chocolate were more satisfied when presented with six varieties than those presented with 30; in addition, they were four times more willing to have chocolate rather than cash for their participation.

When the customers have too few choices, they may be unsatisfied with their purchase because they need more choices for their shopping. However, when customers have too many purchase choices, they may again be unsatisfied due to the effort needed to choose the best product (Schwartz 2009). Schwartz (2009) confirms that there is an optimum number for the choices a customer may have, due to the positive effects of autonomy, control, and liberation that variety brings about.

4.16 The Trade-off

For the involvement of customers, the companies need to provide a foundation for customers to do the design on their own without a need to discuss with a designer or get into the situation where the final product is not producible or functional. This requires that designers limit the user by applying constraints and/or by guiding the user through different steps. These constraints make a company confident that the user will not create a product that is beyond their capabilities. Therefore, in MC toolkits, there is a trade-off between the authority of the designer, the autonomy of customer (Hermans 2012), and the brand identity of the manufacturer (Sinclair & Campbell 2014). A brand's image or identity is protected to keep product design language, which is a combination of a product's forms, surfaces, materials, textures, graphics, colours, details and behaviour, and is communicated with the customer (Brunner et al. 2009). It is what the product says when you see it, hold it, and use it.

This trade-off leads to three possibilities with respect to the DoF of a Solution Space (Hermans 2012). One possibility is to give customers a high DoF, which leads to more manipulation and therefore radical changes to products. However, in some

cases, it may cause non-functional products or compromise the brand identity (Sinclair et al. 2014). The high DoF is also referred to as causing confusion for both manufacturer and customers (Teresko 1994). On the one hand, a company that seeks to create some product variety, which is not efficient to handle, creates internal complexity in its production capabilities. On the other, external complexity causes customers to be overwhelmed with the myriad options presented, which Teresko (1994) describes as 'mass confusion'.

A second approach is to give the customer a low DoF, which prevents them from being highly involved in the creation of a product, leading to low participation and satisfaction. However, the possibility of designing something producible is high, and brand image is not likely to be compromised.

The last approach is to give the customer an average DoF, which holds advantages for both customer and designer (Hermans 2011). However, identifying a suitable DoF is not a straightforward task, and is investigated further in Chapter 6 and Chapter 8 (8.5.7 The DoF). Table 4-1 summarises these three possibilities:

Table 4-1 Three possibilities for DoF of toolkits (Hermans 2011, Sinclair et al. 2014)

High DoF	Average DoF	Low DoF
High customer satisfaction	Average customer satisfaction	Low customer satisfaction
Low product functionality	Average product functionality	High product functionality
High possibility of compromising brand identity	Medium possibility of compromising brand identity	Low possibility of compromising brand identity
High overall risk	Medium overall risk	Low overall risk

4.17 Key Elements of MC Toolkits

The components of a successful UI can be described as: navigation, guidance (U.S. Department of Health and Human Services 2006) and feedback (Rogoll & Piller 2004, Cross et al. 2009). These elements were held in common by those references. Furthermore, it is obvious that the user needs to navigate through options, giving some input and receiving feedback respectively, while going through the process. Each of these key elements can be divided into smaller features concerning MC toolkits; e.g. visual feedback, price feedback, side by side comparison, technical information, etc. All the features in the company are provided next.

4.18 AM-Enabled MC Toolkits

As described by Piller, Salvador and Walcher (2012) MC toolkits allow modification of 'Fit, Form, and Function' of a product by consumers to fulfil their needs. Some toolkits, such as Dell Solutions Configurator offer customisation of function, whereas some others such as NIKEiD configurator provides choices for size (i.e. fit) and colour and material (i.e. form) (Sinclair et al. 2014). In recent years, a number of MC toolkits have benefited from AM to provide customisation of products' shape and styling. It implies that customised products, ordered by the customer, can be readily manufactured by AM. As explained previously, with AM, there are almost no boundaries for complexity of the shape of the product to be manufactured. Therefore, the customer, with a MC toolkit can play with the shape of the product, and create very radical and complex patterns and shapes. However, this would create some implications for designers to protect the brand's image (product design language), as explained previously (4.16 The Trade-off). Therefore, these modifications of shapes and patterns should be constrained by designers; even if the result is manufacturable by AM.

Examples of AM-enabled MC toolkits are shown in Figure 4-6 to 4-9. These provide higher-level as well as lower-level attributes, and can be considered as AM-enabled MC toolkits. Based on criteria established by Hermans (2011), customers should be able to modify the product according to their preferences; the product has to be fully or partially produced by rapid manufacturing and should allow modification of the aesthetic and beyond; and the toolkit should be available for testing. The selected UIs are Cell Cycle (Nervous System 2014) (Figure 4-6), SketchChair (SketchChair 2011) (Figure 4-7), MakieMaker (Makies 2016) (Figure 4-8), and Digital Forming (Digital Forming N/A) (Figure 4-9).
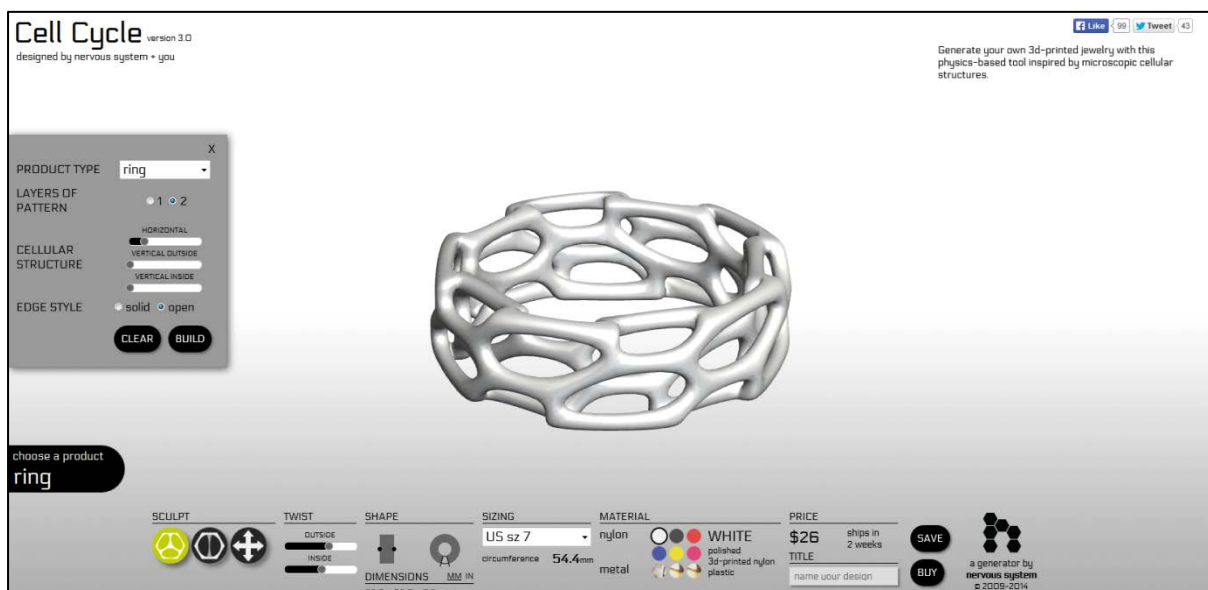
Figure 4-6 Cell Cycle by Nervous System (Nervous System 2014)
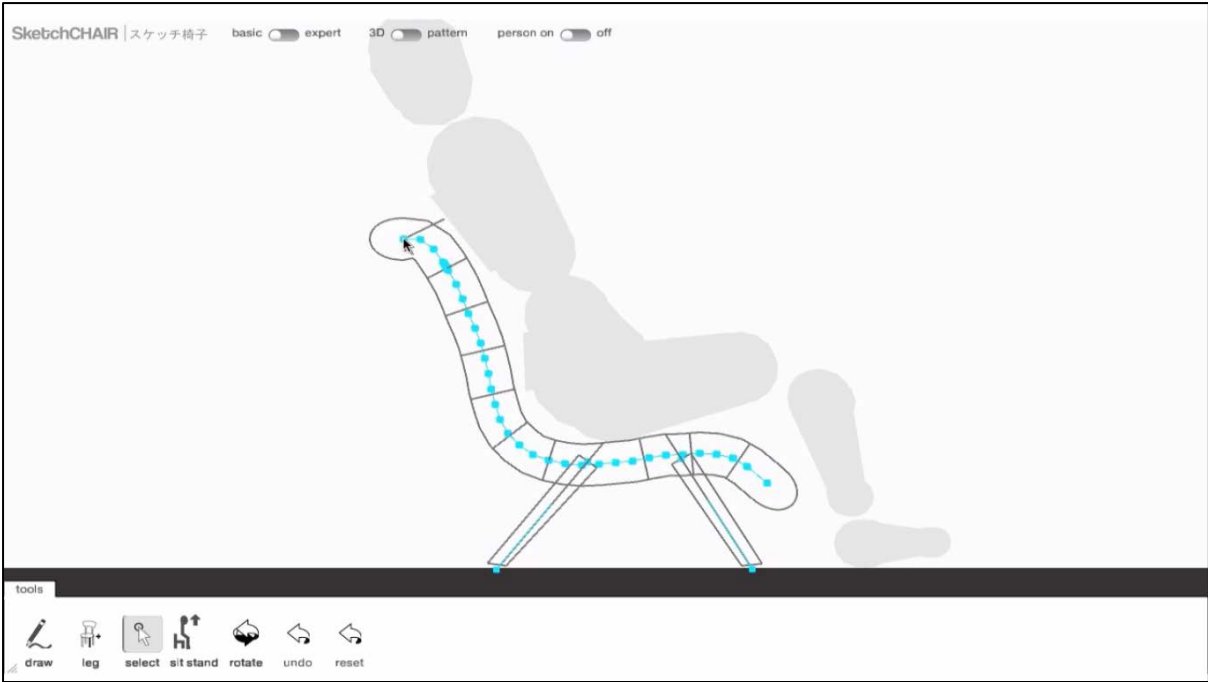
Figure 4-7 SketchChair by Diatom Studio (SketchChair 2011)
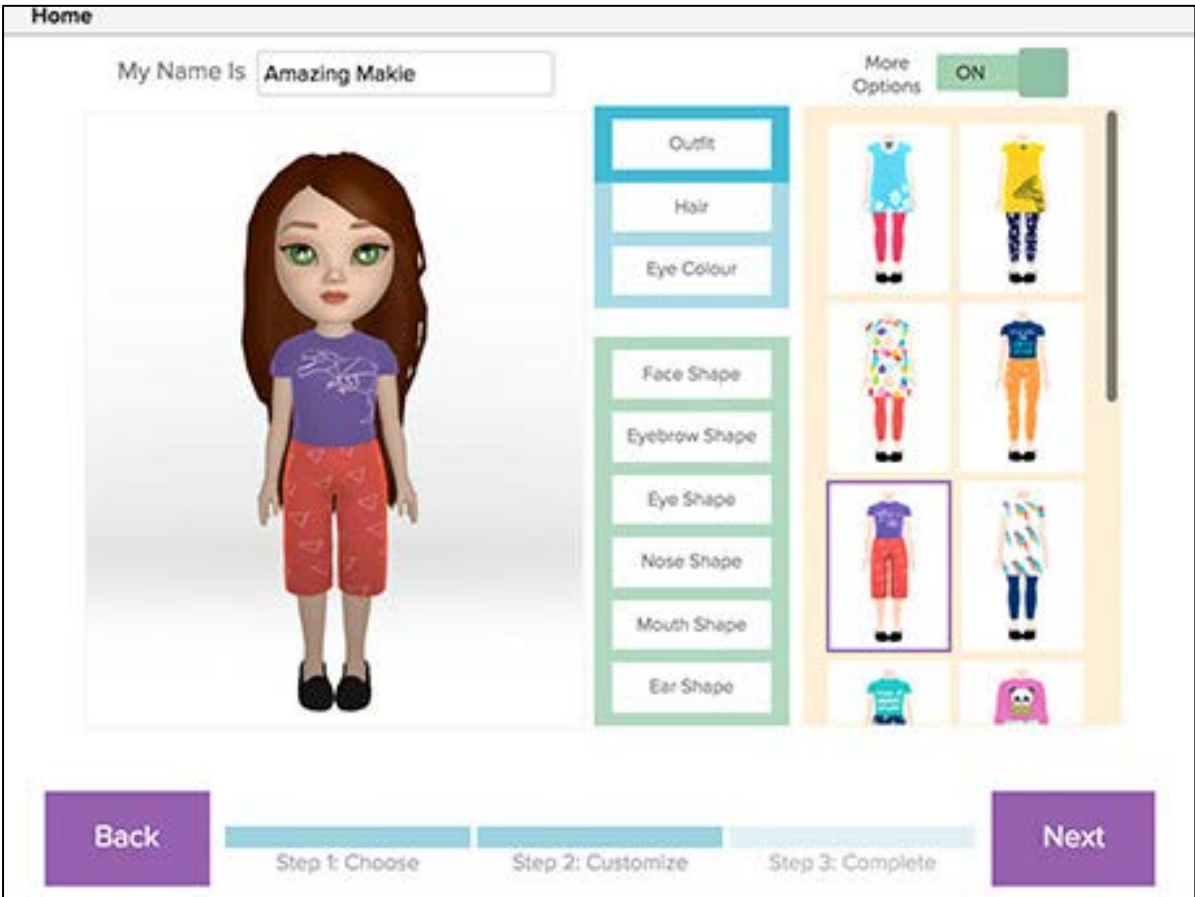
Figure 4-8 MakieMaker by MakieLab (Makies 2016)
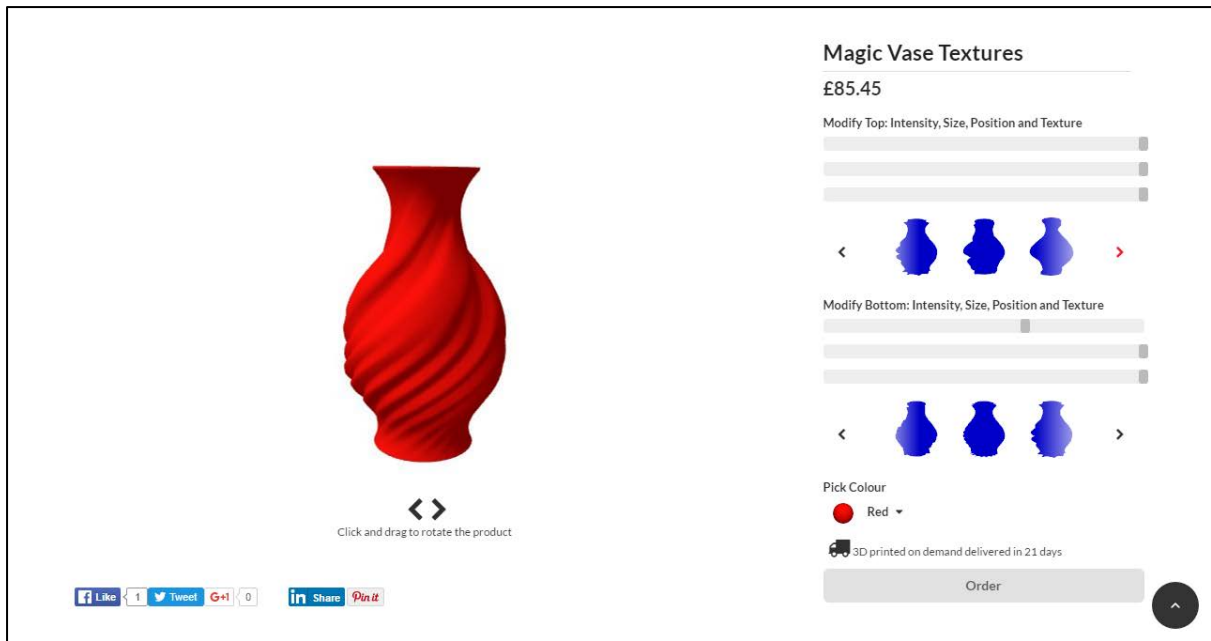
Figure 4-9 Magic Vase Textures by Digital Forming (Digital Forming N/A)

During this PhD research, a relationship was developed with Digital Forming to cooperate with them on AM-enabled MC toolkits. A seminar regarding the use of their application to create these toolkits was given by them at The Design School. The advantage of their application is that it automates the creation of MC toolkits. Therefore, the result of this research could be integrated into that application to easily guide designers and software developers. In other words, these guidelines and their application could be merged so that designers, who want to create these toolkits using the Digital Forming application, could also benefit from the guidelines. Alternatively, the guidelines could be embedded into the application. However, the application is currently limited in its nature, and did not provide enough freedom in terms of available customisation. It was therefore not a good option to create the prototype for the participants with this application as it would not provide a good representation of an AM-enabled MC toolkit.

4.19 Current Guidelines for mass customisation toolkits

One of the most cited specifications as a guideline for the design of MC toolkits is Von Hippel's five objectives (2002). The specifications are as follows: first, the toolkit will have a solution space. This is generic, because a toolkit, in order to expose what the company can offer, needs one. Second, it will be user-friendly. This is referred to as 'the ability of a sales configurator to adapt the description of a company's product space to the individual characteristics of a potential customer as well as to the situational characteristics of his/her using of the sales configurator' (Trentin et al. 2014). Third, it will provide a space for the customer for trial and error. The customer obviously needs to try different options in order to see the favourite outcome. Fourth,

it will provide a library of common modules. Fifth, it will check if the final product is producible or not, considering any manufacturing limitations.

From the most cited specifications, to more recent ones, Hermans (2015) summarizes the 'Guidelines for Developing Toolkits' as below:

1- Domain-specific scope: the MC toolkit needs to be specifically for a product category or as mentioned, product domain. Thus, the toolkit is specific for a particular domain, but not too constrained.

2- Address multiple skills levels: the toolkit should be designed for multiple groups of people with heterogeneous skill levels. Consequently, advanced and novice users can use the system, which fits each group's contextual needs.

3- Deliver the unexpected: the toolkit should provide unexpected features and specifications for the layperson. In other words, it needs to surprise the users and give them the opportunity to create something that they have not thought of or expected.

4- Four mechanisms to create variability: four mechanisms of generative, parametric, modular and veneer should be employed in order to create a better toolkit in terms of openness. For better outcomes, the designer may also use a combination of mechanisms to deliver a more satisfying toolkit.

5- Enable iteration: one of the key specifications of MC toolkits, identified by Von Hippel (2002) similarly, is the ability to allow trial and error. The design team needs to enable trial and error in their toolkit. Therefore, the user can iterate between designs as many times as they want and choose whatever is suitable for them.

6- Adaptability in design and/or use time: this guideline shed light on the requirement to enable testing the customised products and the ability to customise them again after testing, until finally reaching satisfying products. This back and forth requirement may emerge in developing products that are adapted after purchasing, as discussed in adaptive MC (4.9 Consumer Involvement in MC).

7- Expandability (go beyond the toolkit): the toolkits need to have fluid boundaries, which allow them to interact with third-party software programs or export to file formats that are compatible with other programs. This research also found a way to transfer data between different interfaces for more flexibility by using Microsoft Office Excel.

8- Tailor to specific fabrication technique: as similarly specified by Von Hippel (2002), the toolkit must ensure that the final product is producible. Focusing

on a specific manufacturing technology enables the designer not only to make sure the final customised product is producible, but also to deliver right tools, guidelines and features.

9- Non-linear navigation: as also indicated by Matt Sinclair (Sinclair 2012), it is recommended that the users have access to any navigation item at any time, regardless of any sequence or systematic navigation process. This will give enough freedom and openness to the layperson to do the design.

10- Appropriate visualisation: the visualisation of the products should be a good representation of the users' choices and the final products. There is a variety of ways to visualise the product, which represent the choices, user make, and the final product. The important thing to consider is that appropriate visualisation should be chosen based on a trade-off between visual appeal, information, and technical constraints such as rendering time (Hermans 2015).

In addition, Sinclair (2012) has presented the specification and design of a consumer design toolkit:

Table 4-2 Table of guidelines for designing a consumer design toolkit (Sinclair 2012)

Detail design specifications		
AM-enabled	Parameter-based	Maximum realism visualisation
Containing library of modules and producibles	Direct manipulation	Including price feedback
Considering type of modularity	Produced by manufacturer	Containing library of other user's design
Include design tools, such as scale, etc.	Checking the manufacturability	Complemented with peer input
Extent of customisation	Web-based without installation	Non-linear navigation

Other new guidelines were discussed next. A report by 3D Gateway company on customisable products identifies a number of factors to consider while implementing a MC toolkit. It is divided into 5 different categories: product management system, website personalisation app, e-commerce website, auto artwork creation, and order & workflow management. The table below gives the guidelines in each category.

Table 4-3 Important factors for toolkit implementation based on Gateway report (Gateway3D 2015)

Categories	factors
Product Management System	- Choose a base image to personalise - Add image areas with image resolution checking - Add product colour or texture options - Add galleries of images or patterns

	● Add text areas and specify fonts, font sizes and font colours ● Add predesigned templates ● Select effects to represent different decoration methods ● Select other variables such as size ● Add backgrounds and thumbnail images ● Set up different print output options
Website Personalisation App	● Ability to connect to social images sources such as Facebook, Instagram, Flickr, Google+ ● Ability to measure the quality of images uploaded ● Tools to manipulate text and images ● Ability to auto format text to fit boxes ● Ability to curve and move text ● Option to have multi-sided or 3D products ● Ability to save products as well as add them to basket
e-commerce Website	● Add product purchasing capability to the website ● Add design saving capability to the website
Auto Artwork Creation	● Sublimation, digital & DTG Print - jpg, png or pdf ● Engraving - eps or svg ● Embroidery - good quality image to create dst ● Transfer - vector cut line around pdf ● Product configurator - parts list
Order & Workflow Management	● Batching orders by product type ● Auto resizing artwork ● Barcode scanning to confirm processes completed ● Carrier integration ● RIP software Integration ● Customer & retailer notifications

There are five key principles by Randall et al. (2005) which provide design guidelines for MC toolkits:

1- Customise the customisation process. Two different types of UI should be provided to the users: a need-based interface for non-experts and a parameter-based one for experts.

2- Provide starting points. The MC toolkit can provide an initial design from which the customer can continue his/her configuration. Furthermore, the initial design can be differentiated for each customer based on his/her preferred product properties.

3- Support incremental refinement. A product comparison can be provided in order to provide alternatives intuitively to visually show trade-offs between different properties.

4- Exploit prototypes to avoid surprises. Since the utilisation of the product's evaluations is often impossible due to configurations being unique in many cases, the toolkit needs to help the customers to anticipate the post-purchase experience. This can be implemented by features such as using the product virtually or enriched visualisation.

5- Teach the consumer. The customers need to be provided with technical background knowledge in order to increase their personal product domain knowledge. This can be done by providing a help button on the UI. This can help users in two ways: informing them of the reasons why a concrete configuration has been recommended, and explaining to users in situations where no solution can be found by the configuration system.

By analysing 800 online configurators the basic characteristics were detected as follows:

1- the summary of selected components should be available at the end of configuration process

2- Image of products, available for configuration, should be presented

3- Process navigation, if available, is structured on a horizontal plane

4- Choice fields are positioned next to and/or beneath the product picture

5- The visibility of the shopping cart, order button, and total price are clear

(Felfernig et al. 2014)

Based on a configurator application, which has taken into account the aforementioned characteristics, the important hints for designing an individual configurator UI are:

1- The logo should be put in a dominant position which is quickly identifiable

2- The navigation bar should be clearly visible and not shown as fragmented

3- In order to see the detail, the size of the image of the product for configuration should be sufficient

4- A logical clustering should be followed to present selection box(es)

5- In all steps of a session, price (price tables) should be accessible

6- Users should be able to adapt their preferences (e.g. by back/forward navigation)

7- For completion purposes, a shopping cart and order-button should be available

Finally, more detailed discussion on usability issues from Rogoll and Piller (2004) are as follows:

1- Operability and self-explanation. The configuration steps should be built up logically, to makes it obvious how to navigate through the configuration process. The configuration system should be impressive with intuitive handling and navigation, and create the feeling of success as users go through the configuration process.

2- Customer orientation. The whole proposal and functionalities that the system offers should be given to the customer. For this purpose, transparency and traceability of the software is necessary for acting fast, and being provident and goal-oriented.

3- Individual access to information. In order to make the information accessible to the user in any possible access method, which enables them to process, accumulate, and retrieve information in their own way, different kinds of textual, visual, alphabetical, numerical, chronological or geographical information should be provided.

4- Loading time. Since most of the users access high-speed internet, it does not play an important role. However, the visualisation or actualisation after the configuration step should not take too much time for loading.

5- Support. Support for the configuration system can be provided for customers to deal with possible problems and not just to give extra information; however, it is naturally a requirement for the system to be used without any help needed.

These are general guidelines, and a specific guideline for AM-enabled MC toolkits from the users' point of view to improve UX is still lacking. That is, a design team has some tools in hand to decide firstly the feasibility of creating an AM-enabled toolkit, and then consider the features needed for creating a user-centreed interface.

4.20 The Anatomy of MC Toolkits

The anatomy of a MC toolkit is an area that has received little attention. According to research on this area, some information has been derived from evaluation of 111

current online configurators in one research study (Abbasi et al. 2013), and 126 online configurators in another (Streichsbier & Blazek 2009).

In the former research, a set of methods, guidelines, languages, and tools to systemically engineer sales configurators were developed. First, the GUI elements of the toolkit (characteristics) were identified in three categories: configuration options, constraints, and configuration process. Good and bad practices on these topics were reported. All the toolkits were reverse engineered by an add-in extension for Firefox called Firebug (Mozilla Foundation). Since Firebug does not support Flash, all the toolkits, which were based on Flash, were eliminated. The elements are explained as below:

1- Configuration options: the most popular widgets are observed as a combo box, image, radio button, check box, and text box. In some examples, some of these widgets have been combined. Less frequent widgets include slider, label, file chooser, date picker, colours, picker, image needle, and grid. Some of the options are joined together to form a group of items. There are two kinds of these groups, alternative (in which one and only one option has to be selected), and multiple choice (in which a minimum of one option has to be selected). Cloning is another option for sales configurators, for which it can be determined how many instances of an option are preferred for the final product.

2- Constraints: the first group is formatting constraints: type correctness, range control, formatted, and case-sensitive values. It has been observed that sales configurators have two different patterns for checking constraints violation. The first is to prevent illegal values, and the second is to highlight, correct or remove them .

3- Configuration process: the GUI elements of the configuration process include single step (all the options are displayed in one graphical container), basic multi-step (options are displayed across different graphical containers), and hierarchical multi-step (the same as the former, with inner steps). Activation of options is divided into two groups: step-by-step activation (not all the options are available from the beginning), and full-step activation (all the options are available from the beginning). Another important characteristic of sales multi-step configurators is backward navigation: the ability to navigate backward while the product is being customised. These characteristics have been divided into two: a stateful and a stateless arbitrary pattern. In the former, the data is saved by navigating back to the previous page but not in the latter.

The bad and good practices of the 111 configurators in Abbasi et al. (2013) are as follows:

Bad practices:

1- Absence of propagation notification; appearing/disappearing or enabling/disabling options without any notice, making the configuration process confusing especially for a multi-step model. It is better to inform users of their decisions.

2- Incomplete reasoning; some of the configurators do not check if the mandatory options have been selected and/or formatting constraints are right.

3- Stateless backward navigation; in some instances, when navigating back, the data is lost. This is a very important defect, because most of the time users make mistakes, and need to correct them.

4- Decision revision; this downfall is that the user cannot revise his/her decision, for example uncheck his/her selection or go back to correct his/her input. Therefore, he/she needs to start from scratch.

Good practices:

1- Guided consistency checking; only a few of the sales configurators assist users during the configuration process, for instance, by providing explanations, or identifying conflictual decisions. This will improve the usability of the GUI.

2- Auto completion; this is an advantage that allows the sales configurator (SC) to auto complete the options that are mandatory or undecided. This is good when only some of the options are favorable for the user.

3- Self-explanatory process; the SC should provide clear guidance through configuration. Different guidance strategies have been observed: previous and next buttons, permanent display of selected options, a list of complete/incomplete options, etc.

4- Stateful backward navigation and undo; In contrast to some of the SCs that were discussed, some of them allow the user to navigate back to previous steps without losing data, so they will be able to undo their selections (Abbasi et al. 2013).

In the other research study, Streichsbier & Blazek (2009) investigated whether a de-facto design standard for MC toolkits exists, and if so, how to identify it. A de-facto standard is said to exist if a given web-element is designed in the same way on 80% and more of websites (Nielsen & Loranger 2006).

The following conventionally used web objects were chosen for analysis: logo, help-button, horizontal navigation bar, product image(s), selection box(es) used for the configuration process, prices and/or price tables, back- and forward-buttons, shopping cart, and order-button. The grid-based method (Figure 4-10) was employed

for recording the exact position of these web objects of the 126 chosen sales configurators.

11	12	13	14	15	16	17	18
21	22	23	24	25	26	27	28
31	32	33	34	35	36	37	38
41	42	43	44	45	46	47	48
51	52	53	54	55	56	57	58
61	62	63	64	65	66	67	68
71	72	73	74	75	76	77	78

Figure 4-10 The 8-by-7 analysis grid allows web objects to be classified and compared according to their position on the screen. (Streichsbier & Blazek 2009)

In this method, the configurator screens were put on this grid, components' position were recorded and their frequency of appearance was analyzed. (Figure 4-11)
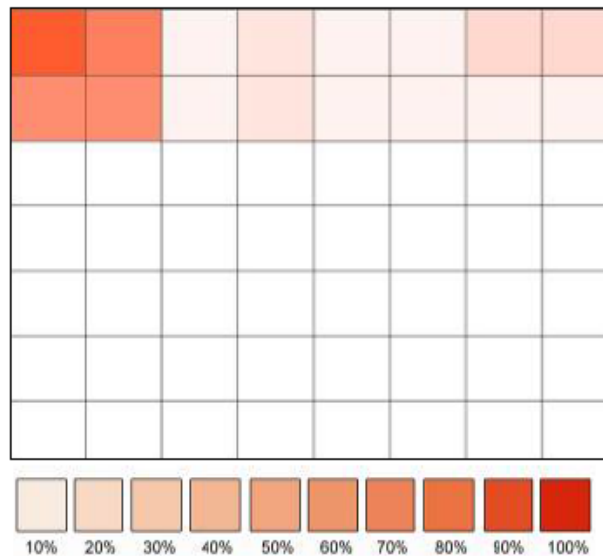
Figure 4-11 An example of frequency analysis for a web object: 'product picture' (Streichsbier & Blazek 2009)

The findings show that there is a lack of standard or universal norms for these UI. The web objects do not have a frequent position on their interfaces. To some extent, the absence of standards is due to the requirements for configurators differing from industry to industry (Streichsbier & Blazek 2009).

4.21 Features of mass customisation Toolkits

A list of features of MC toolkits was gathered in one place by reviewing related articles, different CAD software programs and MC sales websites Table 4-4. The collected features along with their definitions are listed below:

Table 4-4 Collected MC toolkit features

Collected features	Brief definition
Visual feedback (Hermans 2011)	*feedback regarding visualisation of 3D model of the product once a modification was made to it*
Virtual use of object (Saul et al. 2011)	*using the object virtually during or after customisation in order to find any faults or see how it works*
Guidance (help in using the system) (Randall et al. 2005)	*help in using the system*
Technical information (Dell 2014)	*providing information based on products' specifications to ease the process of decision making for customers*
Validation with feedback (Hermans 2011)	*providing information regarding compatibility check and/or any physical or technical faults*
Physics providence (Igarashi 2010, SketchChair 2011)	*providing information about products' choices based on physics law*
Reference object (Hermans 2011, Hermans 2012)	*an object to be accompanied with the customizable product as a reference in order for comparison or colour/size matching*
Starting point (template or blank canvas) (Hermans 2011)	*the place or point from where customers start their design*
Click and show option (Opel 2014)	*the extent to which the interface or customisation process is interactive*
Price update (Hermans 2011)	*feedback regarding the price once a modification is made to the product's variable attributes*
Need-based or parameter-based (Randall et al. 2005)	*demonstrating the way, which the variable attributes are exposed to the customer; either based on relative importance of their needs or the product's design parameters* (Randall et al. 2005)*; for example, choosing a CPU speed for a PC is parameter-based customisation but choosing how fast a program runs on a PC is need-based customisation*
Mechanism (Hermans 2012)	*an enabling technique to gain the high-level process flexibility needed for offering MC* (Hermans 2012)
Users' design access (Franke et al. 2008)	*libraries of other users' products' design*

Selecting manufacturing and assembly method (Hermans 2011)	*selecting how the product is manufactured or assembled*
Material selection (Hermans 2011)	*selecting material for the product or part of the product*
Libraries of modules and producible (Hermans 2012)	*libraries of manufacturer's suggested product variants*
Input type (Hermans 2011)	*the way the variable attributes are exposed based on interaction mode*
Input method (Hermans 2011)	*the device or way in which the data is entered*
Web-based (Nervous System 2014) or Store-based (YouTube 2014)	*the place or environment where the MC is done*
Offline access (AutoCAD 2014)	*the ability to access the toolkit interface and work along if the internet disconnects*
DoF (Hermans 2012)	*the extent to which variable attributes can be varied* (Hermans 2012) *(the number and variety of options)*
Side by side comparison (Trentin et al. 2014)	*ability of a sales configurator to support its users in comparing product configurations they have previously created* (Trentin et al. 2014)
Flexible navigation (Trentin et al. 2014)	*Flexible navigation capability is the ability of a sales configurator to let its users easily and quickly modify a product configuration they have previously created or the one they are currently creating* (Trentin et al. 2014)

As discussed previously, current guidelines for MC toolkits do not consider users explicitly in their definitions, and a standard layout of these toolkits is lacking. These features were then used to find out about the preferred content and layout of MC toolkits based on user perspectives.

4.22 Summary

In this chapter, the MC paradigm has been extensively explained and explored in term of consequences, benefits, success factors, etc. The success factors of MC, including product, customer, organisational, and industry factors, are given. Therefore, based on the product factors explained previously, a lampshade was chosen as the product for the prototype toolkit, developed for the second study (objective 1).

MC toolkits are explained and explored in term of types, advantages, solution space, etc. The solution space was discussed as the area in which companies offer the available options for customisation to the customers, and extract the user preferences in reverse (objective 2). The trade-off between autonomy of customers, authority of designers, and brand identity regarding the solution space is explained in

terms of DoF. The three common and important elements of navigation, feedback, and guidance are considered for MC toolkits in this research. These elements are comprised of features, which are investigated further in this thesis in Chapter 6 and Chapter 7. All the collected features from software programs, online sales websites, and current MC toolkits are presented (objective 3).

The highly cited specifications for MC toolkits from Von Hippel (von Hippel & Katz 2002), alongside guidelines from Hermans (2015) and Sinclair (Sinclair 2012) were discussed. In addition, details of other guidelines and principles for designing MC toolkits were included. Guidelines regarding the layout of MC toolkits were explained with reference to two studies. It was also mentioned that the web objects do not have a frequent position on these toolkits, which indicates the importance of investigating about their layout (objective 4).

Chapter 5 :   Methodology

5.1 Introduction

This chapter starts by presenting the research questions and the justifications of how they were identified. An explanation of design research is then given, together with its relationship to the DRM (Blessing et al. 2009) and design. It is also explained how the DRM suggests the use of a design process to do part of the research. Next, the DRM framework is shown, and different study types for the framework's stages are explained, followed by an explanation of the associated ethical considerations. At each stage, the direction taken by this research is explained.

This chapter's objectives are to:

1- Explain and distinguish between design research and the DRM
2- Justify the integration of the design process into this research
3- Provide the research questions and associated thesis structure
4- Explain what quantitative, qualitative, and mixed research methods indicate
5- Justify the research methods used for each study
6- Explain specific ethical considerations for the studies

5.2 Design Research

Design research is defined by Horvath (2001) as knowledge generation about design and for design. Design research was not considered as a topic, with its own body of knowledge and differences to other sciences, until the second half of the 20th century. Design research has passed three overlapping phases: the experiential (1950s), intellectual (1960s-80), and experimental (1980s-now) (Blessing et al. 2009). It is in the current phase, that empirical studies are being undertaken in order to find out more about how designers and design teams work (Blessing et al. 2009). Design requires a bank of knowledge as well as the appropriate tools and methods. In most of the cases, the knowledge is not available, which leads to two options: relying on assumptions while minimising the risk, or undertaking research (design research) to generate the knowledge (Blessing et al. 2009). The latter is the case in this thesis. A methodology for design research needs to identify the approach or method required to guide the research and encourage reflection on the approach and methods to be used. Figure 5-1 demonstrates a good explanation of the relationship between DRM, design research, and design:
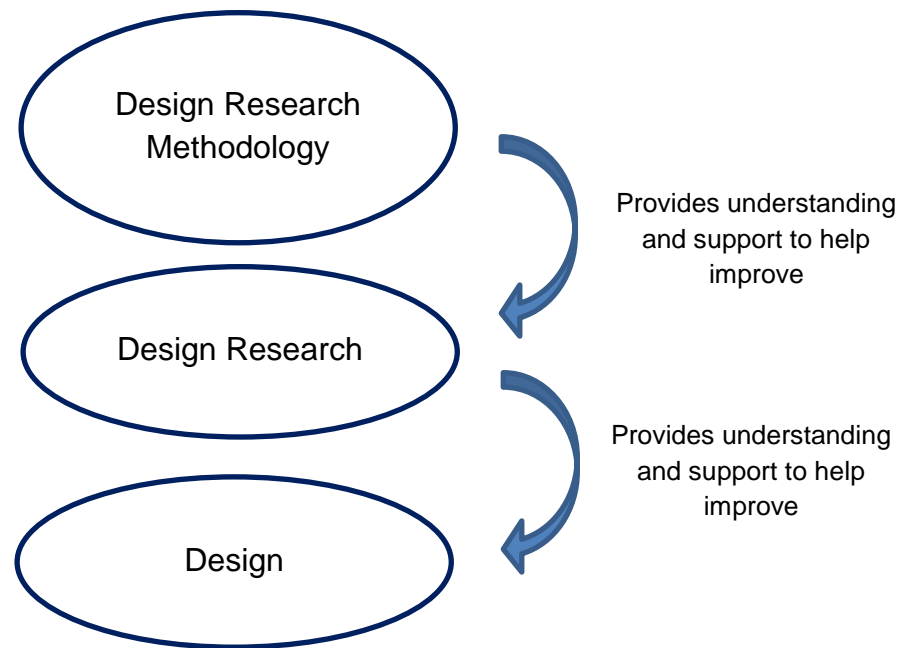
Figure 5-1 The relationship between design, design research, and design research methodology (Blessing et al. 2009)

DRM suggests a design process should be followed in order to extract data, and support (and evaluate data), which was done here.

5.3 Design Research Methodology

DRM (Blessing et al. 2009) consists of four stages: research clarification, descriptive study I, prescriptive study, and descriptive study II. Figure 5-2 shows the links between these stages, the main outcome, and iterations. In the research clarification, the researchers specify a realistic and meaningful research goal based on some evidence or at least indications that support their assumptions. In the descriptive study I, researchers review the literature further for influencing factors to elaborate the existing situation. This is done to improve task clarification as effectively and efficiently as possible by identifying the factors that need to be addressed in detail. In the prescriptive study, the researchers improve the quality of the problem definition through developing various possible scenarios by varying the targeted factor(s). In the descriptive study II, the desired situation is realised through investigating the impact of support and its ability.
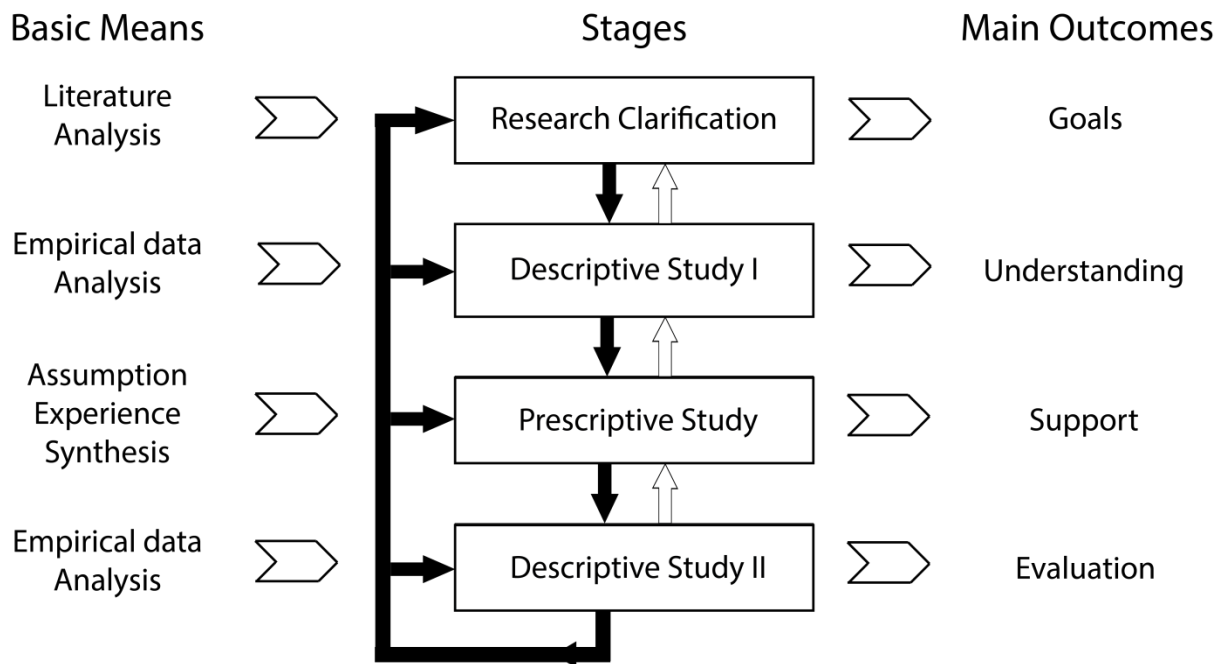
Figure 5-2 DRM framework

Each stage can be done by three types of studies: review-based study, comprehensive study, or initial study. A review-based study is only based on a literature review. A comprehensive study is based on a literature review, as well as a study in which results are produced by the researcher. Finally, an initial study concludes the results to be used by others, closing a project and bringing a few initial steps of a stage to show the consequences of the result.

Based on the selection of each study type for each stage, there are seven possible types of design research. These are ranked in terms of resources and time required. A few projects were seen as type 1 and 4. Most PhD projects are considered to be type 5 and 6, however, the barriers of time and resources limit the research project, and they usually end up as type 2 or 3. In type 7, three stages are taken in depth, which requires a group of researchers to be working on a project. Table 5-1 below shows all the possible types of design research projects:

Table 5-1 Types of design research projects

Research Clarification	Descriptive Study I	Prescriptive Study	Descriptive Study II
1. Review-based ⟶	Comprehensive		
2. Review-based ⟶	Comprehensive ⟶	Initial	
3. Review-based ⟶	Review-based ⟶	Comprehensive ⟶	Initial
4. Review-based ⟶	Review-based ↗	Review-based ↘ / Comprehensive/ Initial ←	Comprehensive
5. Review-based ⟶	Comprehensive ⟶	Comprehensive ⟶	Initial
6. Review-based ⟶	Review-based ⟶	Comprehensive ⟶	Comprehensive
7. Review-based ⟶	Comprehensive ⟶	Comprehensive ⟶	Comprehensive

Considering the type of studies needed to be done for this research, type 3 was most suited, and therefore selected. The literature review was done as the research clarification stage and is review-based. The first study was considered as the review-based stage since it was based on only the literature review. The workshop and the second study count as comprehensive since the data from the literature review as well as the data obtained from the studies (first study and workshop) were used. Finally, the third study is considered as the initial study due to concluding the results to be used by others, closing the project, and showing the consequences of the results as a validation of the framework. This was demonstrated in the table below.

Table 5-2 Demonstration of the selected study types for each stage of DRM framework

Research Clarification (Literature review - Chapter 2, 3 and 4)	Descriptive Study I (Study 1 - Chapter 6)	Prescriptive Study (Workshop and Study 2 – Chapter 7 and 8)	Descriptive Study II (Study 3 - Chapter 9)
Review-based	Review-based	Comprehensive	Initial

5.4 Design Process and Design Research Methodology

This research's main inquiry is what implications users' perspectives will have on the design of MC toolkits. Therefore, as mentioned previously, the research will provide knowledge for design, and can therefore be considered as design research. However, design research also embraces studies and experiments, which lead to finding or improving design processes. Therefore, the DRM was followed to help clarify the path to follow in relation to design.

Looking at the main outcomes of the DRM framework (Figure 5-2), it can be seen that it is similar, in some ways, to a design process. It suggests that the first stage of the research should be a literature review undertaken to identify the research questions (the goals). Next, to understand the user perspective as the main aspect of this research, the user requirement, as one of the minimum requirements of user involvement, should be acquired (Study 1 and the workshop). Next, this understanding should be supported by an assessment and as indicated previously as one of the minimum requirements of user involvement, usability evaluation is required (Study 2). These three studies show similar stages of a design process, which starts with understating/stating user requirements, proposing a solution, and evaluating the solution. Therefore, the design process is easily identifiable from the first study, the workshop and the second study (Figure 5-3).
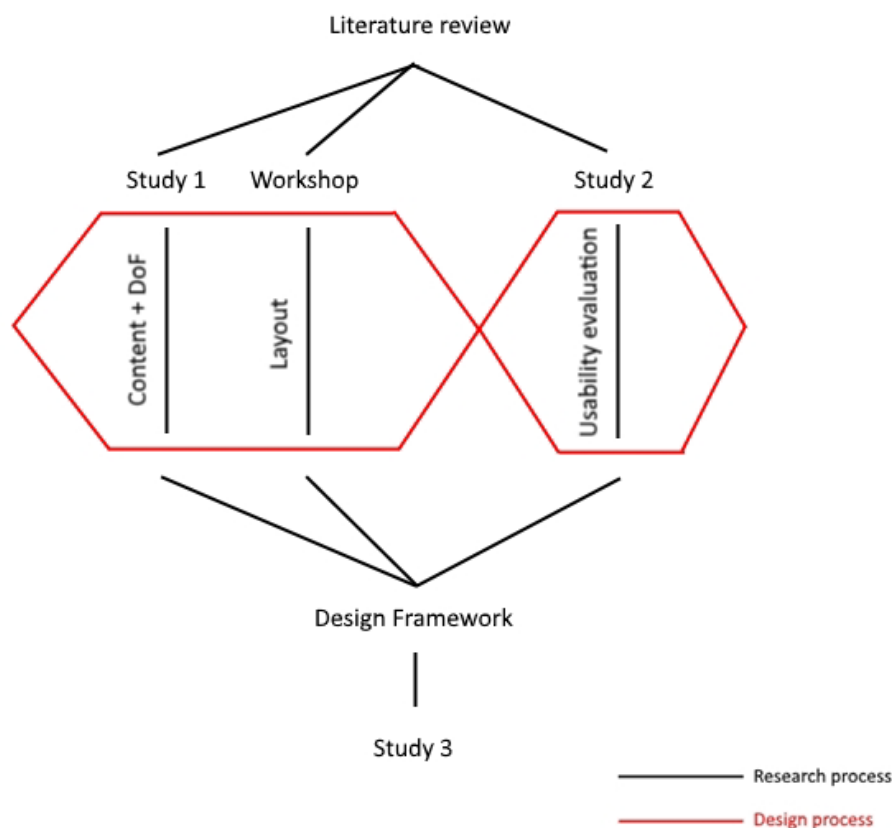
Figure 5-3 The integration of design process into this research

The data extracted, supported (and evaluated) throughout the studies were based on user research. Therefore, the process followed throughout study 1, the workshop, and study 2 simulates a user-centred design process or in other words is based on UX design. By simulating UX design within the studies, not only was the design knowledge for user-centred AM-enabled MC toolkits obtained, but also insights could be obtained regarding the other parts of design research which are related to design processes.

This approach that was generated, and presented in this thesis, can be readily applied as a method for similar research in the area of MC toolkits. This can be used in other research in the area of MC toolkits to enrich the data generated through this research to complete the framework or even generate a new one, for a specific product or product category.

5.5 Research Questions and Direction

This research was completed to acquire users' perspectives on AM-enabled MC Toolkits. The literature review showed that there was a lack of design knowledge on MC toolkits and that current guidelines for their design are relatively generic. Some research has been done around the idea of creating a model for evaluating MC toolkits and, more relevantly setting an agenda for user interaction with MC toolkits, but not from a user perspective (Hermans 2011, Franke & Piller 2003). The literature review also showed that although similar research is currently being undertaken to explore the design of MC toolkits, the concept of AM-enabled toolkits is quite recent and has not yet been explored through a UX design approach. In the commercial domain, AM-enabled toolkits are very new and their availability is limited.

As identified previously, there is a lack of standards for the layout of the UI of MC toolkits (Streichsbier & Blazek 2009). For AM-enabled toolkits, the author first had to acquire user data on the preferred content and layout of the toolkits (hence research question 1). This was followed by implementing and evaluating these in an actual toolkit (as suggested in the DRM). One of the most important and intriguing aspects of these toolkits, the DoF, required a separate investigation, supported by the fact that it was predicted that there is an optimum number of options for each toolkit from a customer's perspective (Schwartz 2009) This is the focus of research question 2. Creating the toolkit also required investigation into appropriate methods of implementation, as different approaches are currently available, such as CAD software programs, 3D-enabling libraries, etc. (hence research question 3). Once created, evaluation of the toolkit enabled its advantages and disadvantages from the user's perspective to be determined (research question 4). Finally, all the acquired findings needed to be communicated to designers through a design framework referred to as design knowledge for user-centred AM-enabled MC toolkits (research question 5). Therefore, the following five research questions were proposed to enable the objectives to be met:

Research Question 1 – Which features are most important for user-centred AM-enabled MC toolkits, and in what layout?

Research Question 2 - How many options are appropriate for a user-centred AM-enabled MC toolkit?

Research Question 3 - Which CAD or 3D-enabling system is most suitable for the implementation of AM-enabled MC toolkits?

Research Question 4 - What are the advantages and disadvantages of an AM-enabled MC toolkit from the user's point of view?

Research Question 5 - What guidelines do designers and software developers need to take into account when designing user-centred AM-enabled MC toolkits?

Therefore, as shown in Figure 5-4, the first study and workshop were required to collect the data that was used for the implementation of the prototyping AM-enabled toolkit, as well as for gathering user insights for the design framework. All the data from the studies and workshop (along with available published data from other researchers) was presented in the form of a web-based framework. This was validated in the final study with designers and a software engineer. This process is demonstrated in Figure 5-4. This methodology can be readily adapted for doing research on other MC toolkits.
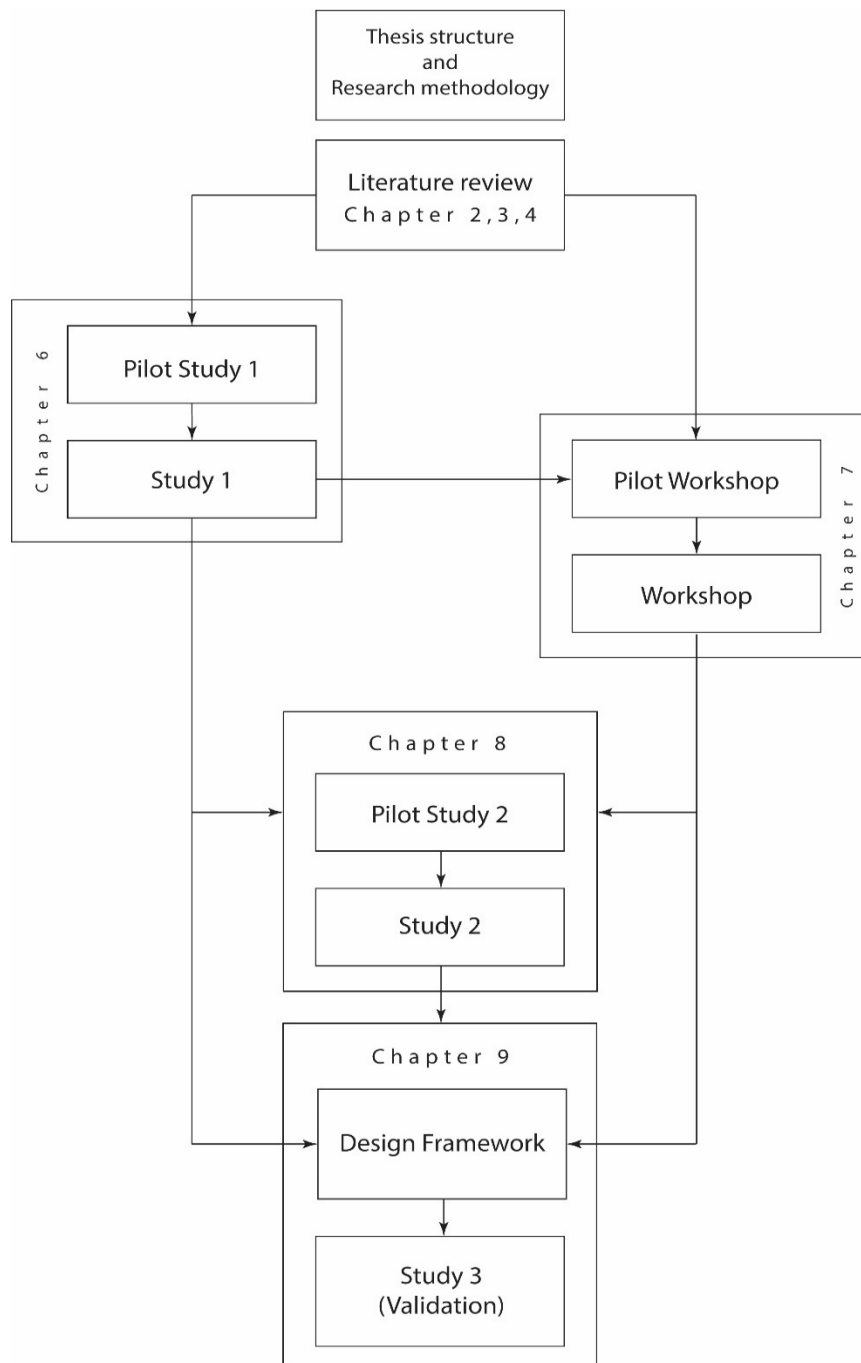
Figure 5-4 Research methodology

Regarding the timeline for the studies and for other actions throughout this research, a timetable is presented in Table 5-3.

Table 5-3 Timetable of the research

PhD Degree Timetable

		2013		2014				2015				2016				2017	
Year / **Tasks**		July-Sept	Oct-Dec	Jan-Mar	Apr-Jun	July-Sept	Oct-Dec	Jan-Mar	Apr-Jun	July-Sept	Oct-Dec	Jan-Mar	Apr-Jun	July-Sept	Oct-Dec	Jan-Mar	Apr-Jun
						writing						Final Writing up					
Year 1 (Regular meeting with supervisor each week or two weeks)	Student registration and induction	▨															
	Formal research plan	▨	▨														
	Lit review and critique of methods	██ (red)	██ (red)	██ (red)	██ (red)	██ (blue)	██ (blue)	██ (blue)	██ (blue)								
	Poster at DesRes			▨													
	Pilot Study			██ (grey)													
	First year research report				▨												
Year 2 (Regular meeting with supervisor each two weeks)	Study 1						██ (purple)										
	Toolkit Implmentation 1							██ (green)	██ (gold)								
	Pilot Workshop								██ (brown)								
	Workshop									██ (brown)							
	Open research presentation to staff and students							▨									
	Second year research report (thesis outline)								▨								
Year 3 (Regular meeting with supervisor each three weeks)	Study 2									██ (blue)							
	Design framework										██ (purple)						
	Validation											██ (black)					
	Open research presentation to staff and students												▨				

Notes (milestones):
- End of year 1 independent review meeting (2014 July-Sept)
- End of year 2 independent review meeting (2015 July-Sept)
- Intention to submit form submittion (2016 Oct-Dec)
- Soft bound copy of thesis submittion (2016 Oct-Dec / 2017 Jan-Mar)
- Hard bound copy of thesis submittion (2017 Apr-Jun)

73

5.6 Research Approaches

Research methodology makes the decisions that researchers need to make clearer. The methodology involves procedure of inquiry, and specific methods of data collection, analysis, and interpretation. There are three research approaches for each study in the methodology: qualitative, quantitative, and mixed methods. They are not as discrete as they may seem, because qualitative and quantitative represent different ends of a continuum (Creswell 2009). As noted by Newman and Benz (1998), rather than representing bi-polar opposites, quantitative and qualitative research represent an interactive continuum. Quantitative methods aim to test and modify theories, whereas qualitative methods aim to build and initiate them. A study may tend to be more qualitative than quantitative or vice versa. Quantitative methods tend to use numbers rather than words, in which the qualitative method is framed. In the qualitative method, open–ended questions (interview questions) are used, but in the quantitative method, closed questions (surveys) are incorporated. The difference is more obvious when researchers assume the basics for their studies, for example the experiments or case studies that are intended, and the specific method that is used to conduct the research, e.g. collecting data through instruments or through observations (Creswell 2009). Mixed methods exist in the middle of this continuum since it uses both methods (Johnson et al. 2007). Table 5-4 summarises and explains this continuum better:

Table 5-4 The continuum of research approaches; quantitative, mixed, and qualitative methods (Creswell 2009)

Quantitative methods	Mixed methods	Qualitative methods
Pre-determined	Both predetermined and emerging methods	Emerging methods
Instrument based questions	Both open- and closed-ended questions	Open-ended questions
Performance data, attitude data, observational data, and census data	Multiple forms of data drawing on all possibilities	Interview data, observation data, document data, and audio-visual data
Statistical analysis	Statistical and text analysis	Text and image analysis
Statistical interpretation	Across databases interpretation	Themes, patterns interpretation

The qualitative and quantitative camps tend to focus on their differences rather than their similarities (Onwuegbuzie & Leech 2005). As indicated by Onwuegbuzie & Leech (2005), a false dichotomy exists between quantitative and qualitative research.

Qualitative research is the way for identifying the meaning and views, individuals or groups have toward social or human problems, while quantitative research is the way to identify the relative importance of variables or relationship among parameters. In quantitative research, there are two major strategies of inquiry: survey research and experimental research (Creswell 2009). In surveys, data collection is performed by studying a sample of a population through providing a quantitative or numeric description of trends, attitudes, or opinions of a population. In experimental research, data is collected within an experiment on potentially multiple groups of a population (usually by providing a specific condition to one group and withholding it from other) and then statistically analysing the obtained data (Creswell 2009).

Both methods incorporate analytical techniques to obtain the maximal meaning of their data. They both try to identify complex relationships and situations in the social science field. In this way, qualitative researchers apply thick and rich collected data into the design with prolonged continuous observation and long engagement, whereas in quantitative research, researchers use multivariate techniques.

Which approach should be taken? Well, it depends on the question, the research is attempting to answer. The quantitative approach is the best way to examine an explanation or theory, on the other hand, if little research has been done on a concept or phenomenon then it is worth using a qualitative method. For example, a researcher may first find out what variables to study using qualitative methods, and then explore more by studying a large sample of individuals to find the relative importance of the parameters (Creswell 2009).

5.7 Overview of Research Approaches in this Thesis

Table 5-5 gives an overview of what approach(es) is/are used to do data collection and analysis for each study or workshop. The method(s) applied to each study and workshop are shown in Table 5-4 as well as the participant's type and their number of studies. This thesis embraces qualitative, quantitative, and mixed methods research approaches to get the preferred result.

What kind of information is needed, from whom and under what circumstances is the basis of method selection. The data collection method needs to be decided on from the early stages of the project, even in flexible ones. Many methods are available, such as interviews and questionnaires to find out what people do in private or to find out what people think, feel or believe (attitude scales are also used for the latter); direct observations to find out what people do in public; and standardised tests to determine people's abilities, intelligence or personalities (Robson 2002).

The chosen method also needs to be within the constraints of available time and resources. The selection of each method is also explained later in each chapter. All the participants indicated in the table are affiliated with the Design School.

Studies	Methods applied	Participants	Data Collection and analysis
Study 1 (Content of MC Toolkits)	Customer survey	30 user individuals	Quantitative
Workshop (Workshop)	Focus group	10 user individuals	Quantitative
Study 2 (Usability and User Interaction of MC toolkits)	Observation/ Attitude survey	10 user individuals	Mixed
Study 3 (Validation of the Design Framework)	Interviews	3 designers and 1 software engineer	Qualitative

5.8 Ethical Considerations

The second major concern that needs to be addressed before designing a study and after reviewing the literature is about ethics. Ethics defines what moral research procedure should be involved. There is a statement on what is proper and improper behaviour to guide professional organisations and research practice in an ethical way according to a code of ethics. The ethical checks should be taken care of as soon as the study is designed. One important note about ethical conduct is that even if the research subjects were unaware or unconcerned about ethics, researchers need to prepare themselves and consider ethical concerns. There should be a balance between advancing knowledge against the value of non-interference in the lives of others. Since the two main methods of data collection in this research are survey and user observation, ethical considerations are discussed here (Newman & Benz 1998).

Survey research is the most widely used social research technique. In survey research, invasion of privacy is the major ethical issue. In order to not intrude into respondents' privacy, the following notes should be considered:

1- Respondents should not be asked for intimate actions, personal beliefs, and personal information

2- Respondents should be treated with dignity and minimising discomfort

3- The responsibility for protecting the confidentiality of data belongs to the researcher

4- The participation of respondents should be voluntary: a consent form needs to be given to respondents and they are allowed to withdraw from the study at any time

5- The survey should not be used as a pseudo-survey: an attempt to persuade someone to do something, with little or no real interest in learning from respondents.

6- The survey must not be poorly designed or purposely rigged: a limited survey must not be performed in terms of answers the respondents can choose. The results must not be misused.

(Newman & Benz 1998).

As mentioned above, the other technique that was used in this research is observation. As it is similar to field research, the ethics considerations for field research were amended to be used for my research. In essence, the concerns that are raised in field research are more significant than simple observation (lab testing) (Redmond-Pyle & Moore 1995). The difference is that instead of observing participants in their own workspace and realistic situation, the research objects are brought to a prepared environment or a lab for observation. This simplifies some of the concerns that are related to field research. The considerations for observation are amended as follows (Newman & Benz 1998):

1- Deception. There are two kinds of field research: covert and overt. The choice between them and justification of covert research is in the hand of the thoughtful and knowledgeable researcher. Covert research is never easier or preferable to overt research.

2- Confidentiality. The intimate knowledge, personal information, and beliefs, that the participants provide, should be kept confidential. This includes disguising participants' name in the notes and data publications.

3- Involvement with deviants. Researchers who conduct observation on people should be careful about who is being observed. The people who are being observed must not engage in illegal, immoral or unethical activity or behaviour, which may cause further dilemmas for researchers.

4- The powerful. For prevention of bias, the powerful, and less powerful - street people, the poor, children, and lower-level workers - all need to be involved or at least free to be involved in the research. However, immersion of researchers in the world of less powerful people, which expresses a rarely heard perspective, may raise the issue of bias.

5- Publishing reports. There is a balance between the right to know and the right to privacy. The researcher must be careful about publishing anything that might offend or harm someone. Instead, what has been learned stays hidden, the report may just be limited, and the confidential data must be omitted.

Therefore, the use and misuse of knowledge and its truthfulness depend on researchers (Newman & Benz 1998), who ultimately need to conduct research in an ethical and moral manner, by considering what is or is not legitimate to do. Each study chapter contains a section specifically for ethical concerns. The required ethics checklist and further considerations are discussed in those sections respectively.

5.9 Summary

At the beginning of this chapter, an overview of design research and the DRM were given, including: 1) the relationship between design, design research, and the DRM, 2) the DRM Framework, and 3) different design research approaches based on choosing different types of study for the stages in the DRM framework. It was explained that type 3 design research (as shown in Table 5-1) is the closest fit to this research (addressing objective 1).

Use of a design process to conduct part of the studies was justified based on the DRM (addressing objective 2). Afterwards, the research questions were presented (addressing objective 3). Next, research approaches (quantitative, qualitative, and mixed) were discussed (addressing objective 4). It was also stated that quantitative, qualitative, and mixed research approaches were all needed to address the five research questions (addressing objective 5). The details of the application of each method for each study will be explained in later chapters. The ethical considerations for the two main methods of data collection (surveys and user observation) were explained (addressing objective 6).

Chapter 6 :   Study 1 – Content of MC Toolkits

6.1 Introduction

Many companies, when confronted by the new era of manufacturing i.e. MC, recognise the need to stay competitive, and have to adopt new methods and strategies. However, the fast-changing nature of competition requires companies to react quickly to it with new approaches. One of the ways that companies respond to MC and try to incorporate it, is by providing MC toolkits for customers (Trentin et al. 2014). However, these interfaces have not been analysed and developed thoroughly in order to be efficient and effective from users' points of view.

Each MC toolkit has its own characteristics (Abbasi et al. 2013). By reading articles about MC toolkits, CAD software programs and MC sale websites, it is possible to find out many specifications that have been created, used or suitable for MC toolkits. They have been applied to the MC toolkits to a greater or lesser extent. One article, which has collected a number of these specifications into one place, is entitled 'A comparison of MC toolkits for consumer product manufactured by Additive Manufacturing' by Guido Hermans. In this article, the author aimed to determine the criteria that define the generic process of the co-creation approach to use, for future development of MC toolkits (Hermans 2011), by comparing the criteria. This comparison helped developed an understanding of MC implementation, and the article's collection of specifications was considered and amended. As a part of the analysis of these toolkits (and solution space design process), the features that need to be chosen for a MC toolkit must be identified. Having all of them in a MC toolkit may be not feasible due to mass confusion, or 3D CAD software limitations or incapability. In this thesis, instead of specifications, the term 'feature' is used to indicate small chunk of each toolkit. Furthermore, this process of identification should be done by the users of the MC toolkits. Therefore, all of the features as mentioned above were collected for this study, and were ranked in order of importance by the participants.

6.2 Aim and Objectives

There are many features that can be collected from available resources (articles. CAD software programs, and MC toolkits), or devised newly. By considering those resources, many features such as visualisation feedback, price update, side-by-side comparison, etc. were obtained. On the other hand, the term 'click and show option' is a newly coined feature by the author through looking at a MC toolkit (Opel 2014). All of the collected or the new ones were listed in Table 4-4..The aim of this study is to find out which of these features play a more important role in MC toolkits based on the views of customers. Therefore, the specific objectives of the study are as follows:

1. Identify which features customers would prefer to be included in a toolkit (the content of MC toolkits)

2. Find out in detail how many options in solution space are preferred by customers

3. Explore any potential relation between different features and DoF

4. Identify which devices are preferred for the data to be input, and what way users would prefer the data to be entered (based on the definition of input type and input method)

6.3 Study Rationale

The main purpose of the study is to find out about the content of MC toolkits, specifically, the essential features to be included in. As mentioned before, a quantitative method was used since it is an appropriate method for investigation of the relative importance of a number of different features of a social phenomenon (Bryman 2012). The features, in this case, belong to MC toolkits, and were collected from related articles, CAD software programs, and MC sale websites. The features are either independent or dependent (have sub-features). Based on this rule, either ranking or sorting was chosen. The data was then analysed to find their relation for reaching further data and results.

6.4 Method

In this section, the overall method, participant selection, material used, presentation performed, procedure of sessions, and method of analysis were discussed.

In order to prepare unambiguous questions and statements for extracting information that is more precise, surveys can be used. There are two types of question structures: open questions, and closed questions. In open questions, the users are allowed to give their idea, and this type is used when there are no pre-determined answers for the question. In closed questions, the users are asked to select from pre-determined answers such as yes or no, or scale choices. Due to type of the study, which is mainly about ranking of the features of MC toolkits in order of importance, self-completion closed survey methodology with a Likert scale was used.

With a self-completion survey, there is no interviewer to ask questions, but the respondents have to fill in a form. Therefore, the survey should: have more closed questions since they are easier to answer; an easy to follow design, to prevent respondents from mistakenly omitting a question; be short enough to encourage completion; be clearly presented with enough space between questions to avoid cramping the presentation; have self-explanatory characteristics; and questions and answers should be together (Bryman 2012).

6.4.1 Participants

The sample size was decided based on the time available for the study. Since this study includes a presentation and a survey afterwards, it required more time and effort than a simple survey task. Therefore, it was decided that 30 would be an appropriate number of participants for this study.

For both observation and survey methods, selecting participants is of a great importance. It is important to select participants who are representatives of the user class for the system. The criteria for choosing required the participants to be computer literate and non-designers since actual users of these toolkits are not necessarily designers, and it would be better to scatter the participants' selection across different areas. There was a good sample of a more general group of people mainly among first year design students, and support staff from The Design School in term of design proficiency.

The study recruited a convenience sample of younger and older participants via email to staff and first year undergraduate design students, online advertisement via 'Call For Participants' website (Call For Participants 2014) and paper flyers around the university. The initial email or flyer contained information on what the study was about, how they could help, how the session would generally go, and what criteria they needed to have.

After accepting to participate, time slots were sent to the participants in order to specify their suitable time. Then an email followed it by confirming the exact meeting place in the Design School. Upon arrival, the investigator checked whether the participants were over 18, but no other personal information was collected.

6.4.2 Materials

6.4.2.1 The collected features

For this study, two tests were supposed to run. In order to run these tests, the collected features (Table 4-4) were divided into two groups. Group 1 (Table 6-1) is the features that are independent. Group 2 (Table 6-2) consists of the features that can be divided into sub-features. The features in group 1, which is for test 1, need to be ranked and scored according to each other. The features in group 2, need to be sorted in their category.

Table 6-1 Group 1 (independent features)

Group 1 of features	
Visual feedback (see Figure 6-1, image b)	Virtual use of object
Physics providence (see Figure 6-1, image c)	Selecting manufacturing and assembly method (see Figure 6-1, image f)
Users' design access	Reference object
Technical information	Guidance (help in using the system)
Validation with feedback	Click and show option (interactivity)
Offline access	Price update
Material selection	Libraries of modules and producible

Table 6-2 Group 2 (features with sub-features)

Group 2 of features	
Mechanism (veneer, modularity, parametric, generative)	DoF
Need-based or parameter-based	Web-based or store-based
Input type (selection, drop-down menu, sliders, drawing, 3D scan) (see Figure 6-1, image e)	Input method (Mouse, Gesture, Haptic, Touch screen, Voice)) (see Figure 6-1, image a)
Starting point (template or blank canvas) (see Figure 6-1, image d)	

6.4.2.2 Questionnaire

The survey was developed to record each participant's data in relation to the features of the toolkits. The survey contains the features from both group 1 and 2, but not input type, input method, and mechanism, which were written on cards and given to the participants separately. The survey was used to find out which cards need to be selected for ranking. It contains five questions (Appendix 2 Online Survey Resource: Survey Monkey) and was prepared in SurveyMonkey (SurveyMonkey 2017) due to its being free, and the author was not aware of the BOS online survey tool.

6.4.3 Presentation

First, the slides were created for each feature, and picture(s) was added as an example, in order for participants to understand each feature well. A brief explanation for some of them was added and some of the titles and pictures were revised. The slides were revised during a few meetings with the author's supervisors in order to prepare something deliverable in the study sessions (Appendix 1 Presentation Slides for Study 1) (some of the slides were depicted in Figure 6-1 as an example).

To support the participants engagement in the activity, and to have them remember what each feature was about, the slides were scaled down and printed in 10.5x7.5 (cm) sized laminated papers (Appendix 1 Presentation Slides for Study 1).
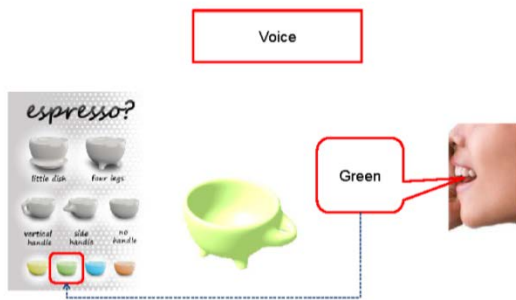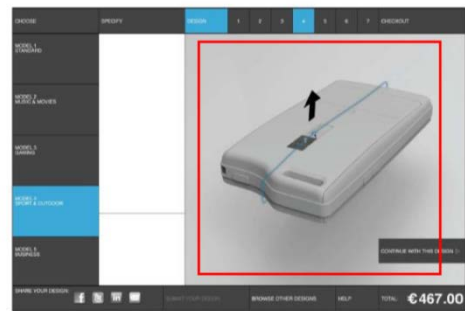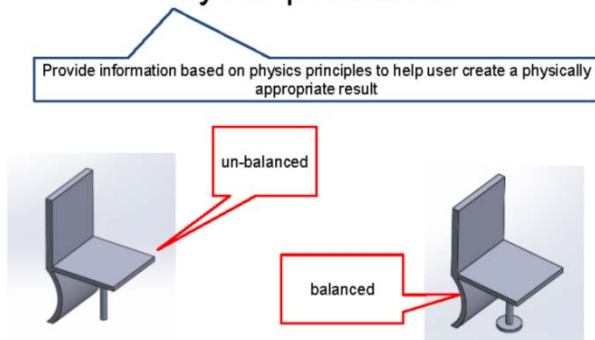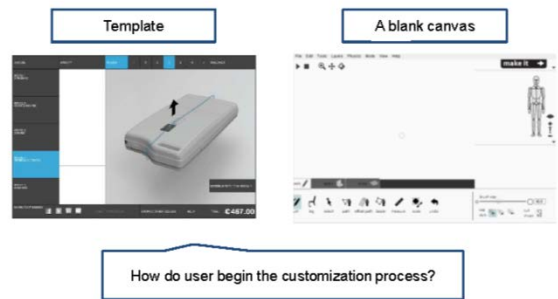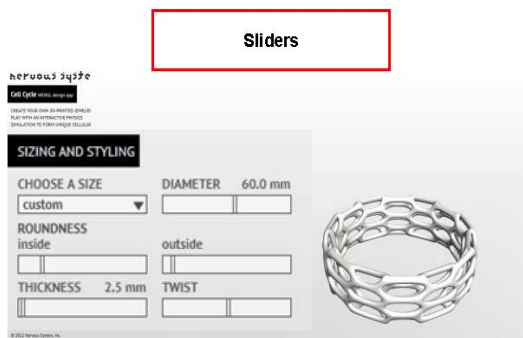
Figure 6-1 Some of the presentation's slides as an example (Appendix 1 Presentation Slides for Study 1)

6.4.4 Ethics

An ethical checklist (Appendix 3 Ethics Clearance Checklist Form for Study 1) needs to be first completed for any research involving human participants. This acts as a screening mechanism to identify those studies, which merit additional ethical support. Ethical clearance was gained for this study from the Loughborough University Ethical

Advisory Committee. Since this study included a £10 voucher to be given to participants for their participation, additional ethical controls were required. These were done by, first correcting the advertisement to not include any mention of the voucher for the study. Secondly, by considering that the voucher was only for the participants' time, spent in the study, not as an inducement to participate.

Furthermore, the following considerations are important (extracted from the ethical checklist of Loughborough University). The researcher should:

1- Make sure that vulnerable participants should be carefully behaved to ensure that they understand the form and scope of the research

2- Make sure that someone else is present in the session other than the instructor and participant, or at least let one more person know of their session

3- Give a consent form to participants to be signed by them and they should be comfortable with the activities

4- Ensure the participants are aware that it is the features of the interface not they who are being tested,

5- Inform participants that they may withdraw from the study whenever they want, and they are not required to give any reason for withdrawing

6- Inform participants of the contact detail of Loughborough University's Ethics Committee in order to contact for any questions, concerns or complains.

Despite these considerations, this study was performed before seeking written permission from the participants; therefore, the issue was raised with the author's supervisors and ethics committee. It was decided to give participants a consent form even though it was after the study had been performed. The participants were asked to sign the consent form and send back a copy to the author. All of them agreed to the publishing of their data anonymously.

6.4.5 Pilot study

Two members of administrative staff in the Design School were selected for the pilot study. They were also selected based on the requirements of being computer literate and not a designer. A date was confirmed with both of them for the session.

In order to do the final design of the study, a revision was done to the tests based on the pilot study. The issues, found in the pilot study, were that:

1- A slide should have been added to the PowerPoint to introduce a generic MC toolkit to the participants, and another slide to identify most of the features in one place. Therefore, they would understand the area and the features better.

2- Two of the features included in the group 1 (see Table 6-1), were not appropriate for test 1 for ranking. In other words, two features in group 1 had to be revised to be eliminated (Table 6-3), these were: 'DoF', and 'need-based or parameter-based'. This is because they belong to group 2 (see Table 6-2) based on the role of grouping, explained earlier.

3- There are many features needed to be ranked according to each other, and this is a long list of fourteen features (group 1 (see Table 6-1)), which may require much time and effort in comparison to test 2.

4- To do the statistical analysis later, a weight should have been added to each answer choice. This was not considered in the pilot study. However, it could be done after the pilot had been performed.

5- As mentioned earlier, the question for test 1 should have been prepared earlier before the sessions to make it consistent without conveying different meanings to participants. It is not easy to individually explain one simple task to number of people and express the same meaning. However, in the session held, the author's meaning was expressed to the participants as clearly as possible, and they understood the meaning well. For instance, for test 1 (for the ranking), it was explained to participant 1 to put the features in order, based on how important she thought they were. Participant 2, was asked to sort the features in order by considering how much he preferred them. Considering that, therefore, they should have been asked one single question.

For addressing those problems, the following amendments were done in each category sequentially:

1. For the method of presentation, two slides were added to the PowerPoint file. One of them included what a MC Toolkit is, and the other one gave an overview of all the features in one place.
2. For the method of evaluation, group 1 was revised as follows:

Revised group 1 of features	
Visual feedback	Virtual use of object
Physics providence	Selecting manufacturing and assembly method
Users' design access	Reference object
Technical information	Guidance (help in using the system)
Validation with feedback	Click and show option (interactivity)
Offline access	Price update
Material selection	Libraries of modules and producible
Side by side comparison	Flexible navigation

3. A revision was done to test 1; It was decided to merge the two parts of test 1, instead of them being done separately. The process, which was used for test 1, was demonstrated in Figure 6-2.

The interpretation of scoring for test 1 is as follows: each feature was scored between 1 and 13. Next, the eight highest scored features were separated out. Then, these eight were ranked 1 to 8. Next, the lowest ranked feature of these eight was assigned a weight of 6, and the highest ranked feature was assigned a weight of 13. The eight lowest scored features that remained were assigned a weight between 1 to 5, based on their ranking within themselves. Therefore, at the end of test 1, each feature was assigned a weight from 1 to 13.
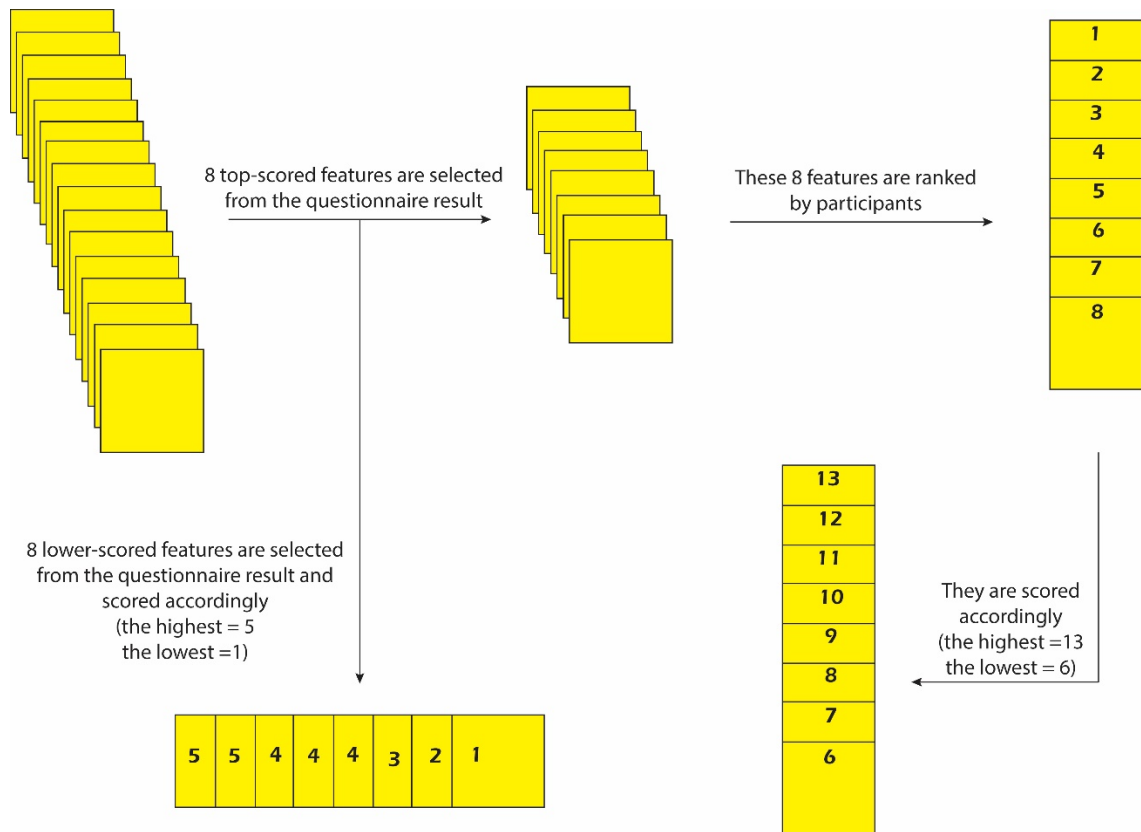
Figure 6-2 The procedure of ranking and scoring for test 1

4. As explained before, a weight was assigned to each answer choice.

5. For the statistical analysis, a weight was assigned to each feature. The weight was then used for the mean or other basic statistical calculation. After collecting data in the survey, the mean value for each feature was calculated as follows:

$$Mean = \frac{weight_1 + weight_2 + \cdots + weight_n}{n} = \frac{\sum_1^n weight}{n}$$

Where n is number of participants. Calculating the mean from the samples, the features were finally sorted based on their mean value.

For evaluation sessions:

6. In order to ask a similar question from all the participants, the question was written down precisely in order for them to be told exactly what the enquiry was about.

Some of the comments of the participants were as follows. During test 1, participant 1 suggested that he would re-arrange the order if he was supposed to do the ranking again, after the first try. Also, he came up with this idea of putting other designs in other users' design library- for which the permission of the co-designer (the customer)

may need to be asked- a discount as an incentive may encourage the users to give the permission. Therefore, other users' design can be made available to others as well. In addition, he pointed out that the ranking depends on the product.

Participant 2 is also mentioned that the ranking depends on the product. She explained that she ranked in second place since MC toolkits were new to her, and she needed help to know how to go through the system. The average duration of each session was around 40 minutes.

In according with what has been done for the pilot study, the first study was conducted similarly with the corrections done.

6.4.6 Procedure

The study was run in the Design School. Each session consisted of two parts: presentation and tests. The amended presentation was used for the sessions. All of the participants were presented with the slides. Then they completed the survey and did the ranking task.

For the presentation phase, the slides were presented for participants one by one. In order to familiarise participants with the features and topic of MC, many examples were given. Most of them indicated that the features were understandable, as they had used them before e.g. side-by-side comparison or material selection. The method of presentation was PowerPoint slides. During the presentation in all sessions, only a few questions were asked, and they were mostly about haptic technology (one of the slides included haptic technology as an input method out of available methods).

In test 1, the survey was given to the participants to be completed. They could mostly do it without any help. While they were filling in the forms, the cards for test 2 were grouped for them in order to be ranked in order of importance in three groups of input: type, input method, and mechanism. In test 2, the eight most important features from the questionnaire were separated and given to participants to be ranked in order of importance. This way, the most important features out of sixteen were obtained. Test 1 and 2 concluded overall ranking of the sixteen features, and test 2 concluded the ranking of the members of the features, grouped as: input type, input method, and mechanism.

With regard to the DoF, a typical toolkit such as NIKEiD was considered. The NIKEiD as shown in Figure 6-3 has around 15 DoF, which is inferred by counting the number of options provided in this specific toolkit (this may not be visible in the image (Figure 6-3) since all of the options are not shown). Therefore, a series of numbers that are lower and higher than this toolkit's DoF was chosen; less than 5, 5, 10, 15, 20, 25, more than 25.

The average duration of each session was around 40 minutes. However, during the sessions, many questions were raised and some comments were given about the toolkits' features. One participant stated that if the interface is intuitive enough, there is no need for a help button to be provided for the toolkit, and the customer can find his/her way out while using this kind of system.

Some of the participants added that libraries of other users' design could be popular as the designs of famous people can be put in the public show to be purchased by others. They explained an interesting point that people usually first customize and see the object and then check the price, so it is probably the second most important factor after visualisation feedback. They mentioned that most people do not have the creativity to start from scratch or a blank canvas, and they are usually frightened when a blank paper is put in front of them. They said that it did not matter if the MC started over from the beginning again.

A number of participants commented that technical information and libraries of other users' design were in the middle in terms of customers' preferences, consequently, half may need it, and half may not. Veneer, and generative mechanisms are good options to have but they do not give as much freedom as modularity and parametric mechanisms to the customer, which provide more options/freedom. Most of the participants said that more than 25 DoF makes the system complex and the design process complicated.

Figure 6-3 Demonstration of options in NIKEiD MC toolkit, for DoF calculation purpose

During the sessions, no issues were encountered, but most of the participants notified the author that the survey was dependent on the MC product. Another point that should be mentioned is that some of the participants did the questionnaire either based on their preferences, or those they considered typical for the general population.

6.4.7 Analysis

In the broad image, there are three types of study design, implying that each study is looking for a different sort of data, including association, prediction, and groups (Laerd Statistics 2013). Statistical tests for the associations group explore possible associations between variables (and measure the associations' strength and direction), likewise for prediction, they predict a score of a group (and relationship between two or more variables), and for groups, they determine differences between groups and treatments (and where these differences lie). It is interesting that these study designs have overlaps, and it is only the research question that determines which statistical analysis needs to be used.

Since the study in this chapter was designed to answer questions about association and prediction, the comparison between different statistical tests in those two items was explained.

The common statistical analyses for exploring associations are Pearson's correlation, Spearman's correlation, Chi-Square, and Loglinear (Laerd Statistics 2013, Corder, et al. 2009, Bluman 2004). The selections between these tests were done based on the number and type of variables. There are four types of variables summarised below. Table 6-5 summarises the differences between the statistical tests for examining association to ease the selection of the most appropriate one.

Table 6-4 A summary of different types of variables with examples (Laerd Statistics 2013)

Type of variables	Definition	Examples
Continuous	'Continuous variables can be measured along a continuum and have a numerical value'	1. Distance 2. Temperature 3. IQ 4. Exam score
Ordinal	'Ordinal variables have two or more categories, similar to nominal variables. However, with ordinal variables, these categories are ordered or ranked.'	Strongly agree Agree Neither agree nor disagree Disagree Strongly disagree
Nominal	'Nominal variables have two or more categories, similar to ordinal variables. However, with nominal variables, these categories are not ordered or ranked.'	Heterosexual Homosexual Bisexual Transsexual
Dichotomous	Dichotomous variables are nominal variable with just two categories.	1. Yes and No 2. Male and Female

Table 6-5 The comparison between statistical tests for examining association (Laerd Statistics 2013)

Statistical test	Number of variables	Type of variables
Pearson	2	Two Continuous
Spearman	2	Two Ordinal
Chi-Square	2	Two Nominal One Nominal, One Ordinal
Loglinear	3	three Nominal

Consequently, Table 6-6 summarises the differences between the statistical tests for examining prediction to ease the selection of the most appropriate one. For this table, two variables need to be explained; independent and dependent variables. An independent variable is one that is being manipulated in an experiment in order to observe the effects on a dependent one. Simply, the dependent variable is one that is dependent on an independent variable(s). Other name(s) for independent variables are experimental and predictor variables, and for a dependent variable is outcome variable.

Statistical test	Number of independent variables	Number of groups of independent variable	Type of independent variables
T-Test	1	2	Continuous
Anova	1 or more than 1	More than 2	Continuous
Friedman	1	More than 2	Ordinal

Therefore, each study section requires a different test. In order to facilitate selection of an appropriate test, Table 6-7 summarises the measuring characteristics of questions that are required to be answered in this study. The IBM SPSS software was used in order to do the calculations.

As seen in Table 6-7, the second question enquires about two nominal variables: DoF and the approach (need-based or parameter-based approach). However, due to the low number of participants, the frequency of answers is very low, and zero in some cases. Therefore, Chi-square is not applicable for this question. The alternative method is the Mann-Whitney test Corder et al. 2009), which was used and mentioned in the table.

Table 6-7 Research questions of study 1, their characteristics and the selected statistical test for them

Research question	Type of question	Number of all variables (or independent variables)	Number of groups of independent variable	Type of variables (or independent variables)	Selected test
Is there a significant difference between features' ranking?	Prediction	Features' ranking (1)	All the features: visualisation, price, help, etc. (More than 2)	Categorised variables with no ranking (Nominal)	Friedman
Does the preference for the number of DoF depend on the preference of a need-based/parameter-based approach?	Association	Number of DoF, approach (2)	Not applicable	Categorised variables with no ranking (Nominal) (Coded to continuous and ordinal variables for Mann-Whitney test)	Mann-Whitney test

Furthermore, for reflecting on the data and the result, a hypothesis testing was required. In this testing, the research hypotheses are expressed as a null and alternative hypothesis. The alternative hypothesis is the one that is tried to be proven and the null hypothesis is in reverse.

6.5 Results and Discussion

6.5.1 Importance ranking of toolkit's features

The ranking and scoring of features resulted in two different sets of data, which are analysed according to the importance ranking of features of group 1 (Table 6-1)and the ranking of features of group 2 (Tables 6-2).

The main result of study 1 is the importance ranking of features (group 1) of MC toolkits (Table 6-8). This ranking is based on participants' answers. The sum was obtained by adding all the scores of each feature from each participant. The mean value was obtained by dividing the sum by the number of participants, which is 30.

Table 6-8 The ranking of the features (group 1 - Table 6-1) based on their importance

		Features	Sum	Mean
Chosen features	1	Visual feedback	327	10.9
	2	Price update	277	9.2
	3	Click and show option	269	9
	4	Material selection	241	8
	5	Flexible navigation	235	7.8
	6	Guidance	199	6.6
	7	Libraries of modules and producible	188	6.3
	8	Side by side comparison	186	6.2
	9	Technical information	186	6.2
	10	Validation with feedback	164	5.5
	11	Physics providence	142	4.7
	12	Offline access	138	4.6
	13	Virtual use of product	137	4.6
	14	Users' design access	112	3.7
	15	Reference object	109	3.6
	16	Selecting manufacturing method	84	2.8

The ranking as well as the participants' feedback in sessions made it obvious that visual feedback and price update were sequentially the most important features. This indicates that those two important features along with next three features from Table 6-8 (first five important features) are essential in a MC toolkit. The reason is that from the fifth feature in Table 6-8, there is a noticeable jump in the mean value considering other jumps from top to bottom. In order to make it clearer, Figure 6-4 is generated, which shows the noticeable jump (golden circle) in the sum value after the fifth important feature. Therefore, the first five features in Table 6-8 (Figure 6-4) are mandatory in toolkit implementation for customer satisfaction.
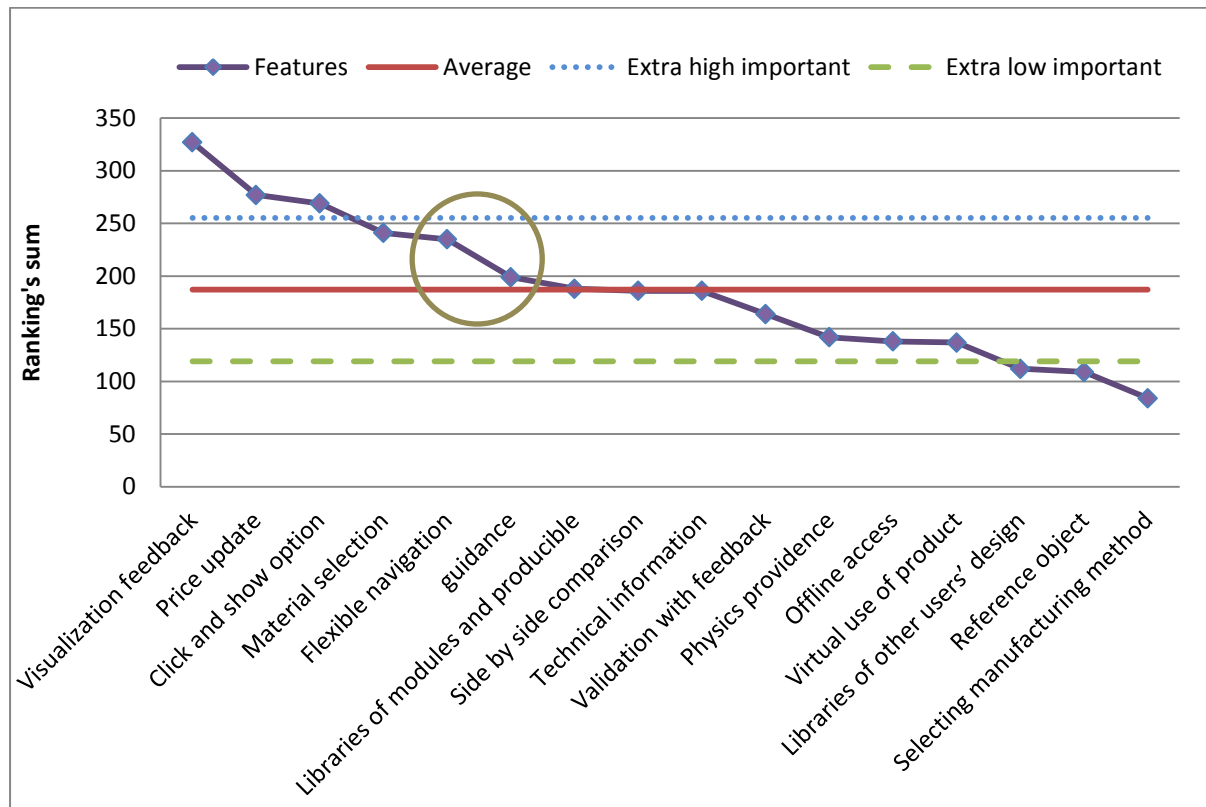
Figure 6-4 The participants' scoring sum for each feature (showing the noticeable jump with the circle with golden border)

Based on the collected data, the average of the ranking's sum is 187.13, and the standard deviation is 68.1. Standard deviation is a way to show what is standard and what is extra low or high. Therefore, the three straight lines in Figure 6-4, show three borders of standard (187.13), the extra high important (255.2), and extra low important (119), which divide the features, and are drawn based on adding and subtracting deviation from the average of the sum. Therefore, considering Figure 6-4, the first three features (above the blue dotted line) are the extra high important ones, and the last three (under the green dashed line) are the extra low important features, which are not worth integrating, according to the users. The rankings of other features in group 2, as mentioned previously, are presented in three different parts in Table 6-10 due to their different type of scoring.

As Table 6-9 shows, participants voted for a need-based approach (~73%) more than a parameter-based approach (~27%). This indicates that customers usually presume that the technical aspects of the products, which are customizable, are challenging. This may need further investigation if a need-based approach is preferred for almost all products even for simple ones, such as a ring or lampshade. However, this is always true that the task of translating parameters of products into needs, which is more digestible for customers, is more preferable, and easier-to-use. Unfortunately, this is not usually applicable to all parameters, and this is not an easy task for companies.

Table 6-9 shows that most of the participants voted for, so preferred, a web-based toolkit (27 or 90%) in comparison to store-based (3 or 10%). This confirms that the advantages of web-based toolkits such as: the ability to go through all the options and check the price conveniently, and experiment with different configuration options outweigh the advantages of store-based toolkits, such as: handling the product, seeing the colours and textures from closer and getting a sense of the final product. It is worth mentioning that these advantages and disadvantages were shown to the participants during the presentation. Furthermore, as explained before, it is predicted that 3D-enabling libraries will be used increasingly in the future, not only because they enable various features' integration, but also allow implementation of MC toolkits on the web.

Table 6-9 also shows that most of the participants preferred a template (~93%) as a starting point of customisation, rather than a blank canvas (~7%). This shows that customers usually have the fear of creating a product from scratch, and this may seem very daunting even to highly creative individuals. Furthermore, customers usually do not have the knowledge to create a product from scratch, which requires a great amount of technical, engineering, industrial, and manufacturing knowledge.

There is no other indication for other rankings, shown in Table 6-9. However, they are all useful in order to implement a toolkit, to make it more enjoyable and productive, according to participants.

Group 2 features		Degree of Freedom	Participants' vote (n=30)
Feature name	**Participants' vote (n=30)**	less than 5	1
Web-based	27	5	0
Store-based	3	10	5
		15	4
Template	28	20	6
Blank canvas	2	25	8
		more than 25	6
Need-based	22		
Parameter-based	8		

Feature name	**Sum of participants' score**
Mouse	138
Touch Screen	126
Voice	72
Haptic	65
Gesture	49
Modularity	101
Parametric	88
Generative	66
Veneer	50
Selection	126
Drop-Down Menu	111
Slider	99
Drawing	58
3D-scan	56

6.5.2 Optimum number of DoF for each toolkit

In order to find out if there is an optimum number for DoF for each toolkit, Figure 6-5 was created, based on the acquired data. The figure shows the participant's preferences regarding the number of DoF for MC toolkits.

In Figure 6-5 below, analysis of the survey showed that most of the participants indicated their interest in a relatively high number of DoF (60%) for a MC toolkit. Figure 6-5 shows participants' preferences against the number of DoF, with 25 DoF being seen as the most popular number (26.6%).
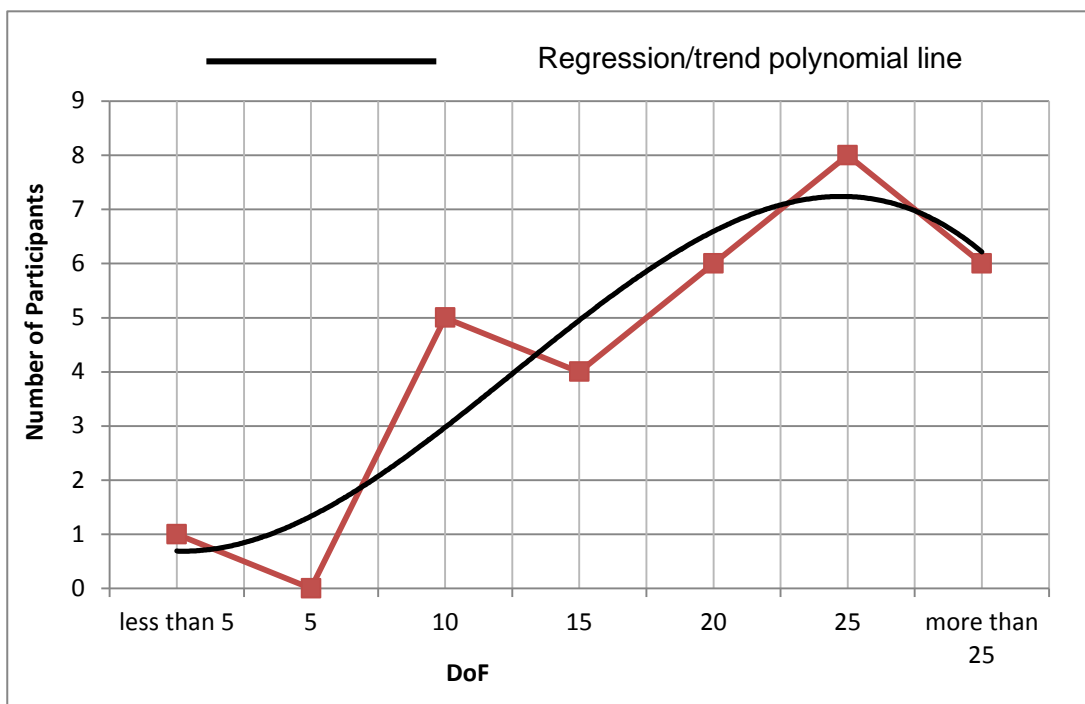
Figure 6-5 Participants' preferences versus DoF of toolkits

More satisfaction is shown with a relatively high DoF, with 25 DoF as the most popular number, emphasizes the balance required between customer autonomy and designer authority. This can be a win-win situation as a relatively high DoF means that there is a relatively high chance of radical and complex customisation. Therefore, companies have to be cautious about the manufacturability of final products and their time and cost efficiency. However, it may be a relief for manufacturers that making all the available options accessible to customers is not a requirement.

For further analysis, if DoF is divided into three items of low (less than 5, and 5), average (10, 15, and 20), and high DoF (25, more than 25), then the average will be highest preferred one, and the others are as in Table 6-10. The score is calculated by the number of participants' preferences for each category divided by the 2 or 3 based on the categorisation. For example, for low, there is only 1 participant, who voted for it considering 'both less than 5' and '5' number of options, therefore, 1 was divided by 2, and the final score is 0.5.

DoF	score
low (less than 5, and 5)	1/2 = 0.5
average (10, 15, and 20)	15/3 = 5
high (25, more than 25)	14/2 = 7

As Figure 6-5 and Table 6-11 show, there is a little difference between an average and a high DoF. Therefore, it seems that high DoF is the most popular one. However, to be more specific, the DoF were divided again into 5 items of low (less than 5, and 5), averagely low (5, 10, and15), average (10, 15, and 20), averagely high (15, 20, and 25), and high (25, and more than 25) DoF. Based on that categorisation, the same procedure for calculating the score was done for each member, and was demonstrated as in Table 6-12:

Table 6-11 Customer preference for DoF based on second categorisation (5 items)

DoF	score
low	0.5
relatively low	3
average	5
relatively high	6
high	7

This is a better division since it shows a difference between average, relatively high, and high. However, this kind of categorisation is not right, since one DoF is put into two groups. It was decided that it should be sufficient to either use the graph only, or ask about DoF in another study in a better way, either by: choosing an even number of choices for further categorising, so none of the groups has one member more or less than the others; or from the beginning, grouping them into the categories intended, such as low, relatively low, average, relatively high, and high.

6.5.3 Is the difference between the ranking of features significant or not?

The Friedman test was done to find out if there is a significant difference between features' ranking. Therefore, the null and alternative hypotheses are as below:

Null hypothesis: the difference between variables is not significant. $p > 0.05$

Alternative hypothesis: the difference between variables is significant. $p < 0.05$

The Friedman test result is shown as in Table 6-13 below:

Friedman Test Statistics	
N	30
Chi-Square	156.618
df	15
Asymp. Sig.	.000

Looking at Table 6-13, it is shown that there is a statistically significant difference in the features ($\chi^2(2) = 156.618$, $p = 0.000$), consistent with the predictions, since p is less than 0.05. Therefore, the difference between variables (features' rankings) is significant, and the alternative hypothesis is approved.

6.5.4 Impact of need-based/parameter-based approach on DoF preference

Participants with the preference for a parameter-based approach may prefer higher DoF. This is implied because they may have the knowledge to manipulate technical aspects of the products or they have no fear to confront a higher number of parameters in comparison to participants with a need-based approach preference. A Mann-Whitney test was done to find out if the preference for the number of DoF depends on the preference of need-based/parameter-based approach. Therefore, the null and alternative hypotheses are as below:

Null hypothesis: the preference for number of DoF does not depend on the preference of need-based/parameter-based approach. $p > 0.05$

Alternative hypothesis: the preference for number of DoF depends on the preference of need-based/parameter-based approach. $p < 0.05$

The Mann-Whitney test result is shown in Table 6-13 below.

Table 6-13 The Mann-Whitney test result showing the independency of DoF from need-based/parameter-based approach

Hypothesis Test Summary

	Null Hypothesis	Test	Sig.	Decision
1	The distribution of dof4 is the same across categories of approach3.	Independent-Samples Mann-Whitney U Test	.696[1]	Retain the null hypothesis.

Asymptotic significances are displayed. The significance level is .05.

[1]Exact significance is displayed for this test.
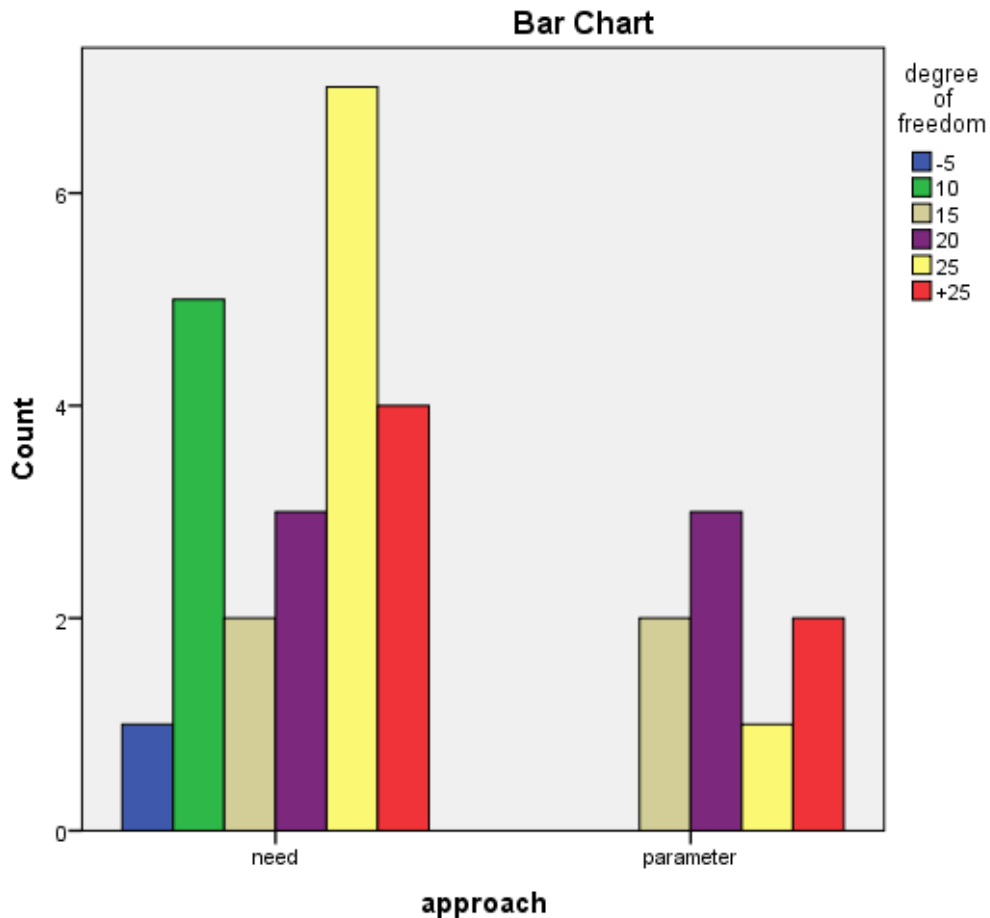
Figure 6-6 The independency of DoF from need-based/parameter-based approach

Table 6-13 shows that there is no association between preferences for number of DoF and preferences for a need-based/parameter-based approach ($p = 0.696 > 0.05$), contrary to the predictions, since p is more than 0.05.

As the Sig. number (Table 6-13) and bar chart shows (Figure 6-6), there is not enough evidence to show that the DoF is dependent on the need-based/parameter-based approach. Nevertheless, it was suggested to divide the sample into two groups that have quite similar populations. Therefore, participants were divided into two groups: those satisfied with 20 and less DoF (16 participants) and those satisfied with 25 and more DoF (14 participants). The result of the analysis is as follows:

Table 6-14 The Mann-Whitney test result showing the independency of DoF from need-based/parameter-based approach based on new categorisation

Figure 6-7 The independency of DoF from a need-based/parameter-based approach based on new categorisation

Table 6-14, shows that the alternative hypothesis has still been rejected, $p = 0.629 > 0.05$. It means that there is still a lack of evidence to confirm the dependency of DoF on a need-based/parameter-based approach, and apparently, there is no association yet found.

6.5.5 The impact of DoF on Features of Solution Space

A Mann-Whitney test was carried out to discover whether an association exists between the preference for the number of DoF and any of the features of Table 6-1. It was predicted that when the solution space includes more options (as was preferred by most participants), some features, such as guidance, may also need to be better provided in the toolkit. Therefore, each feature was tested one by one

104

through a Mann-Whitney test to see if any association existed. The reason for choosing the Mann-Whitney test instead of the Chi-Square is that the frequency of answers for each feature regarding the DoF is low (Corder et al. 2009).

By looking at Table 6-15, it can be seen that no significant association between DoF was recognised due to the fact that all the acquired sigma numbers were higher than 0.05. However, any relation between these features with DoF could be investigated more directly in an explicit way. That is, participants could be asked about this association specifically, and also a study with a larger population of participants should be undertaken.

Table 6-15 The Mann-Whitney test result for testing the association between DoF and the MC toolkit's features

Feature	Sig.
Visual feedback	0.108
Price update	0.939
Click and show option	0.545
Material selection	0.125
Flexible navigation	0.140
Guidance	0.393
Libraries of modules & producibles	0.113
Side by side comparison	0.219
Technical information	0.754
Validation with feedback	0.449
Physics providence	0.411
Offline access	0.222
Virtual use of object	0.839
Users' design access	0.742
Reference object	0.545
Selecting manufacturing method	0.576

6.6 Conclusion

This study aimed to investigate further about the user requirements for the content of MC toolkits. PowerPoint slides were chosen for a presentation of the features, and a survey was selected for data collection. It was decided to run two tests to identify which features were the most important ones to be included in the content of MC toolkits.

The importance rankings of the selected features were obtained and analysed. Results from the analysis indicated that visual feedback, price update, click and show option, material selection, and flexible navigation were, in this order, the most important features to be included in MC toolkits. Similarly, selecting manufacturing method, a reference object, and a library of other users' designs were, in this order, the least important features. These findings helped to satisfy research objective 1. The analysis generally showed that customers do not like a small number of buying options, and neither do they usually like a very high number of options. They would like to have a 'reasonably high number' of DoF, which would be different depending on the product the toolkit relates to (see section 8.5.7 The DoF). This finding helped to satisfy research objective 2. Web-based toolkits were preferred over store-based ones, a need-based approach over a parameter-based approach and a template starting point over a blank canvas starting point. In addition, no association between DoF and any features of Table 6-1 was found; however, further investigation into this aspect is suggested. These findings helped to satisfy research objective 3.

The preferred input type based on user preferences was as follows (listed from high to low preference): selection, drop-down menu, slider, drawing and 3D-scan. Furthermore, the preferred input methods were as follows (listed from high to low preference): mouse, touch screen, voice, haptic, and gesture. These findings helped to satisfy research objective 4.

Chapter 7 : Workshop – Content and Layout of MC Toolkits

7.1 Introduction

As previously discussed, interfaces for MC toolkits have not been analysed and developed thoroughly in order to be efficient and effective from users' points of view, or at least that design knowledge is not available. These toolkits do not usually have a common structure (Streichsbier & Blazek 2009), and there is no design guideline available for user-centred MC toolkits. This chapter documents a workshop aimed at finding out more about the content and layout/structure of MC toolkits. First, the collected features were ranked according to expectancy. Second, the features were categorised based on different elements of solution space of these toolkits for further analysis. Finally, the preferred layout of MC toolkits was achieved through positioning the features on a blank sheet of paper. All these tasks were done by the participants, who are the general users of these toolkits. The findings are not only useful for creating an efficient and effective toolkit, which was prototyped and used for the second study, but also for including in the framework at the end.

7.2 Aim and Objectives

A functional toolkit prototype, preferably high fidelity (considering the preparation time needed), was started during the first study to be built as soon as possible. The toolkit's configuration was missing for preparing its prototype. Therefore, the design knowledge that was pursued in this workshop includes:

1- The preferred structure or layout of the toolkit by users.

2- The expectancy ranking of the features, which can be used to validate the ranking from the first study

3- Which element each feature belongs to

7.3 Workshop Rationale

For the preparation required, a number of methods were investigated. These were collected from the 'Interaction Design' module (14DSB022) and its references from the Design School. The collected methods are explained briefly below:

1- Sketch boarding/story boarding: user needs and problems are investigated through drawings of how users will journey through the app or website when performing key tasks (Interaction Design module (14DSB022), Design School, Loughborough University).

2- Kano analysis: to identify which features need to be included in a website/product from customers' points of view (Technori NA).

3- Sitemaps: reveal the hierarchy of information and overview of design within a website or app (Technori n.d.).

4- Site process flow: find out about a specific process of UX when using a website. This method provides insight through building diagrams, for example for a sign-up process (Technori n.d.).

5- Card sorting: get feedback on the information architecture of a website (Technori n.d.).

6- Wireframing: receive feedback by taking the user through the journey of doing a task, which presents a low fidelity representation of the website (Interaction Design module (14DSB022), Design School, Loughborough University).

Based on the explained objectives in this chapter, the three tasks that were chosen to be done in the workshop to fulfil the objectives were sequentially: Kano analysis, Card sorting, and Wireframing.

From the features, which had been collected for study 1, two more features were added to the list for the workshop, as follows:

Table 7-1 Extra features added to the collected features (Table 4-4) from study 1

Added features	
Name	**Brief definition**
Undo	ability to undo the performed steps
Camera reset	Ability to reset the camera rotation, transformation, and location (in case the pan/zoom/rotation of the product results in a view that is out of sight)

Furthermore, the feature 'click and show option' was changed to 'DM', since the latter had already been created and indicated a similar characteristic. Furthermore, DoF, input method and input type (Table 6-2) were eliminated from the list since they are not suitable for ranking, and indicating features that can be divided into sub-features.

7.4 Method

The workshop was chosen to be done in the form of focus groups because collaboration of participants was preferred rather than individual inputs, since individual inputs would lead to highly variant layout designs, which might not be merged into one specific layout at the end. The sequential Kano analysis, card sorting, and wireframing are now described in more detail:

- **Kano Analysis** (Ullman 2010)**:** this was performed to determine which features are expected by users to constitute the toolkit. In the Kano analysis, the features (**r**Table 4-4) were divided into three groups: threshold attributes, performance attributes, and excitement attributes. Threshold attributes are those that are expected by customers to be built into the toolkit. Performance attributes are those that customers enjoy using. Excitement attributes are not expected in a product, but if presented in a product, they will delight customers. For example, for a cell phone, the contact list is a threshold attribute, the camera is a performance attribute, and fingerprint recognition is an excitement attribute. This grouping gives designers some clue to include features that improve customer satisfaction. In other words, to improve customer satisfaction, and at the same time maximize profit, as many expected features as possible should be included in the toolkit. Based on the recommendations of a Kano analysis, a designer should implement all the threshold attributes, maximise the performance attributes, and include as many excitement attributes as possible, considering the time and cost of doing so.

- **Card Sorting** (Lazar 2006): Card sorting was selected to find out which feature belongs to which elements, as explained in 4.17 Key Elements of MC Toolkits . It is simply done by putting the features (Table 4-4) into the groups (the solution space's elements) that preferably have been assigned a name previously (in this case feedback, guidance, and navigation). For example, price update and visualisation feedback might be expected to appear in the feedback group, due to their relevance.

- **Wireframing** (Garrett 2002)**:** The intended wireframe task in this workshop was for finding out about the layout of the website, and where the features should be placed generally. Therefore, it constitutes a relatively basic usage of the wireframing method. Wireframing involves the creation of a basic and schematic illustration of the website, which allows arrangement and selection of interface elements, identification of core navigational systems, and placement of information components.

7.4.1 Participants

In line with recommendations by Bryman (2012), the number of participants engaged in the workshop was 10.

The participants were required to be computer literate and have at least some initial experience with online shopping. Furthermore, participants were preferred to be among designers, and specifically interaction designers, since the wireframing task intended, requires some knowledge of design, especially interaction design. The participants who attended the session were one Interaction Design Masters student, one Art Masters student, and the remainder were PhD students from the Design

School. Once again, other than checking that the participants were over the age of 18, no other personal information were gathered.

7.4.2 Presentation

The presentation's slides from the first study were improved and recreated for the workshop. They contained a brief introduction to MC, and MC toolkits. Each feature was explained with a picture as an example, in order for participants to understand each one well; some of them also contained a brief explanation of the feature, again to make them more easily understood. It was important that the presentation should not contain any information that suggested a solution, as this might affect the participant's judgement. Therefore, all the hints from the cards and presentation were deleted and replaced. During the presentation, the participants were free to ask questions. All the slides used in the workshop are available in Appendix 6 Presentation Slides for the Workshop. To support the participants to engage in the activity, and remember what each feature was about, the slides were scaled down and printed in 10.5x7.5 (cm) sized laminated papers.

7.4.3 Ethics

As explained previously, an ethical form needed to be completed for this workshop (Appendix 7 Ethics Clearance Checklist Form for the Workshop). Since the workshop included a £10 voucher to be given to participants for their participations, extra ethical controls needed to be done. These indicated that the vouchers must be only used for the participants' time, spent in the study, not as an inducement to participate in the study.

In addition, informed consent and participant information sheets were developed and used in the study (Appendix 8 Permission Letter for the Workshop and Appendix 9 Participants Information Sheet for the Workshop).

7.4.4 Pilot

Three PhD students, considering the same criteria as mentioned previously, from The Design School were selected for a pilot study, which revealed that:

1- Cards need to be the same so all of them were made the same size and laminated

2- Images (on cards) that suggest or give an idea of what is preferred or conventional need to be removed, for example, an image of the price update on a toolkit interface may recommend the place for it, based on the image. So, all the images were either removed (and the appropriate one added) or were checked to not contain any hints

3 - There were too many features required to be placed on the page (as the representative of the website page) and some cards, which were not applicable to the third task. So, all the irrelevant cards for the last task were removed, resulting in enough space for all the cards to be put on the blank sheet of paper.

During the Kano analysis task in the pilot workshop, participants wanted to put some of the features in spaces between the designated groups. They were allowed to do so since this grouping represents a spectrum, from not expected to expected features. Therefore, the task was amended so that it was not mandatory to put the features in those three groups, and they could be placed anywhere along the spectrum.

7.4.5 Procedure

The study was run in a meeting room in the Design School. The workshop was structured in a way that the participants could not only conduct the tasks easily, but also reflect on the problems and issues in the session openly. The session consisted of two parts: a presentation by the researcher followed by user-performed tasks done by the participants. For the presentation phase, PowerPoint slides were shown to participants so that all features were understood. Most participants communicated that the features were familiar, as they had used them before, or they were very easy to understand, e.g. side-by-side comparison, material selection, etc. In the presentation, as many examples as possible were shown to familiarise participants with the topic.

After the first task, the intention was that active and talkative participants were identified, and put into one group for the next tasks, therefore, encouraging other participants to engage in the activities. However, just one participant was observed to be not engaging, and so the grouping remained the same for the entire tasks.

For the tasks phase, three activities were conducted. Firstly, the previously prepared laminated cards were given to participants, who were asked to sort them according to the attributes of threshold, performance, and excitement for the Kano analysis. Next, the second task regarding the card sorting was done by asking participants to sort the same cards under the headings of guidance, navigation, and feedback for card sorting. For the last task, participants were given a large blank sheet of paper that was a representation of the website; they were then asked to put each feature in the space they believed it was most suitable, i.e. to create a wireframe of the MC toolkit website.

The average duration of the session was 90 minutes. Some participants stayed afterwards to discuss the workshop, and possible improvements, which were:

1- Asking people to do the tasks individually to get better feedback and reflection (which is very close to what is intended in the next study).

2- Adding more features to the list, such as the ability to add images to the canvas from one's personal computer, and providing a theme for the product customisation, such as sport, outdoor, business, etc.

7.4.6 Analysis

The findings regarding the expectancy ranking (Kano analysis) were analysed, validated, and presented side by side with the ranking obtained from the first study. The findings concerning the layout (Wireframe) of the toolkit were analysed by regenerating them in Adobe Illustrator. More analysis regarding the sorting of features under the elements of UI were done and presented.

7.5 Results and Discussion

7.5.1 The expectancy ranking (Kano analysis result)

The data from the first task is presented in Table 7-2. For exploring customer expectation regarding features in the toolkit, the table can be explained as follows. Firstly, there are three columns representing threshold, performance, and excitement features, containing the votes that each group had given to them for the features. The groups were asked to choose 'threshold' if they thought it was essential to include the feature in the toolkit, 'performance' if the feature was something that would improve their enjoyment using the product and 'excitement' if the feature was beyond customers' expectation. Table 7-2 shows, for example, that all the groups assigned visual feedback to the 'threshold' column, which is shown by the number three under 'threshold for visual feedback'.

This can similarly be done by assigning a value to each category. This has not only provided the same result as the previous method, but also helps the ranking of these attributes overall. Therefore, each attribute was assigned a value: threshold = 1, performance = 0.5, and excitement = 0. After assigning a value to each heading, it was multiplied by the number of groups' votes. Basically, any number could have been assigned, but this selection of numbers helped to distinguish their expectancy in more detail. For example, for the feature 'undo', all the groups placed 'undo' under the 'threshold' heading, therefore the assigned number of '1' was multiplied by 3, and the result was 3. This is not a recognised way of analysing the data; however, this is a general way of ranking the data to simply sort the features even in their own category.

The last column shows each feature's overall result. Based on Table 7-2, a spectrum is acquired from most expected to least expected features to be included in a toolkit from customers' point of view, which is presented side by side with the first study's ranking in Figure 7-2.

Group 1	Threshold (1)	Performance (0.5)	Excitement (0)	Result	Mean
Visual feedback	3	0	0	Basics	3
Price update	3	0	0	Basics	3
Material selection	3	0	0	Basics	3
Undo	3	0	0	Basics	3
Guidance	3	0	0	Basics	3
Flexible navigation	2	1	0	Basics	2.5
Validation with feedback	2	1	0	Basics	2.5
Library of modules and producible	2	1	0	Basics	2.5
Camera reset	2	1	0	Basics	2.5
Direct manipulation	2	0	1	Basics	2
Need-based or parameter -based	2	0	1	Basics	2
Technical information	1	2	0	Performance	2
Side by side comparison	1	1	1	Indeterminable	1.5
Physics providence	0	3	0	Performance	1.5
Virtual use of product	0	2	1	Performance	1
Reference object	1	0	2	Excitement	1
Multiple mechanisms	0	1	2	Excitement	0.5
Offline access	0	0	3	Excitement	0
Users' design access	0	0	3	Excitement	0
Selecting manufacturing and assembly method	0	0	3	Excitement	0

A comparison of participants' scores regarding the importance of the features (from the first study - Table 6-8) and expectancy of features (Table 7-2) is depicted in Figure 7-1. In this figure, the horizontal line is arranged based on the ranking of the first study (this could be arranged based on this study's ranking as well), and the vertical line shows the sum obtained from each ranking for each feature. Since the sum values are different for each ranking due to the different data collection and analysis methods, the sum from the first study was mapped to the range of sum value of the second ranking. It also shows that the most important features are the ones that are most expected to be in the toolkit from the customer's point of view, therefore, the content of the toolkits should contain those important/expected features. These features include: visualisation feedback, price update, flexible navigation, and material selection. Due to the big difference in the scores for DM, it is not definite if this feature is essential for MC toolkits.

Figure 7-2 shows the expectancy ranking of features side by side with the importance ranking of features. It is obvious that the result from this workshop mostly overlaps with the result from the first study. The random colour, given to each feature, shown in Figure 7-2, is based on the sum value of futures from the workshop (Table 7-2). The features on the left side of Figure 7-2 are arranged based on their sum value from Table 7-2 , and the features on the right side of the figure are arranged based on their sum obtained from the initial study (Table 6-8).
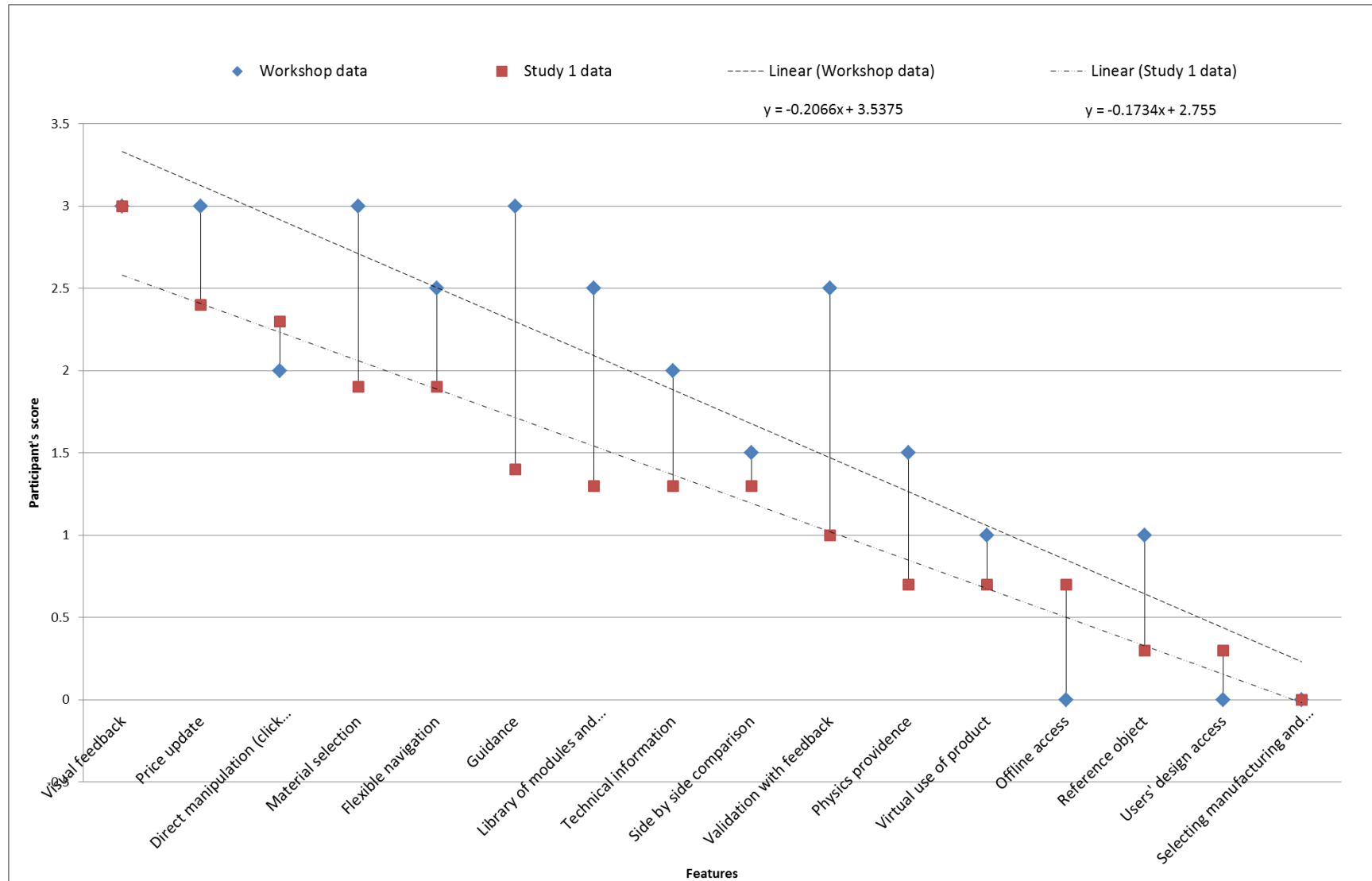
Figure 7-1 Almost similar result, obtained from the comparison of participants' scores of each feature in the first study and workshop

Workshop Result   Previous Study

Visual Feedback   Visual Feedback
Price Update
Material Selection
Undo
Guidance

Flexible Navigation
Validation with Feedback
Libraries of modules and producible
Camera Reset   Price Update
                                                   Click and Show Option

Direct Manipulation
Need-based or Paraemter-based   Material Selection
TechnicalInformation   Flexible Navigation

Side by SIde Comparison
Physics Providence   Guidance
                                                   Libraries of Modules & Producible
                                                   Technical Information /
                                                   Side by Side Comparison

Virtual Use of Product   Validation with Feedback
Reference Object

                                                   Physics Providence
                                                   Offline Access
                                                   Virtual Use of Product

Multiple Mechanisms
                                                   Users' Design Access
                                                   Reference Object

Offline Access
Users' Design Access
Selecting Manufacturing   Selecting Manufacturing
and assembly Method   and assembly Method

(vertical axis labels: Expected / Not Expected; High Importance / Low Importance)

Figure 7-2 Similar results, obtained from the comparison of the rankings from the first study and workshop

116

7.5.2 Navigation, Feedback and Guidance (Card Sorting Result)

The card sorting result was instrumental in two ways:

1- It helped to find out which element each feature belongs to (specifically in the first study, the elements of solution space: guidance, feedback, and navigation had not been analysed in association with DoF, however, at this stage, with the result of this task, the elements could be grouped into three main categories).

2- It helped the participants to undertake the final task, which was designing of the website's layout. It could be helpful for them to group the items into the navigation, guidance or feedback and put them together in a place on the website for ease of access for customers. Interestingly, in one of the layout configurations (Figure 7-3), this was obvious.

The same analysis methods as the Kano analysis have been used for the card sorting. The result of this task is depicted below.

Table 7-3 The sorting of features in the solution space's elements: Feedback, Navigation, and Guidance

Group 1	Feedback (1)	Navigation (0.5)	Guidance (0)	Result
Validation with feedback	3	0	0	Feedback
Virtual use of product	2	1	0	Feedback
Visual feedback	2	0	1	Feedback
Direct manipulation	2	1	0	Feedback
Price update	2	0	1	Feedback
Technical information	2	0	1	Feedback
Camera reset	1	2	0	Navigation
Undo	0	3	0	Navigation
Material selection	0	3	0	Navigation
Flexible navigation	0	2	1	Navigation
Offline access	0	3	0	Navigation
Need-based or parameter -based	0	3	0	Navigation
Reference object	1	0	2	Guidance
Physics providence	1	0	2	Guidance
Guidance	0	1	2	Guidance
Selecting manufacturing and assembly method	0	1	2	Guidance
Multiple mechanisms	0	1	2	Guidance
Side by side comparison	0	0	3	Guidance
Library of modules and producible	0	0	3	Guidance
Users' design access	0	0	3	Guidance

7.5.3 The toolkits' layout

From the beginning of the first study, the author tried to create a user-centred high-fidelity prototype. However, the layout or structure of the prototype was always in question, due to the lack of existing knowledge. Therefore, the result of the third task was not only helpful to make a toolkit with a satisfying layout, but also to gather more insight to create the design framework later.

Each group's layout design is depicted sequentially in Figure 7-3, Figure 7-4 and Figure 7-5 below. For exploring customer preferences more easily regarding the on-screen location of various features, the layout generated by each participant group was re-created in Adobe Illustrator Figure 7-6, Figure 7-7, and Figure 7-8. The integration of these three designs into a single composite image was achieved by calculating the average location of each feature relative to the top left corner of the screen. This was an arbitrary coordinate centre, and any other screen position could have been used. Figure 7-9 shows the overall integration of features' locations in one representation. The features that had different locations are excluded from this composite, including physics providence, and price update.
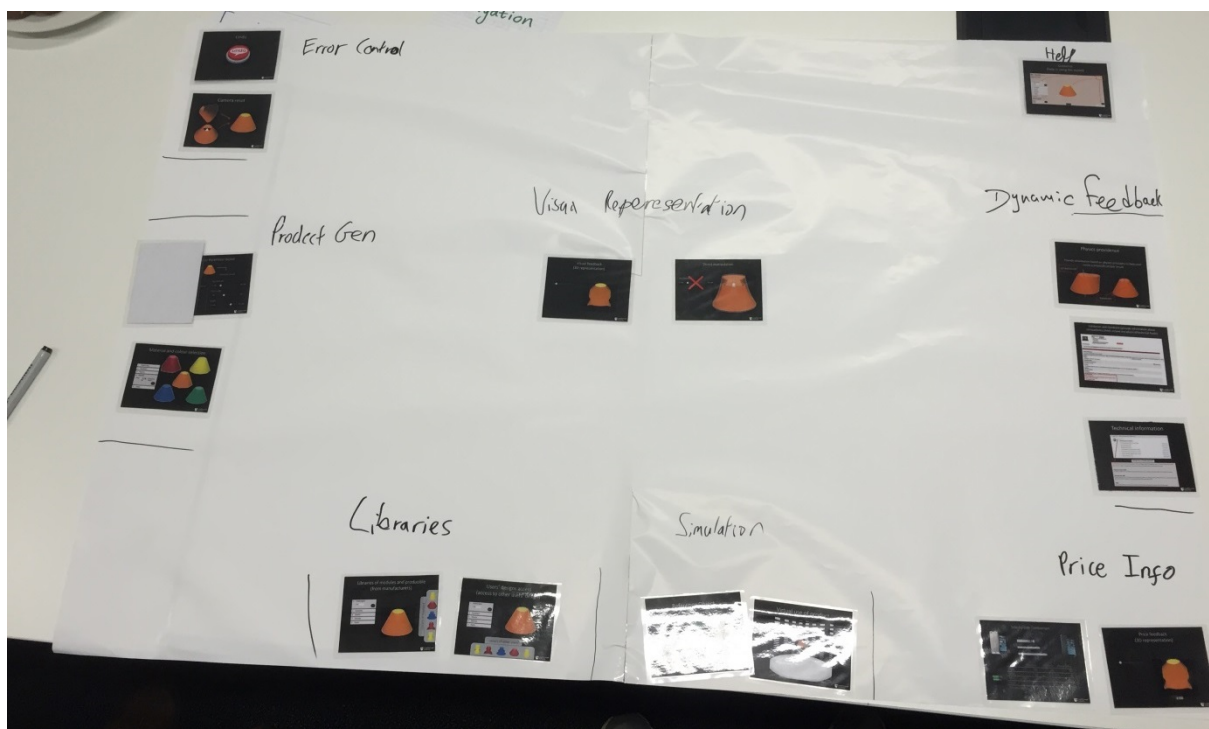
Figure 7-3 Group 1's layout design for the toolkit

119
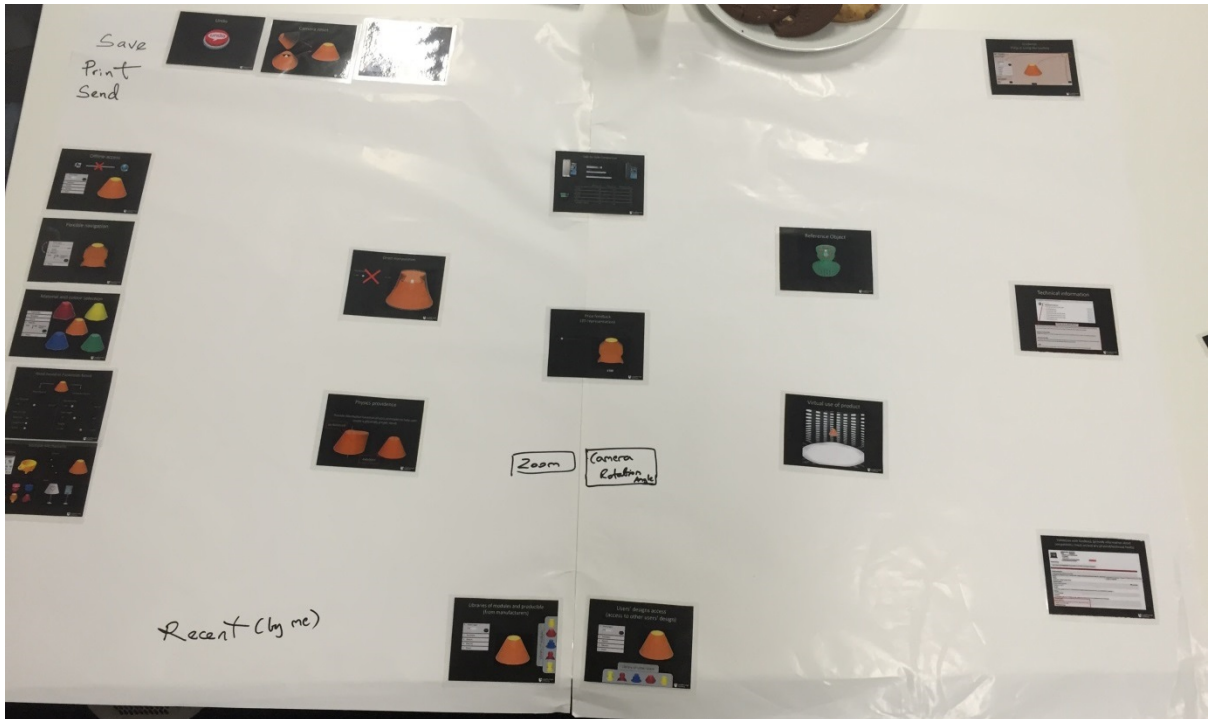
Figure 7-4 Group 2's layout design for the toolkit

Figure 7-5 Group 3's layout design for the toolkit

The integration result of all the layout designs was instrumental to design the prototype layout for the second study (Chapter 8). Most notably, the features that represent navigation are concentrated on the left side of the screen. The features for guidance are scattered on the right side and bottom of the screen, and the features for feedback are scattered unevenly through the centre, right and bottom of the screen.

Black font: extra information by groups
Red: Feedback
Blue: Guidance
Green: Navigation

Figure 7-6 Group 1's layout design representation
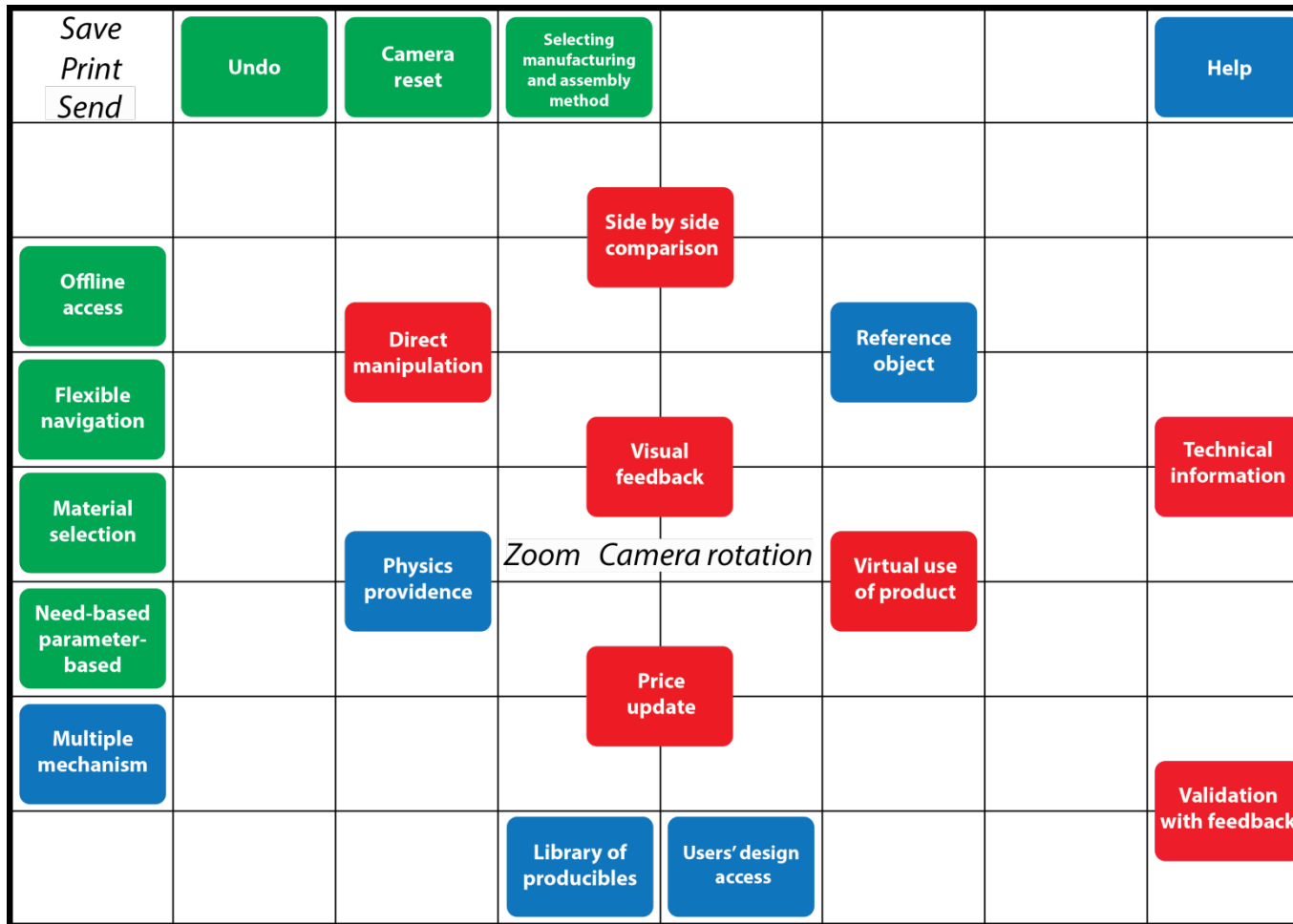
Black font: extra information by groups
Red: Feedback
Blue: Guidance
Green: Navigation

Figure 7-7 Group 2's layout design representation

Help							**Validation with feedback**
Need-based parameter-based							**Technical information**
Users' design access							**Selecting manufacturing and assembly method**
Material selection	*Main functions*		**Direct manipulation**	**Visual feedback**			**Side by side comparison**
Multiple mechanism			*Main display*				*Options*
Price update							
			Feedback diplay buttons				
Undo	*Redo*	**Physics providence**	**Reference object**	**Virtual use of product**	**Camera reset**		

Black font: extra information by groups
Red: Feedback
Blue: Guidance
Green: Navigation

Figure 7-8 Group 3's layout design representation

123
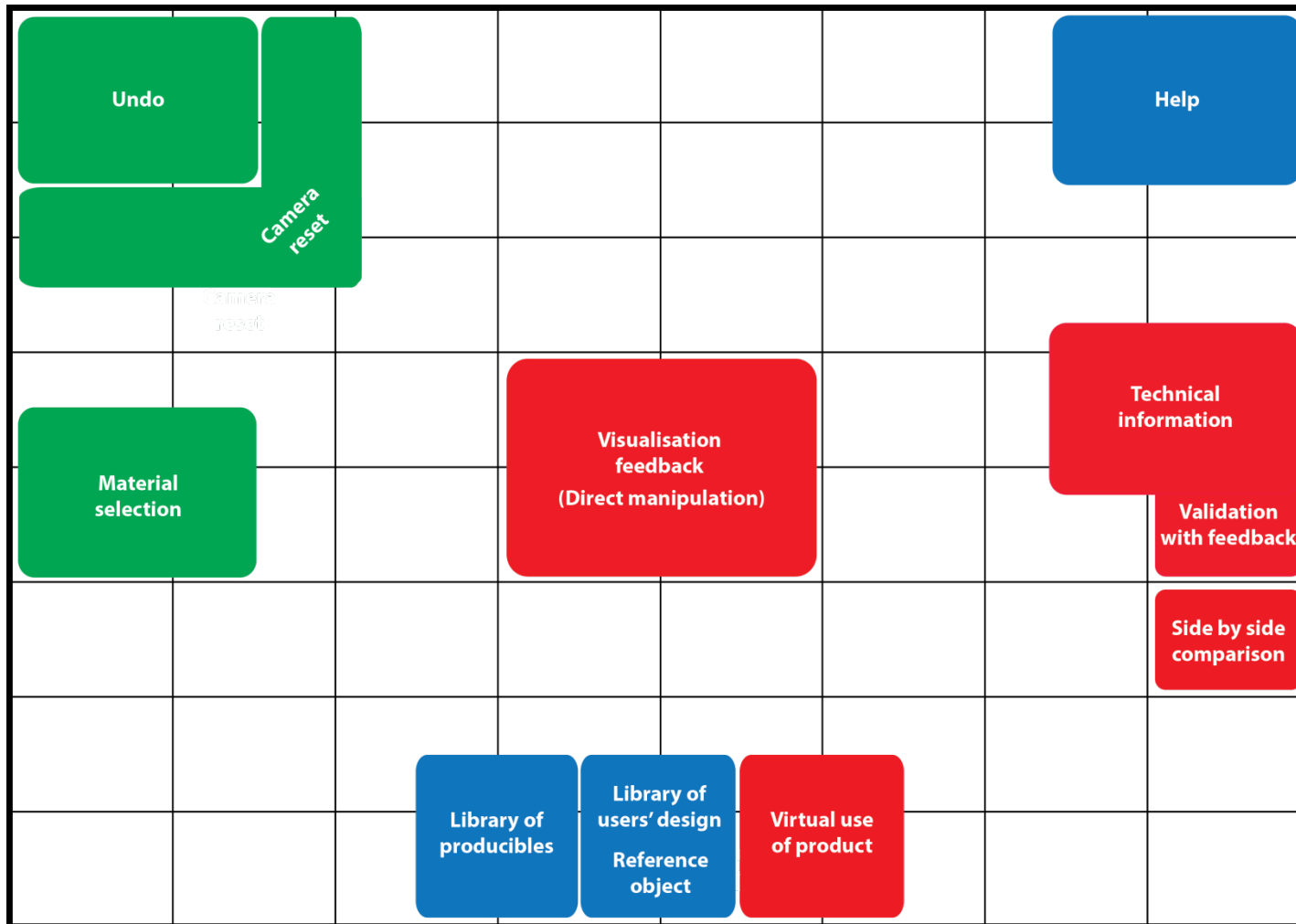
Red: Feedback
Blue: Guidance
Green: Navigation

Figure 7-9 Integration of all layout designs into one joint layout

The toolkit had an intuitive structure, and common layout that was acquired from the workshop. The workshop participants tried to put elements in the place where they usually encounter them in common software programs such as Word (Microsoft). As an example, the undo button had been placed beneath the product visualisation in the first instance in the prototype, but as the workshop result showed, the participants' preference was at the top left corner, where undo is commonly placed in most Office programs such as Word, Excel, etc.

7.6 Conclusion

This workshop aimed to investigate further the content and layout of MC toolkits. This is helpful not only to prepare the prototype for the second study, but also to enrich the framework. With the first task, an expectancy ranking of the features from the users' point of view was obtained. It was shown that it shares almost the same result with the first study's, and validates the selection of visual feedback, price update, material selection and flexible navigation as the four most important features in the first study. Therefore, it was concluded that the most important features are almost identical to the most expected features of the MC toolkits (objective 2).

Concerning the second task, the categorisation helped participants to understand which feature belongs to which element of the UI, and this helped them in the final task. However, it did not bring about any outstanding results (objective 4). The final task, wireframing, led to discovering the favourable layout for these toolkits (objective 3). Toolkit layout can help users navigate through the options easily, and get useful feedback instantly when needed. The findings from this workshop shed light on user-centred MC toolkit design, especially on content and layout, specifically layout configuration.

Overall, from the first task, visual feedback, price update, material selection, undo and guidance are sequentially the most expected features to be included in the toolkits.

More specifically, the workshop led to the following conclusions:

- The representation of a feature's location on the screen based on integration of the groups' layout design is mostly in line with official internet usability guidelines (U.S. Department of Health and Human Services 2006). For example, the usability guidelines state that navigation features should be included in the left panel of a webpage, whether they are primary or secondary, which is consistent with the workshop`s results. This shows that it is more likely for MC toolkits to inherit their UI characteristics more from online websites rather than CAD software programs (objective 1).

- Four features that were put in the threshold group (the most expected ones) were the ones that were previously ranked as the most important ones.

Similarly, the features that were put in the excitement attributes group were previously ranked as the least important ones. The overlapped results from workshop and study 1 specified which features are essential for a toolkit: visual feedback, price feedback, material selection, and flexible navigation (objective 2).

What users say they do and what they actually do are often not the same (Sainio et al. 2006). Even though self-reporting and data collection based on users' self-reporting can potentially provide data relating to preferences, performance measures and observation are also needed to achieve a more comprehensive view (Sainio et al. 2006). The study detailed in the following chapter addresses this issue.

Chapter 8 : Study 2 – Usability and User Interaction of MC toolkits

8.1 Introduction

After obtaining the preferred content from the first study and workshop, and the layout from the workshop, the findings were then integrated into a prototype toolkit for lampshades. Then, it was ready for validation, examinations and data collection. Therefore, the toolkit had to be tried by different users to be investigated further. This study was performed on the usability of solution space of the prototype to obtain user insights. Furthermore, the number of DoF of the MC toolkit could be further investigated through creating and testing different versions of the toolkit. In order to do so, three versions of the prototype were created, based on three levels of DoF: low, average, and high. Consequently, in the first task, the participants have three versions of the toolkit to use and decide which one they prefer more. In the second task, the selected version out of the three is presented to the participant to go through a process of creating their own lampshade. A survey was used to find out about the pros and cons of the AM-enabled toolkit in detail. The data collected from this study were integrated into the design framework later.

8.2 Aim and Objectives

The main purpose of doing this study was to find out about the usability and interaction of users with AM-enabled MC toolkits, and extract user insights that would help to create the design framework. The participants were asked to go through a process of customisation using the prototype AM-enabled MC toolkit for lampshades. This was done in order to:

1- Find out the most suitable system to implement a user-centred AM-enabled MC toolkit

2- Observe the customisation process on the prototype

3- Collect likes/dislikes or positive/negative points of the prototype

4- Discover participants' preference regarding DoF for MC toolkits

Furthermore, these questions and results of the study help to validate the collected data and results obtained from the first study and workshop.

8.3 Study Rationale

Users do not approach a system completely devoid of capability when faced with an unfamiliar system. It has been suggested that we have a mental model of the world in our heads that enables us to explore unfamiliar situations 'they are … the models people have of themselves, others, the environment and the things with which they

interact. People form mental models through experience, training and instruction.' (Norman 1988, p. 17):

Several studies have been carried out in order to discover whether mental models are used by people when performing tasks on devices and systems (Rogers et al. 1992). The general assumption is that they use some type of incomplete or vague models. Unfortunately, the UI designers cannot simply ask users to describe or draw a picture of their mental models since (1) the users do not have access to their models; either they are not aware of them, nor can they provide insight about them (2) all kinds of users are not accessible. Therefore, in order to develop mental models, information needs to be collected by observing users in their workspace or laboratory environment, directly or indirectly, and by doing interviews or asking them to fill in questionnaires or surveys. It is therefore, important to not just talk to users, but observe them in their own or simulated environment (Hackos & Redish 1998), as decided in this study.

8.4 Method

According to Redmond-Pyle & Moore (1995), investigating users' mental models will help UI designers discover the design strategies that can be used to make a new system easily understandable and accessible They identify three main types of evaluation for UI:

1- Review of a UI by a Human-Computer interaction (HCI) expert (or heuristic evaluation)

2- User testing (or observation of users)

3- Survey of user attitudes and perception

As described by Stone (2005), the first method is a very quick way of evaluating by letting the HCI expert review a UI; however, the expert may not have some problems that a real user will encounter. Therefore, expert evaluation is complementary to end-user evaluation (Redmond-Pyle & Moore 1995).

The second type of evaluation is observation. It is done to see how the users perform the tasks using the GUI, what errors they make, how long the task takes, etc. observation produces rich qualitative data, and the difficulties of using the system can be highlighted by observing the users. One method of this second type of evaluation is called 'cooperative evaluation' in which users are encouraged to think aloud about what they are trying to do, and the system's responses they receive by their actions (simply their reactions) (Redmond-Pyle & Moore 1995).

In addition, the third type of evaluation involves asking users to answer a number of questions about the system. Surveys can be used on a large number of users.

However, the questions need to be phrased carefully to prevent bias (Redmond-Pyle & Moore 1995).

The focus of research needs to be on understanding deeply who the users are, and how they perform their tasks, in order for UI to be designed in a user-friendly way. Users are mostly unsuccessful to articulate what they really do with UI; even if they are very familiar with the task, which they perform (Hackos & Redish 1998). The more appropriate way to analyses the user's behaviour and consequently the interface, is to observe them while they are using the interface. Since the aim of this study was to explore user interaction with toolkits, and extract useful data for creating the design framework, based on the available usability evaluation methods, a combination of observation and survey was chosen. The reason for choosing this was that accessing HCI experts is more difficult and more expensive than ordinary users, also because as mentioned previously, it is not the first best option, but complementary to the end-user evaluation.

Observing users in their natural setting is an essential part of user-centred design. In addition to finding out what users do, those parts of the system, which users like or dislike, can also be discovered. The observation can be either direct or indirect. In the direct observation, users may be interrupted by the observer either in their natural/workspace or in a laboratory environment. In indirect observation, users are monitored without any interruption, and usually video recorded (Stone 2005). Since participants were required to be monitored specifically when they were using the interface, direct observation had to be chosen.

Observing, listening, and talking to users in their own workspace (site visits/field testing) counts as the best and more realistic way to design useful products (Hackos & Redish 1998). Participants need to be observed while they are doing the customisation. This was not a feasible approach for this study, therefore, the easier technique of site visits was chosen, to bring the user to a work place and locate them in an artificial workspace (controlled study - laboratory testing), and to ask them to do the tasks (Redmond-Pyle & Moore 1995). In terms of artificial environment or workspace, users were offered some biscuits to simulate their home environment. There was also a draw to motivate the users to take the customisation task seriously. The winner would receive the lampshade he or she designed in the toolkit.

Task scenarios are given to typical end-users, who are observed to see how they perform the task using the GUI, how long the tasks take, what errors they make, etc. An observational task is usually based on requesting participants to do pre-defined task scenarios. There are various techniques for collecting the observational data (Redmond-Pyle & Moore 1995). The observation in this study supported a number of methods to maximise the data extraction process. The methods used were real-time note taking, and thinking aloud. The simplest way for the data collection among the various techniques is real-time note taking. The significant events, errors, and users'

actions are recorded, and in this format, a prepared structured worksheet made the task easier (Redmond-Pyle & Moore 1995).

In the thinking aloud method, the user is encouraged to think aloud while they are executing the task. The user is prompted with questions such as: 'What are you doing now?', 'What are you looking for?', 'How do we do that?', 'What will happen if you choose that option or why has the system done that?' It is important to ask users to explain in their own words, and let the observer know if they are confused about anything to ensure that the problem is identified (Redmond-Pyle & Moore 1995).

Screen-capturing the participants' interaction was considered as an option. However, that would have required a lengthier analysis, which would have related more to user behaviour or psychological research rather than helping to understand better the previous findings, namely evaluation of obtained usability requirements and finding out more about DoF. Therefore, screen capturing was deemed as being beyond the scope of the research questions being pursued.

8.4.1 Participants

Each evaluation session had a single participant using the system on his/her own. Five participants are enough for this type of data collection (Stone 2005), but the sessions were continued with more than five users until the data gathered were sufficient for helping the author to decide what to do next. Furthermore, the collected data showed a similar pattern and information after the eighth or ninth participants. Therefore, the final number of participants was 10.

Participants had to be computer literate and although the toolkit could be used by any individual, all the participants were over 18 years old, to simplify the controls needed to be done over the study. Other than checking the age of the participants, no other personal information was collected.

The recruited participants needed to represent typical and real users, reflecting different skills, domain knowledge, and system experience. Participants were recruited with this in mind.

8.4.2 Material

8.4.2.1 AM-enabled MC toolkit

The main source of material for this study was an AM-enabled MC toolkit. The programming of the toolkit was started during the first study. The content and arrangement of the elements were then amended step-by-step based on the result obtained from the first study and workshop.

For the implementation part of this prototype toolkit, an experiment was initialised to compare four different systems. This experiment was based on creating the AM-

enabled MC toolkit in two popular CAD (SolidWorks API and Grasshopper) and two available 3D-enabling libraries (Three.js and Processing), and comparing them in action.

For the purpose of investigating the possibility of using SolidWorks API as a platform for MC toolkit, a laptop was modelled in SolidWorks with the aid of its API (Figure 8-1). The decription about how the laptop was programmed in the API is explained in Appendix 18 SolidWorks API Code. The same laptop was also modelled in Grasshopper as well (Figure 8-2). The detailed modelling of the components in Grasshopper was not explained because a huge number of connections and components were required to create a complex object like a laptop (Figure 8-3).

The investigation into the possibility of using 3D-enabling libraries was done using Three.js and Processing, which were both used for this research because of their easier way of programming than WebGL. Furthermore, Three.js is a library for WebGL, so in fact for the purpose of a basic toolkit, it was appropriate. Furthermore, as discussed before, it is currently used in several AM-enabled toolkits. A similar laptop was modelled in HTML with the aid of Processing. The description about the detail of the code in Processing was omitted here. Finally, a lampshade was selected and modelled with the Three.js library, and the details of the programming are explained in the next section. The reason for moving from laptop in the past three systems to a lampshade in Three.js was that customisation of the surface of the laptop was not feasible, at least at the time of this thesis and the near future.
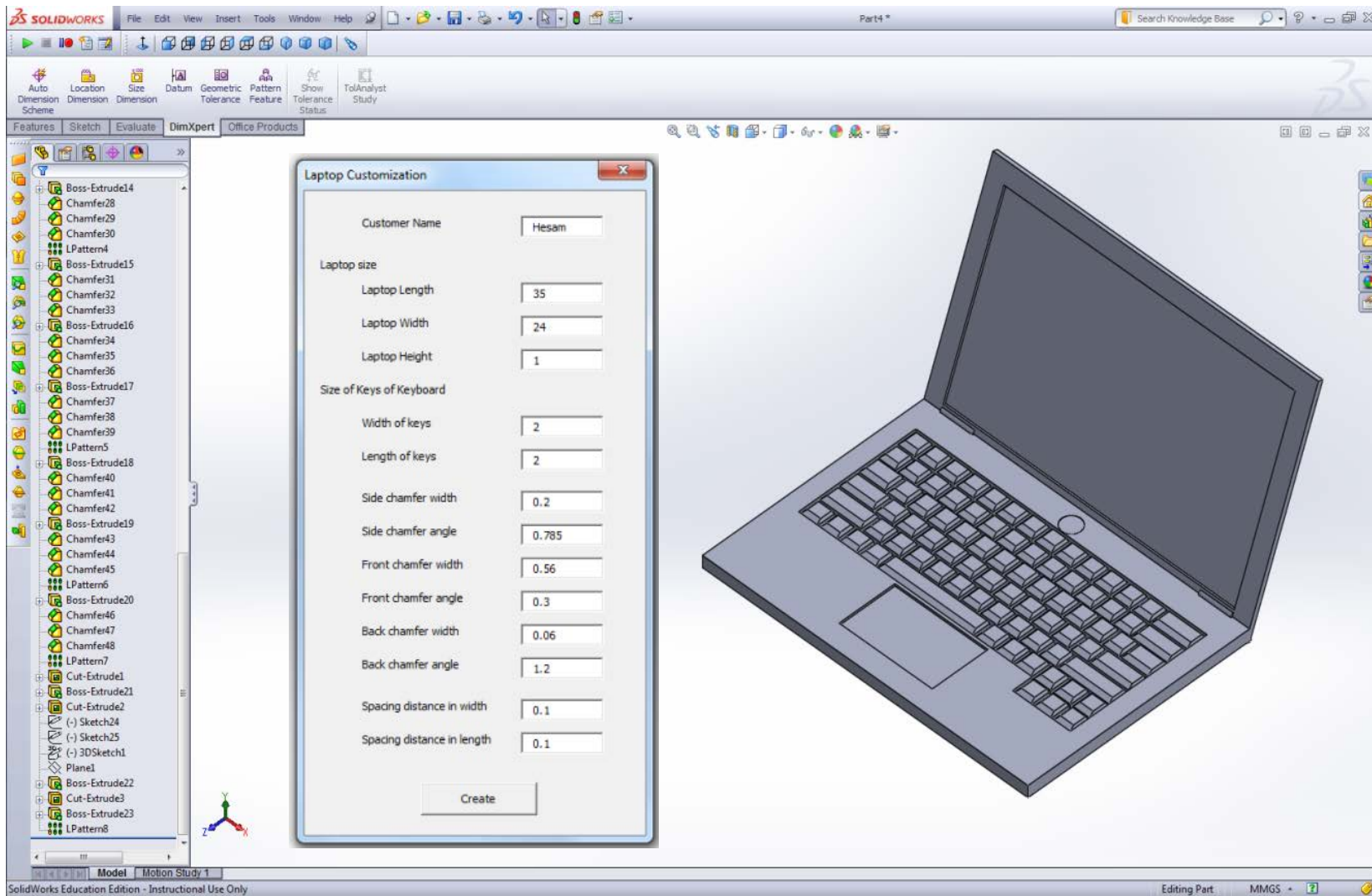
Figure 8-1 A demonstration of parametric modelling in SolidWorks API (the userform on the left and 3D model on the right)
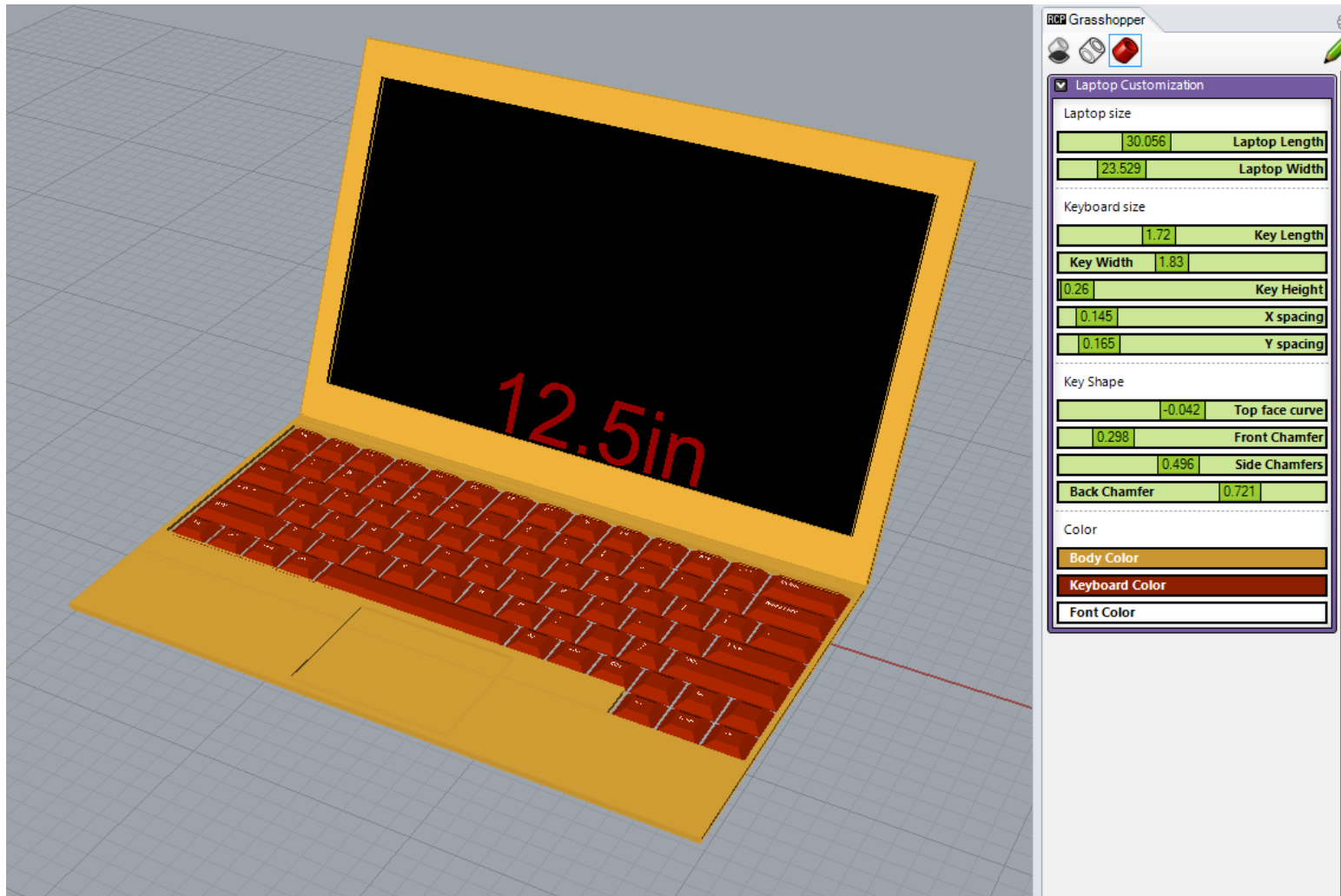
Figure 8-2 An example of Grasshopper interface, specifically to show control panel (on the right)

133

For the purpose of doing this investigation, six specifications were devised as explained below:

Automation: so that similar products based on specific input parameters can be created through running a set of commands repeatedly. This facilitates automatically building similar products that only differ in a few details.

Real-time update: enables any changes made to the parameters to take effect as they are happening. For example, the real-time visual update of a 3D CAD model of a product would show any small changes made to the parameters of the shape as it happens. This eliminates the frustration of pressing a 'build' or 'run' button to see the feedback after any changes have been made to the parameters.

Common CAD tools: such as extrude, revolve, loft, etc. make modelling easy for experienced users. The construction and modification of solids and surfaces without such tools can be difficult for users or designers.

Web-based capability: to access and manipulate data online through a web site makes the customisation task more convenient by allowing customers to go through the options and configurations online.

No installation or add-in: means that there is no need to install any programmes or add-ons to have the 3D graphics shown on the screen. Technologies such as WebGL provide such functionality.

Feature integration: MC toolkits typically contain features such as visual update, price update, side-by-side comparison, material selection, etc. Allowing this means that it is possible to integrate these features as diversely as possible in the solution space of these interfaces.

The selection of these specifications are based on the nature of AM-enabled toolkits, which borrow specifications/features from both CAD systems and sale websites. Therefore, the specifications of CAD systems which ease the customisation, either for designers and users, as well as the characteristics of (MC) sales websites for users were summarised and presented here. Table 8-1 summarises the characteristics of each CAD and 3D-enabling system tested.

Table 8-1 Comparison of characteristics of CAD software programs and 3D-enabling libraries

	CAD programs/3D-enabling libraries	Characteristics
CAD programs	SolidWorks API	Automation Common CAD tools
	Grasshopper	Automation Common CAD tools Real time update
3D-enabling libraries	Processing	Automation Real time update Web-based capability No Installation or add-in
	Three.js	Automation Real time update Web-based capability No Installation or add-in Feature integration

Based on Table 8-1, 3D-enabling libraries are the most promising way for implementing MC toolkits since not only do they enable web-based capability, but also integration of variety of features. Specifically, Three.js is the best for this. Furthermore, there is no need for customers to own or register for a license in order to use these 3D-enabling libraries, and they are available free for personal or commercial use. The feature integration plays a key role here for the selection of Three.js for the rest of this thesis. This is due to the fact that the previous study and workshop highlighted the most essential features, such as price feedback, etc. which are almost impossible with any other program.

In the toolkit developed for this study, a product type can be chosen (Figure 8-5). After choosing the product type, a parameter can be selected, such as radius, edges, sides, and none (which means putting the visualisation in the preview mode without showing any control points) (Figure 8-6). Next, a pattern can be tried to be put on top of the design, such as hive, star, bevel, etc. (Figure 8-7). Next, a colour or transparency/opacity can be added to the lampshade design (Figure 8-8). Finally, in the physics section, installation of the lampshade can be assessed in term of proper installation after manufacturing (Figure 8-9). At the same time, there is access to price, dimension, and shadow visualisation (Figure 8-10), which shows virtually the reflection of shadow on the walls (Figure 8-11). It is also possible to undo, reset

camera view and save the design at any stage of the process (Figure 8-12). The whole process is shown as a flow diagram in Figure 8-4.

1 Selecting the product type (design base)

2 Customising of different parameters of the shape (design parameters)

3 Selecting patterns to integrate on the design

4 Modification of colours and transparency

1 **Product types**
CONE   NEXT

2 **Parameters**
RADIUS ○ EDGES ○
SIDES ○ NONE ○   NEXT

3 **Patterns**
Flower | Bevel | Star
Leaf | Hive | Ring
Polka | None
NEXT

4 **Materials**
Plastic   ○ Transparent
○ Opaque
NEXT

8 Saving the result, using undo or resetting the camera view

7 Shadow visualisation for shade simulation

6 Checking the dimension in real time

5 Checking the centre of gravity for installation and physics check

SAVE   UNDO   CAMERA RESET
name your design

SHADOW VISUALIZATION
Shadow visualization ☐

Dimensions: 25 x 10 x 15cm

5 **Physics**
☐ Center of Gravity   START OVER

Figure 8-4 The process of customisation of the lampshade in the developed toolkit as a flow diagram

138

Figure 8-5 The product types menu element in the lampshade MC toolkit (cone and poly-cylinder are two available product types)

Figure 8-6 The parameter menu element in the lampshade MC toolkit (radius, edges, sides are the available parameters)

Figure 8-7 The patterns menu element in the lampshade MC toolkit (there are seven available patterns)

141

Figure 8-8 The materials menu element in the lampshade MC toolkit (there are six available colours and transparency options)
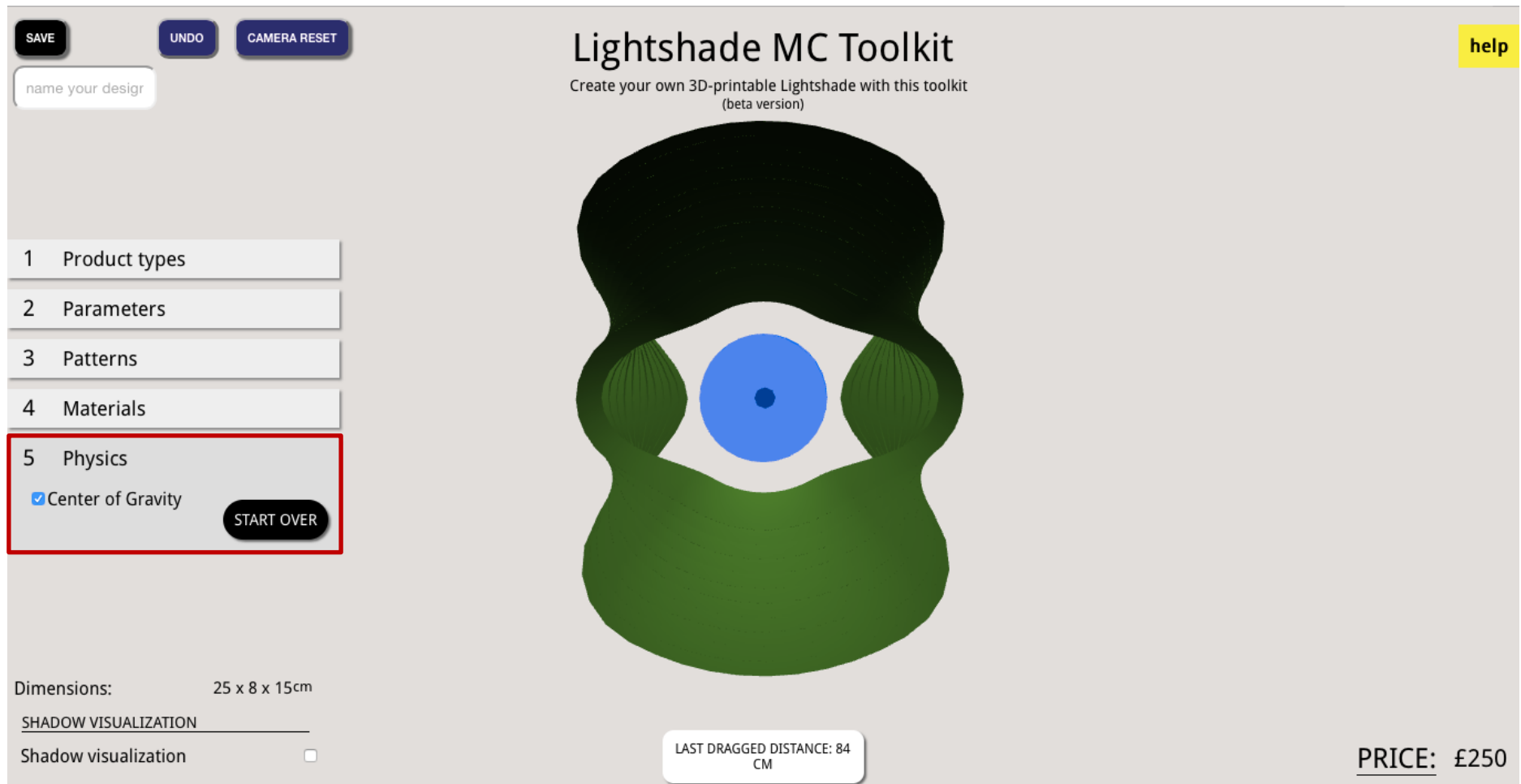
Figure 8-9 The physics menu element in the lampshade MC toolkit (the black dot must be inside the blue cylinder)

Figure 8-10 The price, dimension, and shadow visualisation as the feedback of the lampshade MC toolkit
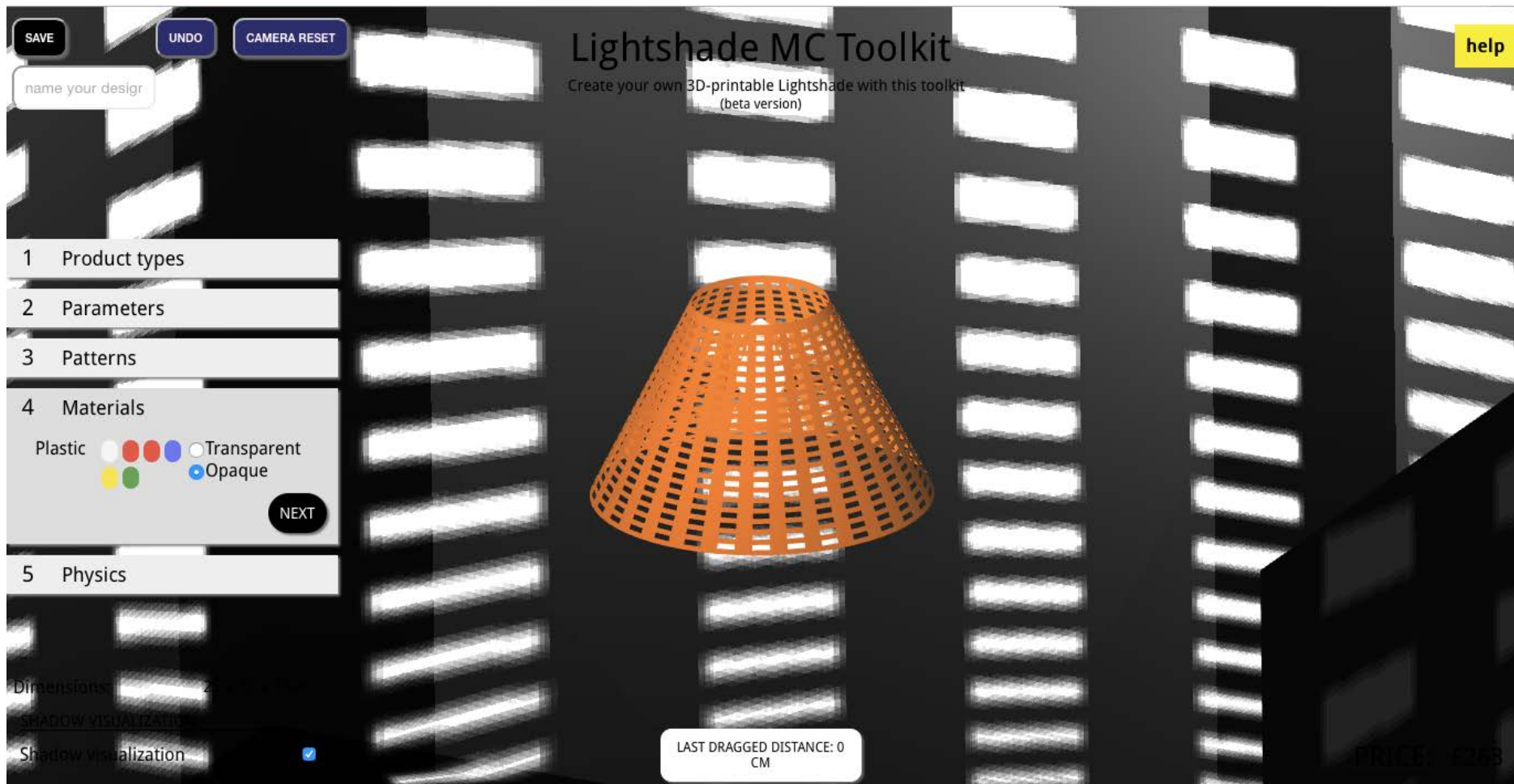
Figure 8-11 The shadow visualisation as virtual shade representation in the lampshade MC toolkit

145

Figure 8-12 The save, undo, and camera reset buttons in the lampshade MC toolkit

146

The amount of DoF (high, average or low) was uncertain. Based on the result from the first study, 25 was considered by most of the participants as the preferred number of options, therefore, 25 was chosen as the reference for the normal or average amount. It should also be noted that creating a toolkit exactly for 25 DoF may not be very applicable, therefore, counting the varying parameters can be a good scale for DoF (Franke & Piller 2003). Finally, three toolkits with 18 (low), 23 (average), and 28 (high) DoF were created.

8.4.2.2 Questionnaire

Another material that was required for this study was the questionnaire. As creating a valid survey for evaluating usability is a time-consuming and a professional activity, the most effective approach was to use a standard usability survey such as SUS (the System Usability Scale test) (Redmond-Pyle & Moore 1995). SUS is a Likert-scale questionnaire. It contains a variety of aspects of system usability. SUS is freely available for use in usability assessment, and has been used for a variety of research projects and industrial evaluations; the only requirement for its use is that any published report should acknowledge the source of the survey.

Table 8-2 brings together a comparison summary of different usability surveys. The SUS test has several good attributes that have been chosen for this study (Bangor et al. 2008):

1- The main distinguishing attribute is that it can be used for any interfaces, from interactive voice response systems and novel hardware platforms to the more traditional computer websites

2- The test is relatively quick and easy to use and administer by both participants and administrator

3- The score that is provided by the survey is on a scale that is easily understood by a wide range of people, who may have little or no experience of usability

4- The survey is a cost effective tool since it is a non-proprietary test.

Table 8-2 Summary of explored usability surveys (Bangor et al. 2008, p. 575)

Survey Name	Abbreviation	Developer	Survey Length (questions)	Availability	Interface Measured
After Scenario Questionnaire	ASQ	IBM	3	Non-proprietary	Any
Computer System Usability Questionnaire	CSUQ	IBM	19	Non-proprietary	Computer-based
Post-Study System Usability Questionnaire	PSSUQ	IBM	19	Non-proprietary	Computer-based
Software Usability Measurement Inventory	SUMI	HFRG	50	Proprietary	Software
System Usability Scale	SUS	DEC	10	Non-proprietary	Any
Usefulness Satisfaction and Ease of Use	USE	Lund	30	Non-proprietary	Any
Web Site Analysis and Measurement Inventory	WAMMI	HFRG	20	Proprietary	Web-based

The original SUS instrument (Brooke 1996) includes 10 statements that are scored on a 5-point scale measuring strength of agreement from strongly disagree to strongly agree. Final scores from SUS will be scored between 0 and 100, where a higher score shows a better usability. In this study, a slightly modified version of the survey was used:

1- The word 'cumbersome' in the statement 'I found the system very cumbersome to use' is not as recognisable to non-English speakers as its more common synonym: 'awkward' (The British National Corpus, version 2 (BNC World) 2001), and most test administrators reported success in using the latter in their explanation of 'cumbersome' (Bangor et al. 2008). Therefore, both words were used together to clarify meaning for non-native English speakers.

2- The word 'very' and 'unnecessarily' in the statements below have been eliminated:

'I found the system 'unnecessarily' complex'
'I would imagine that most people would learn to use this system 'very' quickly'

'I found the system 'very' cumbersome to use'
'I felt 'very' confident using the system'

This is due to the fact that the words 'very' is understood differently by participants (potentially causing bias), and it is suggested that it should not be used in surveys or questionnaires (Finstad 2006).

Therefore, the modified version and the original version of the SUS test are brought together in Table 8-3.

Table 8-3 The original SUS statements (Brooke 1996) **and the modified statements used in this study**

Original SUS Statements	Modified SUS Statements
I think that I would like to use this system frequently	I think that I would like to use this system frequently
I found the system unnecessarily complex	I found the system complex
I thought the system was easy to use	I thought the system was easy to use
I think that I would need the support of a technical person to be able to use this system	I think that I would need the support of a technical person to be able to use this system
I found that the various functions in this system were well integrated	I found that the various functions in this system were well integrated
I thought that there was too much inconsistency in this system	I thought that there was too much inconsistency in this system
I would imagine that most people would learn to use this system very quickly	I would imagine that most people would learn to use this system quickly
I found the system very cumbersome to use	I found the system cumbersome/awkward to use
I felt very confident using the system	I felt confident using the system
I needed to learn a lot of things before I could get going with this system	I needed to learn a lot of things before I could get going with this system

Due to the fact that a number of different questions for extracting other data were needed to be included in the survey, a customised version of the SUS questionnaire was generated. The customised version of SUS includes all of the questions of SUS for usability testing, plus some questions about DoF, based on different products, and an overall evaluation of the toolkit's elements.

In order to make the note taking task fluent and easy, an observation worksheet for note-taking was generated by merging two available tables in two books (Stone 2005, Redmond-Pyle & Moore 1995). The generated table is shown in Appendix 13 The

Evaluation Form for Study 2). The table has spaces for errors the user made, how long each task takes, and any significant events (such as a long pause while the participant is thinking about what to do next, or a question they raised).

8.4.3 Pilot

Two participants, one member of academic staff and a PhD student in the Design School were selected for the pilot study. They were selected based on the same requirements as mentioned previously for the main participants. A date was confirmed with them for the session, which was held in the Design School. To identify the final design of the study, a pilot study was held, and revisions were made according to the following issues, found in it:

- The video recording of the task was distracting as it was too close to the participants so the camera needed to be placed fairly far from them, which meant it was of no use. The video recording was therefore replaced by voice recording

- Some issues regarding the UI were identified, which caused errors during customisation. These were mainly identified as bugs in the programming of the interface, and were corrected by amending the code

- The user interface was not clear enough to the participants, especially who have not had experience with these toolkits.

8.4.4 Procedure

The participants were requested to participate in the study by an email containing the participant's information sheet (Appendix 12 Participant's Information Sheet for Study 2). They were also informed of the incentives, as a compensation for their time and effort for their participation. Following their agreement, a time was agreed for the session with an email.

There was no need for them to bring anything to the session. However, they were provided with snacks to simulate their home or work environment. They were also encouraged to bring anything with them that they wanted to show or discuss in relation to the study.

Each participant was required to sign the consent form (Appendix 11 Consent Form for Study 2) at the beginning of the session. After signing the consent form, they were asked to sit comfortably as if they were customising a product at home or work.

After signing the consent form, they were given the first task. In this task, they were provided with three versions of the interface. Screen captures of those three versions were presented briefly (Figure 8-13, Figure 8-14 and Figure 8-15), however, for example in the 'pattern' section, the number of options are clearly different

throughout in terms of different DoF. They were asked to use those three interfaces to create a lampshade in each, and to choose their preferred one. They were also asked to think aloud during interaction with the toolkit in terms of what they were trying to do, and why, and what responses they were expecting to receive, and why. Overall, their thoughts about the responses, they actually received was important.
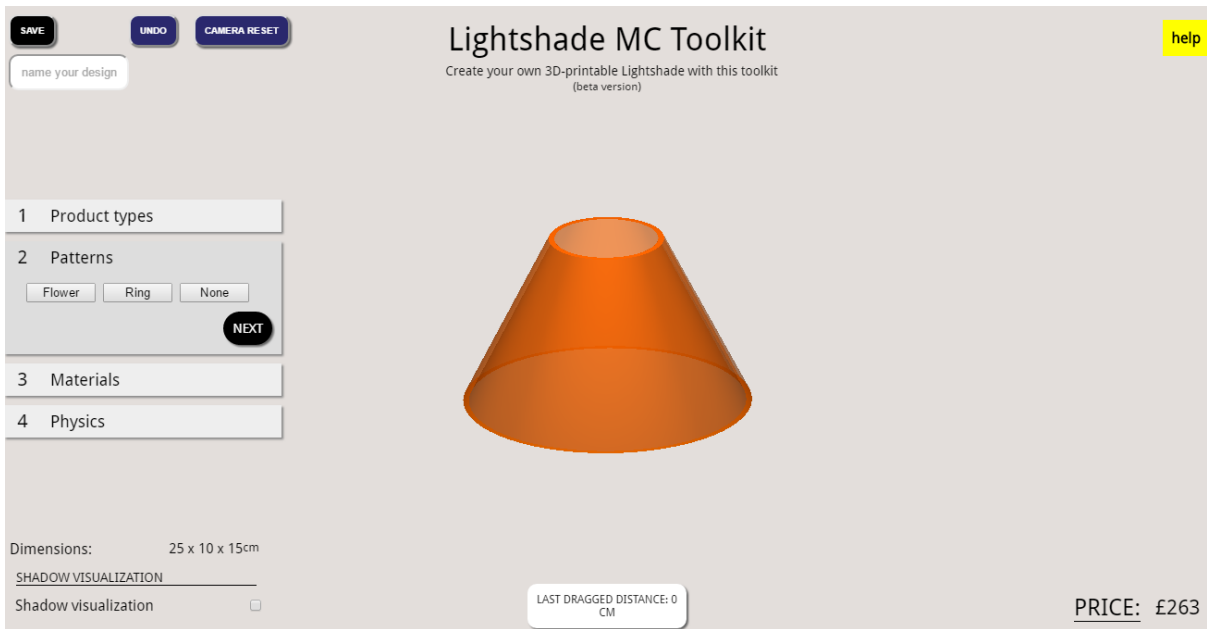
Figure 8-13 Low DoF version of the prototype
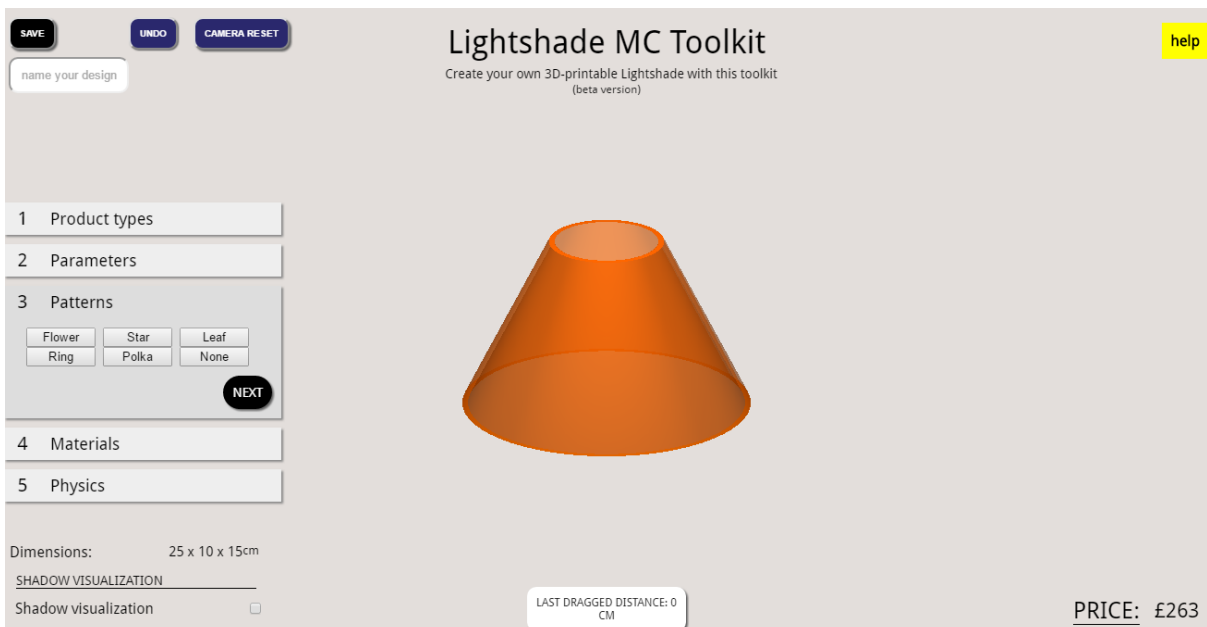
Figure 8-14 Medium DoF version of the prototype

151
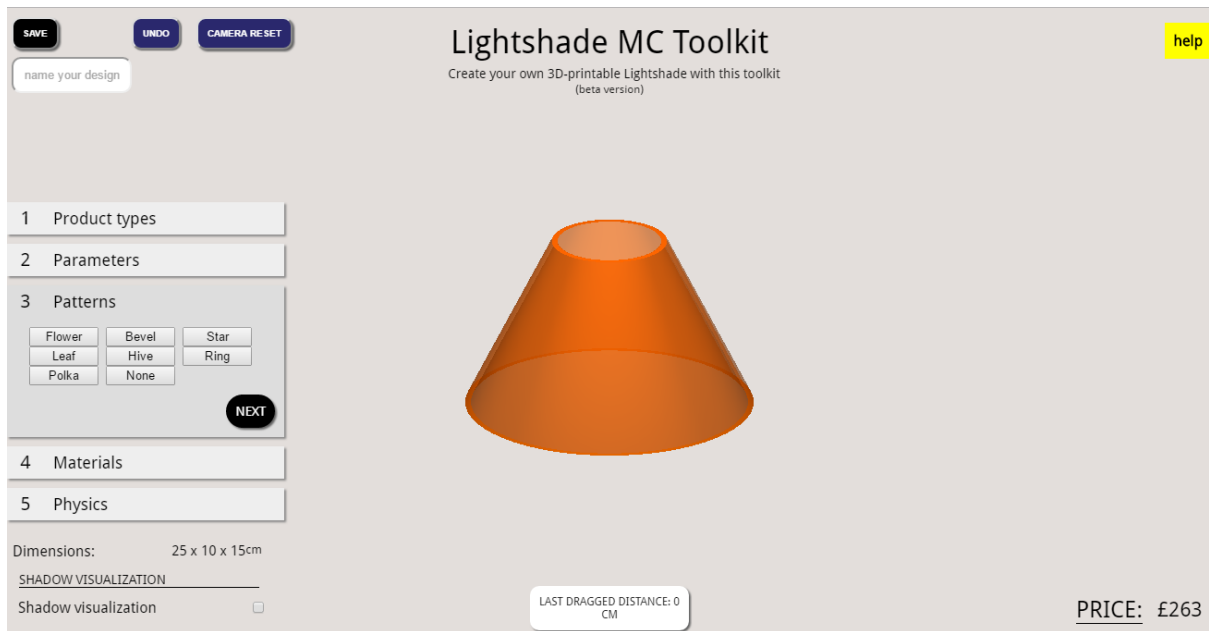
The next task continued with the interface they had chosen in the first task. In this task, they were required to customise a lampshade as if they were going to buy it. They had already been informed about the draw, to encourage them to take the tasks seriously. Likewise, they were requested to think aloud during their interaction. At the final stage, they were given a customised usability questionnaire to complete.

Whenever they found themselves in a situation, where they were unsure about what to do or what effects commands might have, they were allowed to ask the evaluator for advice. The evaluator suggested things for them to try or if they were really stuck, explained exactly what to do. This situation only happened a few times, and in most cases, it was due to a bug in the system that made the customisation task impossible. In this case, the evaluator tried to solve the issue, otherwise, the participant was asked to start the customisation from the beginning.

8.4.5 Analysis

This study resulted in two different data sets, which required different methods of analysis. The first part of data analysis belonged to the observation from the session itself. The second part related to the analysis of the data from the survey.

There are three different approaches to qualitative analysis of transcribed recordings from the observation (Robson 2011):

1- Quasi-statistical approaches: this approach uses phrase or word frequencies and inter-correlations as key ways of identifying the relative importance of concepts and terms

2- Thematic coding approach: in this approach, all parts of the data are coded, and labelled. Codes with the same label are grouped together as a theme. The research question, previous research, and theoretical considerations form the codes and theme occurrence. The themes are then used as a basis for further data analysis and interpretation

3- Grounded theory approach: a similar way of coding happens in this approach, with the difference being that the code arises from interaction with the data, the meaning or patterns in the texts, from the researchers' interpretation and coding consequently.

It is true that thematic coding is a less commonly used form of analysis compared to the other two; however, it can be used in a wide variety of settings. It is a relatively easy and quick method to learn and use. It is also accessible to researchers with little or no experience of qualitative research (Robson 2011). These all suggested that thematic coding should be chosen for the analysis of voice recording data and note-taking sheets. The analysis was undertaken following the procedure by Robson (2011). The steps toward thematic coding analysis are as follows:

The steps toward thematic coding analysis are as follows:

familiarising with the data, generating initial coding, identifying themes, constructing thematic networks, and integration and interpretation.

The audio recordings from the first and second tasks. were fully transcribed and imported into the QSR International NVivo software. After the transcription, initial ideas were identified through reading the data. Most of the phrases and sentences were assigned a node in the NVivo software.

The nodes were categorised as themes relating to similar issues. The themes were identified based on two techniques; repetitions and theory-related material. In the former technique, the topics that occur and reoccur are more likely to be a theme. In the latter one, the theoretical importance of a topic can be used to suggest a possible theme. Thematic networks were constructed when the nodes were connected to the related theme afterwards. Finally, describing, summarising and interpreting the patterns and network, and making comparison between different aspects of the data were undertaken and presented in the discussion section below.

The second part of the analysis was for the survey. For the first part of the survey, which used the free evaluation test (SUS), the analysis is as follows:

After asking participants to respond to each item after using the system, the data was then collected for calculating a single number representing a measurement of the overall usability of the system being studied. The scores for the items are not individually interpretable or meaningful on their own.

In order to calculate the score, first the score contributions from each item were summed. The score contribution of each item ranged from 0 to 4. For items 3, 5, 7, 9, 11 in this customised questionnaire, the score contribution is the scale position minus 1. For items 4, 6, 8, 10, and 12, the contribution is 5 minus the scale position. The sum of the scores was multiplied by 2.5 to obtain the overall value of the SUS score. The range of this score is 0 to 100, meaning that 100 is the value for the system with the most usability and 0 is the value for the system with the least usability.

For the second part of the survey, the data were tried to be interpreted individually and in some cases compared to literature if available.

8.5 Results and Discussion

The study aimed to examine the presence of potential use of the newly designed and prepared AM-enabled toolkit for MC. This study provided a large volume of data. For clarity, this section combined the result and discussion into one. Due to the data's qualitative nature, the results were summarised and discussed in subcategories. Additionally, a description of the observations noted by the researcher accompanied the results at some points. First, each participant's level of expertise on computer skills and knowledge was presented, and following that, the result of the thematic analysis was presented and discussed. As the next step, according to the research question, three themes were defined from the importance of the data, and they represented some level of patterned response or meaning within the analysed data. Finally, the results from the survey were presented and analysed.

8.5.1 Participants characteristics

Among the ten people that participated in the toolkit evaluation study, four had previous experience with similar MC toolkits, and six had had no experience. Their level of expertise on computer skills and knowledge is shown below. This also indicates that they have a wide range of knowledge of computer literacy to support their selection.

Variable	Number (percentage)
Very experienced and technical	4 (40%)
I'm good but not very technical	4 (40%)
I can cope with most software/websites	2 (20%)
I find most software/websites difficult to use	0 (0%)
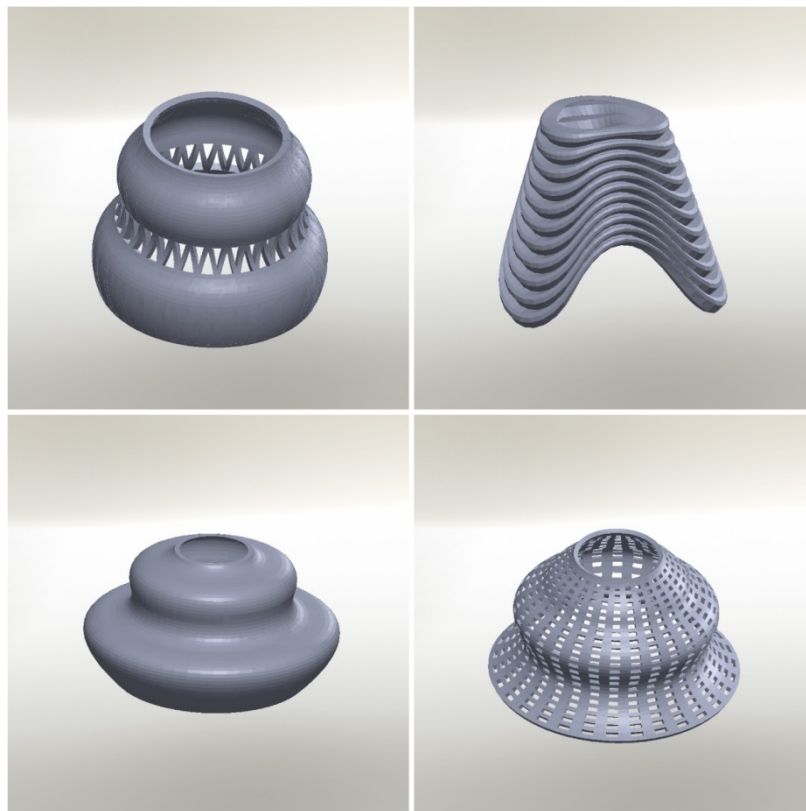
Figure 8-16 Several lampshade designs from participants, created by the developed toolkit

8.5.2 Ranking of the keywords (issues and positive comments)

It is important to examine if the issues regarding using the toolkit have any relation to the ranking obtained from the first study and workshop. In other words, if the toolkit was well prepared and designed, then there should not be issues from the highest ranked features included in the toolkit. The result showed this, and demonstrated that the findings from the first study and workshop were meeting participants'

preferences. However, several issues were raised, and Table 8-5 shows the ranking regarding the issues obtained from the participants. Guidance on control points, explanation of titles, and lack of design tools, wrong titles, and hovering and pop-out information were ranked in the first five places as the most problematic issues. Furthermore, there were also positive comments on the toolkit, which were presented afterwards in Table 8-6.

Table 8-5 Ranking of the lampshade MC toolkit issues obtained by the participants

Rank	Issues	Number of participants' comments
1	Lack of guidance on control points	8
2	Lack of explanation on titles	6
3	Lack of design tools	6
4	Wrong titles	5
5	Lack of hovering or pop out information	5
6	Lack of colour choices	4
7	Lack of customisation options	4
8	Unclear and inaccurate shadow visualisation	3
9	Too small control points	3
10	Poor demonstration of patterns	3
11	Too small price feedback	3
12	Wrong location for undo button	2
13	Lack of explanation on physics	2
14	Inconsistent use of none button	2
15	Need for pattern combination	2
16	Automatic physics check	1

Rank	Comments	Number of participants' comments
1	Varied/interesting/enough patterns	4
2	The ability to zoom in/out and dragging	3
3	Transparency option in material	2
4	Shadow visualisation is interesting	1
5	Helpful/encouraging usage of next button	1
6	Usage of selection as an input type for patterns	1
7	Usage of selection as an input type for colours	1
8	Help button is good	1
9	Attractive idea of creating an object by myself	1
10	Feedback on control points by changing colours	1
11	Unavailable options are greyed out	1
12	The existence of reference object	1

8.5.3 Thematic analysis of issues

Themes were mostly selected based on two techniques of repetition and theory-related material. Many of the issues regarding guidance were occurring and reoccurring, making it one of the themes. Arrangement was the main aspect of the previous workshop, which required an assessment in this study, and formed a theme. Usability was recognised as a theme because of the technique of theory-related material. Therefore, the issues mentioned in the previous section were categorised into these three themes, shown in Figure 8-17. The figure depicts the association of each issue and its impact on themes. It is possible to identify how each issue can cause multiple impacts on UX, and reversely, each of the themes can be affected by various elements of the UI.
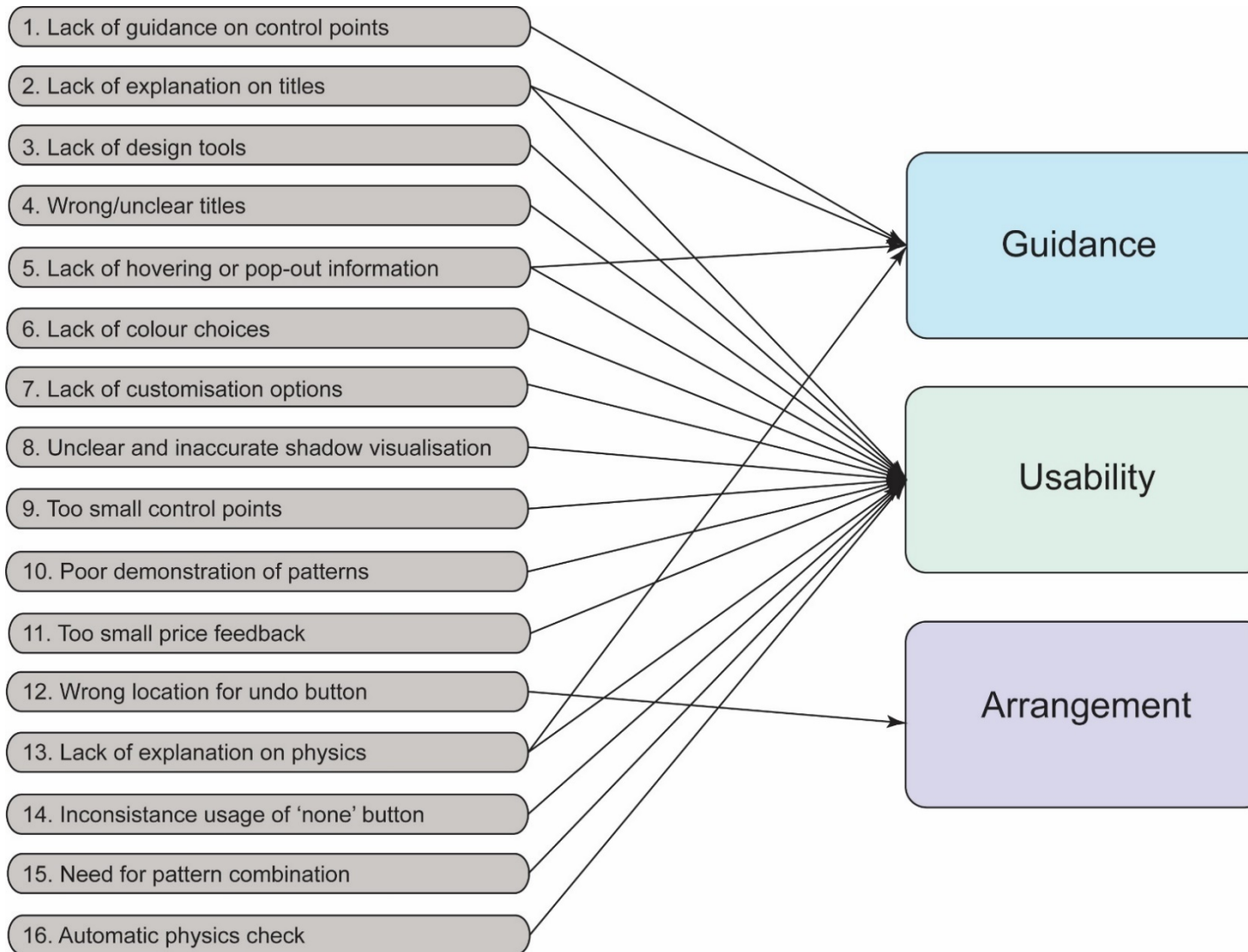
Figure 8-17 The toolkit's issues and its impact on the themes

158

8.5.4 The impact of issues on arrangement

There was only one issue identified for arrangement of the interface, which was about the place of undo (Figure 8-18). Two of the participants commented that it should be somewhere close to the product, not only to make it easy to recognise in the first place, but also for ease of frequent use .

The major part of the previous workshop was about the arrangement of the collected features on MC toolkits. The features of the MC toolkits were obtained from reviewing different CAD software programs and retail sale websites. This identifies a need for further exploration of the arrangement and representation of MC toolkits in comparison to CAD software programs and retail sale websites.
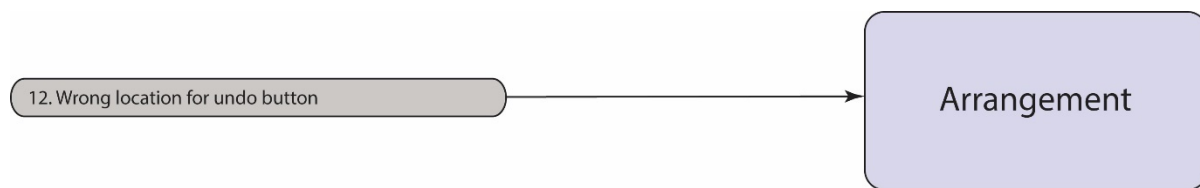
Figure 8-18 The toolkit's issues have a major impact on arrangement

8.5.5 The impact of issues on guidance

The next important suggestion for these toolkits is the need for an easy to use and interactive guidance. The toolkits had two types of helps: pop-out/hovering windows and help on a separate page. Based on the participants' comments, the pop-out window is preferred. They were looking for basic guidance for using control points and the physics section, which requires a quick and simple window, which pops out by hovering over the features. However, a separate page for helps can be used in order to explain more about the features/items. A participant commented that:

> *'the problem with help in separate screen is that you feel you have got to remember it for where you get back to the interface, I wonder whether the help could be like a drop-down list as well, where you just select the topic and the small windows appears with the information about that specific topic.'*

In other words, either on screen helps by hovering on the items, or by clicking the features/items on the side of the screen seems to be essential in the first instance. Using pop-outs and also hovering windows to inform users of the titles, and their job makes the interface more understandable, and at the same time only requires a short amount of time (done with HTML and CSS) in comparison to creating customisation options (done with JavaScript and Three.js). The introductory video appeared to be effective in terms of introducing the participants to the notion of customisation, and how the system works. Furthermore, this complete and initial help for using the system can be very effective in teaching the user the most important elements of the website, and guiding him/her through the process.

The issues of the MC toolkit with a major impact on guidance are shown below. Topics, such as physics and shadow visualisation also need more clarification since most of the participants did not understand this section of the toolkit, and complained about it being abstract. Perhaps a better visualisation or simulation showing the virtual installation of the lampshade would be useful. For any other products, it was observed that some companies implement a virtual experience for a user who customises a product, such as virtual driving a customised car.
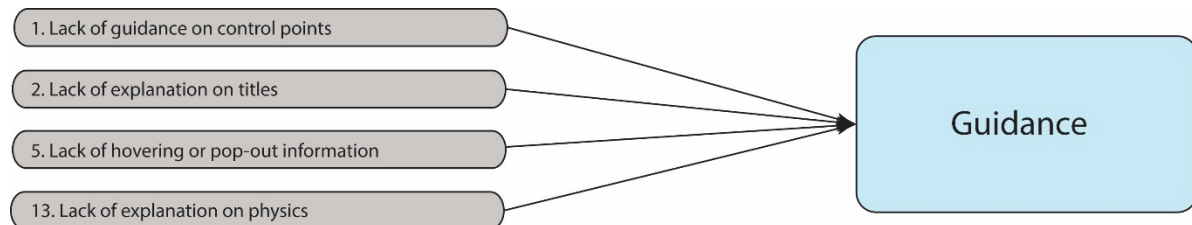
Figure 8-19 The toolkit's issues with a major impact on guidance

Control points were possibly the most intriguing aspect of the system. From one point of view, they increase the freedom of users dramatically, and give them the flexibility to change the product to drastic shapes. However, from another point of view, it intimidates them from adventuring further, possibly due to lack of tools and guidance. Therefore, concerning solution space, it was identified that the sections of the toolkit, which are more demanding in terms of creativity and level of customisation require more guidance. The guidance is also required to be easy to navigate, and to be convenient enough to encourage customers to explore.

8.5.6 The impact of issues on usability

Designing usable services is part of the aim of a UI design (Stone 2005). Usability is influenced by many factors of the UI. The present study aimed to identify which features of the UI impose greater difficulty in the use of the toolkit, and their impacts on the users. The issues of the MC toolkit with a major impact on usability are shown below.
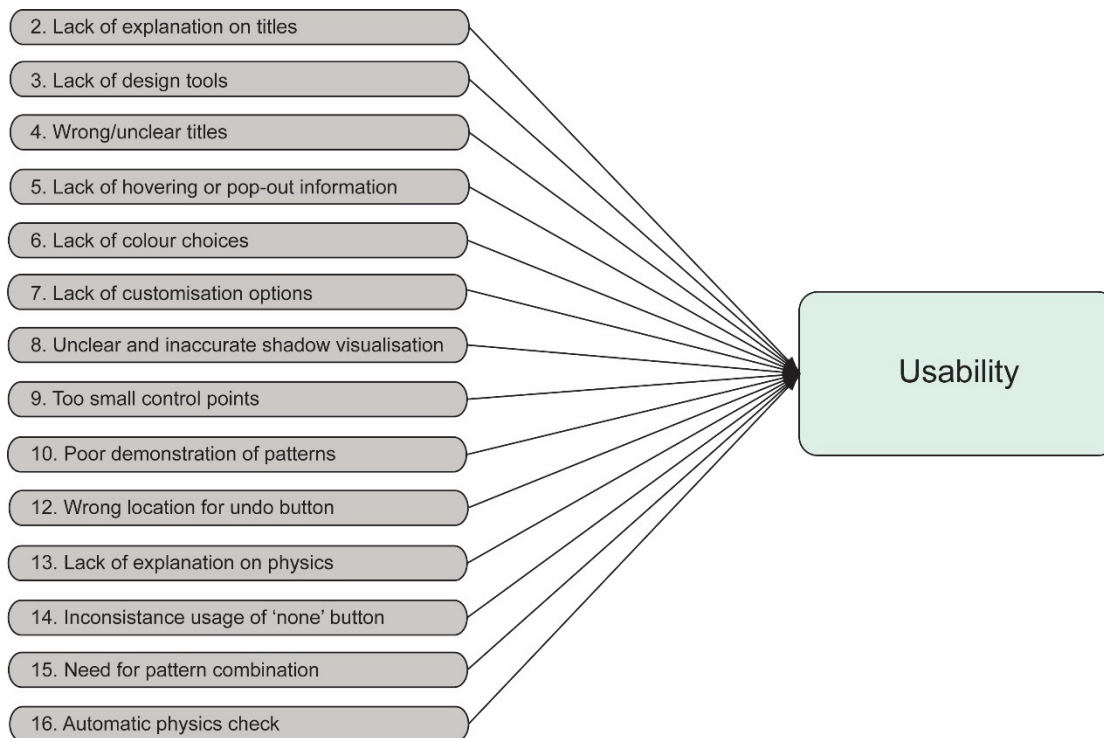
Figure 8-20 The toolkit's issues with major impact on usability

The usability of the system was separately measured by the questionnaire. Results showed that 5 out of 10 participants reported at least one problem in using the system. The usability scores from the SUS were calculated as follows:

161

Modified SUS Statements	Strongly Disagree				Strongly Agree	Weighted total
I think that I would like to use this system frequently	0	2	6	1	1	21
I found the system complex	4	4	1	1	0	31
I thought the system was easy to use	0	0	0	5	5	35
I think that I would need the support of a technical person to be able to use this system	1	7	1	1	0	28
I found that the various functions in this system were well integrated	0	0	2	5	3	31
I thought that there was too much inconsistency in this system	5	3	1	1	0	32
I would imagine that most people would learn to use this system quickly	0	0	0	8	2	32
I found the system cumbersome/awkward to use	4	4	2	0	0	32
I felt confident using the system	0	0	2	6	2	30
I needed to learn a lot of things before I could get going with this system	4	6	0	0	0	32
Total						304

As explained previously, the average score was calculated by dividing 304 by 10 (number of participants). The acquired number is 30.4. The SUS score was obtained by multiplying the obtained score (30.4) by 2.5:

SUS Score = 30.4 x 2.5 = 76 (out of 100)

This shows that the usability of the system is considerably high. However, issues were identified by participants while using the system, which can be considered as minor ones. Furthermore, it is true that guidance and usability are two separated themes, but some of the issues related to the guidance needed for titles and control points are related to usability as well, as demonstrated in Figure 8-17. The issues regarding usability are mainly concerned with the explanations, and therefore guidance, which should be considered for creating future MC toolkits. Furthermore, the size of control points (see Figure 8-21) and visualisation of some patterns were not clear enough for users to recognise. This also affected the users in terms of

manipulation of the control points devised for manipulation of patterns. As in at least 3 cases, it was realised that the user does not recognise that there are some control points for patterns. Some users also did not realise that with selecting each parameter, a number of control points will appear on the screen, which enable them to manipulate the shape of the lampshade. Since this was just a simulation, not a real experience, due to participants not necessarily intending to buy the lampshade at the end, this might be justified. Three participants complained that the size of price feedback (see Figure 8-21) at the corner of the screen was not big enough to be noticed. However, if an interface had enough free space, then implementation of a bigger button or more prominent price feedback would be a requirement. Three participants mentioned that the current number of options is enough for the high UI, but they added that some tools are required to make the changes in a more preferred and precise way. For example, common 3D CAD tools such as mirror, symmetrical, and parallel were mentioned by participants. The perceived issue of a lack of expected design tools, such as mirrors, radial patterns, etc. shows that they wanted some tools that would make the current options easier to manipulate to create what they want more precisely. Finally, multi selection of control points for symmetrical or identical modifications was mentioned by one of the participants.

Figure 8-21 Demonstration of control point and price feedback on the toolkit

8.5.7 The DoF

Solution space is concerned with the balance between the number of option (DoF) and constraints, which are the limitations imposed on these options. The higher the number of options the more complex the system becomes and the more guidance and navigation solutions are likely to be required. The lower the number of options is,

163

the simpler the system becomes, and the lower the customer satisfaction will be. The required number of options for a toolkit for a specific product is questionable, and no research was found in this area by the author (Franke & Piller 2003). It is true that this number is limited by manufacturing and management capabilities, but the solution space of these toolkits at least needs a requirement for different numbers of DoF for different products.

In this study, three different interfaces were presented to the participants, low DoF, average DoF, and high DoF. This scaling was decided based on the first study, where participants identified a number of DoF for a toolkit generally. 25 was selected and preferred for a generic toolkit by most of the participants in the first study based on the fact that three toolkits with 28 (high), 23 (average), and 18 (low) numbers of options were presented to participants, and results showed that 4 out of 10 preferred the average and 6 preferred the high number of options. This is an interesting result, as calculating the sum gives the number of 26, which is close to the result from the first study, 25. They also preferred to have less control on parameters of the shape (by suggesting to not directly change the shape via control points). Two participants were interested in combining patterns (which was not available in the toolkit), which may add to the current number of options. Four participants mentioned that the numbers of customisation options are not enough for the lampshade toolkit. One of them was among those who chose the medium number of options at the first stage. Therefore, three of them looked for more options in the toolkit. These participants may prefer to use selection and menus, because they are easier to manipulate. Three also mentioned that the current number of options in the high UI is too many, and some tools are required to ease the manipulation process of control points specifically. Multi-selection of control points for symmetrical or identical modifications is mentioned by one of them. Part of the questionnaire dealt with comparison of toolkits based on DoF for different products; car, ring, laptop, chair, and shoe. The question was if they would prefer a lower or higher number options for those products, comparing to the lampshade toolkit, they just used. The more complex the product is, the higher the preferred number of options needs to be, obviously. Figure 8-22 shows the preferred number of options for different products in comparison to the lampshade toolkit based on the study's results. Finally, most of the participants complained about a lack of colour choices in the system, which was limited entirely because of time limitation of the project.
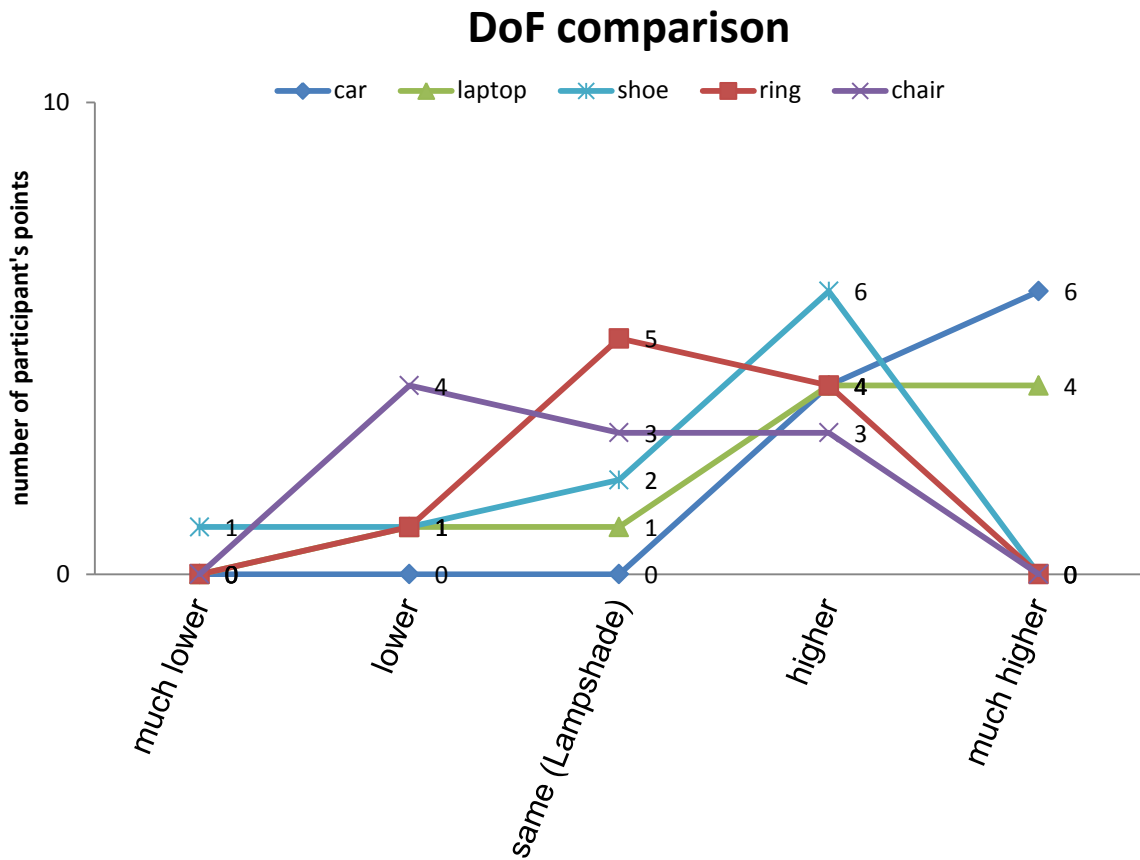
DoF comparison

Figure 8-22 Comparison of different products with lampshade in term of preferred number of options for their MC toolkit

Comments showed that participants enjoyed examining different patterns, which were in the form of selection buttons more than exploring the parameters section, which was in the form of control points and directly could be manipulated (DM). This partly confirms previously identified results from the first study (Yavari 2015) that participants prefer modular toolkits than parametric. However, this does not indicate that control points should not be used in these toolkits, as presenting options for manipulation of the surface freely is hardly possible using only buttons. Therefore, what seems to be important about options is their presentation in a simple and interactive way with enough guidance.

Having a continuous type of option such as sliders or dragging a control point seems to be less desirable than selections and drop-down menus (First study - Table 6-2). This simply implies that having a medium (23) or high (28) number of options for a toolkit, such as a lampshade toolkit, is not as important as presenting the guidance and navigation effectively and efficiently, which facilitates choosing and applying the options, no matter how numerous they are.

8.5.8 Participants' expectations from the MC toolkit

Part of the questionnaire dealt with what makes the participants hesitate about buying their customised lampshade, and part of it took into account what makes them more willing to do so. Table 8-8 and Table 8-9 below show respondents' answers to their experience in which the toolkit allowed them to design a unique lampshade.

Finally, control points were also very intriguing aspect of the system. From one point of view, they increase the freedom of users dramatically, and give them the flexibility to change the product to an interesting shape. This is usually provided in an AM-enabled MC toolkit such as in CellCycle by Nervous System (2014) (Figure 4-6). Furthermore, DM is achievable with control points. However, from another point of view, they intimidate the users from venturing further, possibly due to lack of easy to use tools and guidance, or difficulty in using control points themselves.

Table 8-8 Participants' responses to the questions regarding hesitation to buy their design

Questions	Strongly Disagree				Strongly Agree
My final lampshade design is not exactly what I want due to lack of options in the system.	30%	20%	30%	20%	0%
The process was confusing due to number of options in the system.	40%	50%	10%	0%	0%
The customisation process was not enjoyable due to complexity of customisation process.	30%	60%	10%	0%	0%
I am unsure of the final result of my customised lampshade due to lack of general knowledge about my customised lampshade.	0%	60%	20%	20%	0%
I am unsure of the final result of my customised lampshade due to the quality of visual representation of the final product.	0%	40%	10%	40%	10%
The customisation process was burdensome due to lack of help in using the system.	20%	70%	10%	0%	0%
My customised result is not reliable due to lack of technical help about the product.	10%	60%	30%	0%	0%
The customisation process was not satisfying due to weak layout and visualisation of the website's elements.	30%	60%	10%	0%	0%
I am not sure if I have reached my goals since the options were not based on my needs, but the product's parameters.	20%	10%	30%	40%	0%
I could not communicate my needs and desire since the process did not begin with my needs and requirements.	10%	50%	10%	30%	0%
Cost (time and effort)	30%	20%	20%	20%	10%
Cost (price)	0%	10%	20%	50%	20%

166

- A 50:30:20 (disagreed:neutral:agreed) ratio occurs in opinions regarding whether the system lacks enough design freedom, however 90% of respondents believed it was not confusing due to the number of options. This along with the previous result shows that more DoF is not undesirable if it is accompanied with enough guidance that makes it less confusing. However, such answers show that there is a less common agreement amongst participants regarding the number of options in a toolkit such as the lampshade one.

- A 40:10:50 (disagreed:neutral:agreed) ratio occurred in opinions regarding being unsure about the final design due to the quality of visual representation. This shows richer product visualisation is needed. Perhaps, a stand for the lampshade and connections to the stand would make participants more comfortable about their final design. This includes virtual demonstration of the lampshade functional and aesthetical aspects. Furthermore, it is definite that the shadow visualisation needs to be improved.

- A 30:30:40 (disagreed:neutral:agreed) ratio occurs in opinions concerning whether the presentation of options should be in the form of needs rather than parameters, which confirms the previous study's results. This says that converting parameters into needs and presenting them in a more understandable form would improve participants' MC toolkit experience. The next question, regarding communicating the needs, suggests that the process does not necessarily need to begin with answering some need-based questions.

- A 10:20:70 (disagreed:neutral:agreed) ratio occurs in opinions regarding how much the cost of the product makes them hesitant about buying their customised lampshade. This shows that the price of customised or personalised products plays an important role, even though they feel attached to the product because of co-designing or added self-expression to it.

Table 8-9 Participants' responses to the questions regarding willingness to buy their design

Questions	Strongly Disagree				Strongly Agree
The process was enjoyable due to guided navigation pane.	0%	0%	10%	60%	30%
My design is creative enough due to the high freedom I felt during customisation.	0%	0%	40%	40%	20%
I am confident with my lampshade design since I had enough feedback, e.g. size, colour, dimension.	0%	10%	20%	60%	10%
The customisation process was easy with the tools such as undo and camera reset.	0%	20%	10%	60%	10%
I enjoyed using this system due to the new and exciting user interface.	0%	10%	0%	50%	40%
I like my lampshade design since it is a representation of me.	0%	10%	30%	20%	40%
I like my lampshade design since it is unique.	0%	0%	30%	40%	30%
I had a good customisation experience.	0%	0%	10%	50%	40%

- A 60:40 (Disagreed:Neutral) ratio score occurs in opinions regarding if the result of the participants' design is creative enough due to enough freedom during customisation. This again demonstrates the intriguing nature of DoF. A comment by a participant shed light on this matter:

  > *'So, going back to my earlier comment about having too much control on the parameters I am begin[ning] to change my mind now, and I think it is helpful to have that level of control. It is just a matter of practice playing around with different ideas and obviously, it gives you a lot more flexibility to be creative…yeah, and once you see the possibilities to have extra options, people will naturally prefer to have them, because it just gives you much more control to create shapes that people like.'*

This participant commented that there are too many parameters that intimidate the user, resulting in them not using the options, however, after he became more experienced in using the system and grew familiar with the options, he took his comment back. What can be inferred is that participants do not desire lack of options, as in low UI with low numbers of DoF. Furthermore, possibly there is no one correct choice for every target customer. Even the toolkits themselves needs to be customised by customers before they start to use them, a very simple and basic approach can be providing users with three kinds of the UI with different levels of

DoF: low, medium and high. Therefore, customers would have the freedom to choose between different types of the toolkit in term of DoF.

8.6 Critique of the Study

In general, observation and a survey afterwards was an effective method for gaining information of users' experiences, and participants were willing to share their perceptions, needs, and desires with regard to the toolkit. This method is mentioned by Redmond and Moore (1995), who stated that it is an appropriate and popular way to gain insight about the UI and needs and opinions of users with regard to it. Furthermore, since people's actions may be different from what they say in real situations, observation was also needed to achieve a more comprehensive view of the UI (Sainio et al. 2006).

One of the potential limitations of the study was that the participants were not necessarily intending to buy a MC lampshade. It is about how much they explore the interface and explore the elements of the website, and the depth of the participants' comments, which can be influenced by their intention. Therefore, a participant in the study may not be motivated enough to experience all the elements of the toolkit. In this case, their low level of comments may not mean that all the elements have been implemented on the UI correctly. However, in order to improve the study, and encourage the participants to take the tasks more seriously, they were put into a draw and given the chance to win their lampshade at the end. This did not only act as an incentive compensating them for their time and effort, but also encouraged them to explore more and examine different options/features. However, this also may have limited their creativity and caused them to create something more functional without considering aesthetical aspects. This incentive, however, is more likely to have improved their exploration of the system overall.

8.7 Summary

Apart from the important findings obtained, this study, in general, illustrated how challenging user involvement can be in the design of a product, and also specifically for an AM-enabled MC toolkit.

The created toolkit allowed users to experience MC activity by directly manipulating design parameters. This interaction led to a more appreciated product in terms of the personalisation experience and increased product value. To create the prototype for the study, an experiment was conducted, which involved two CAD software programs (SolidWorks API, and Grasshopper) and two 3D-enabling libraries (Three.js and Processing). The experiment indicated the specifications for the CAD program or 3D-enabling library that should be used to create an MC toolkit, and the most suitable option was Three.js. Therefore, it is suggested for future AM-enabled toolkits, 3D-enabling libraries, specifically Three.js, are utilised due to having greater advantages (such as web-based capability) and more importantly an integrated

feature ability. As mentioned previously, current examples of AM-enabled web-based 3D modelling toolkits (e.g. shapeshifter.io and Platypus) have also used Three.js, which verifies the outcome of this experiment. These findings helped to satisfy research objective 1.

Through this study, it can be concluded that the lampshade MC toolkit had contents and a layout (based on the first study and workshop) that were relatively easy for users to understand, and it was found to be satisfactory for the participants. However, there is a risk that the user may not understand all the options/features well, and he/she would need more guidance on some topics, e.g. physics providence, control points, etc. This finding helped to satisfy research objective 2.

The use of observation and a structured way of presenting issues in the survey for the study enabled the researcher to identify a broad range of problematic issues. More specifically, the study led to the following conclusions:

- The most important issue was guidance on control points. After that, the next most problematic issues concerning usability were explanation of titles, lack of design tools, wrong/unclear titles and hovering or pop-out information. While most of the comments were related to usability, they were mainly related to guidance, and achieving a high SUS score of 76 out of 100 showed that the first study and workshop had helped to improve usability of the toolkit. Therefore, the guidelines from the first study and workshop were included in the final framework design. Furthermore, the issues raised by participants also need to be addressed in the framework and therefore in the future improvement of the toolkits. These findings help to satisfy research objective 3.
- The data analysis enabled identification of the negative impacts of issues regarding users' experience of the toolkit. These impacts affected the participants and the system under the three themes of guidance, arrangement, and usability. The most affected theme to emerge from the data analysis was the usability.
- The analysis of the results suggested that the impacts on the UXs of the toolkit are not caused by isolated issues alone, but by a combination of issues. For example, a lack of explanation on the titles led to having less information about the control points. Having no guidance on control points led to complaints about the title of each parameter. This means the customisation experience was affected by the issues mentioned previously and the combination of issues, with each issue having an effect on the others. Therefore, improving one aspect of the toolkit may have a knock-on positive effect on other aspects.

In addition, one more important aspect of the toolkit that needs careful consideration is DoF, which is a very intriguing topic because currently it is still

not known how many options will satisfy a customer for a specific product toolkit. Therefore, what was learned in this study was that customers could be provided with two or more versions of the toolkits with different numbers of DoF. Another option can be to add a button called 'more options' to the interface and, as customers click on it, more options are revealed (Makies 2016). These findings helped to satisfy research objective 4. Further investigation into this topic is needed but is outside the scope of this research due to time and resource limitations. The following chapter will deal with creating a design framework for MC toolkits based on all the findings that have been reached, together with other available published guidelines from other researchers.

Chapter 9 : Development of a Design Framework for User-centred AM-enabled MC Toolkits

9.1 Introduction

In order to translate the findings of the preceding chapters into more applicable information (design knowledge) for designers and software developers, this chapter describes the development of a design framework. The literature review previously highlighted the lack of a common structure, or norm, for MC Toolkits, as well as the lack of customer perspective on their design, which is also perceivable from current MC toolkits. A design framework should, therefore, communicate insights from this research into recommendations that can be used as design knowledge for these toolkits, in order to fill the gaps between what design teams do and what users expect or need. This chapter begins with a synthesis of the data from the earlier studies, followed by a description of the creation of the design framework.

The chapter objectives are:

1- Finding out the most suitable way of expressing the guidelines
2- Providing the guidelines thoroughly in a suitable format
3- Collecting the issues of the framework

9.2 Purpose of the Design Framework

The main objective of creating a design framework was to give designers and software developers a tool for creating AM-enabled MC toolkits in a more effective and efficient way to enhance the UX. A design framework is defined as 'the supporting structures and underlying concepts upon which every detail depends' (Goodwin 2009, Sanders 2008). According to Goodwin (2009) and Aceves-Gonzalez (2014), the development of a design framework aims to accomplish the following specific objectives:

According to Goodwin (2009) and Aceves-Gonzalez (2014), the development of a design framework aims to accomplish the following specific objectives: to ensure that the toolkit's design in the future will accommodate all the known requirements and findings; to create a tool to be used commonly by designers; to improve the quality of experience, appearance, layout and structure; to minimise the cost and time required to produce them; and to initiate a step towards creating better toolkit design frameworks in the future.

The framework should help design teams arrive at good solutions in an efficient and replicable way. The framework is not a full recipe though; it requires the designer's application of creativity, judgement, and visualisation skills, otherwise it is entirely possible to follow every step and still end up with a less than optimum result. Rather,

the process provides enough steps to increase the outcome of generating user-centred AM-enabled MC toolkits.

9.3 Data from Studies Used for Framework Development

The first study (Chapter 6) raised a number of important points related to how customers would like to experience MC toolkits, and therefore how the content of these toolkits need to be implemented. These data were mainly used to complete initial and general steps of the design framework. In summary, the points raised were:

- The visual feedback counts as the most important feature, showing that customers need a good image (possibly 3D) of what they customise and buy at the final stage.

- The second most important feature was price update. This shows that after customers are satisfied with their product's appearance, then they look at the price. It may show an obvious fact that customers intending to engage with MC, are looking for something with quality, uniqueness, etc., and therefore, what they pay attention to first is the visualisation of the product rather than the price.

- The third most important feature was the click and show option. This feature provides a user-friendly interface, which customers can interact with intuitively.

- The fourth important feature was material selection. This feature obviously plays an important role in MC. The capability that this feature provides for the toolkit and consequentially its impact on the product allows for high differentiation and satisfaction. Not only customers may use this feature for creating a unique product, but also a more functional one. The inclusion of this feature in toolkits for utilitarian products is to be strongly recommended .

- The fifth most important feature was flexible navigation. This is important because customers would like to play with these toolkits, and it would be a serious downfall if the toolkit cannot save their process continuously.

- Selection of manufacturing method was the least important feature. Although, this will add a dimension to MC, and give more freedom, generally customers would not look for a specific manufacturing process to select, preferring to leave this to the manufacturer to choose the best possible option. This functionality may make the decision making so hard that the customers may not finish the transaction, and if included it should only be optional, rather than mandatory for completing the process.

- Reference object was the second least important feature. Creating a simple reference object in the product's visualisation may not require a long or tedious effort, but its implementation can give customers some insights into

the harmony, size, etc. However, its ranking may be justified by the fact that this capability seems like an extra or exciting feature to have.

- A library of other users' designs was the third least important feature. It was raised by number of participants that customers would like to create a unique product with MC, and this is contrary to this capability. Furthermore, if the inclusion of this feature needs a lot of effort for programmer, then it is not recommended to be implemented in a toolkit.

The data from the workshop (Chapter 7) has identified a number of facts that are considered to support the first study result, and create a better framework. The insights generated are:

- Visual feedback counts as the most expected feature in the toolkit by participants.

- Participants chose the second essential and expected feature of these toolkits to be price update again. Furthermore, this feature alongside the visual feedback is a "must have" feature, which every design team needs to include in the toolkit.

- Users' design access (libraries of other users' design) was the second least expected feature in these toolkits, again confirming previous research suggesting this is not a highly desirable feature. This supports the contention that the uniqueness of mass customised products is one of the reasons for using MC (Miceli et al. 2013), and shows that to a significant extent, users do not wish to share their designs with other people for copying.

- Selecting the manufacturing method was the least expected feature in MC toolkits. It can be inferred that people are not concerned with the manufacturing technique that is used for their product, or they look at it as something too technical. However, it is worth mentioning that the participants selected the material selection as the fourth most expected feature, which to some extent overlaps with the manufacturing method used in terms of finishing, etc. Therefore, the material and finishing of the product is of importance.

The features that were selected as the least expected/important ones by the participants do not need to be included in a toolkit, since they are shown to have the lowest expectancy and importance from the workshop and the first study. Findings from study 2 that have been integrated into the framework are discussed in section 9.4.2 (Design of the content)

9.4 Design Framework Creation Process

The creation of a design framework usually follows these three basic guidelines (Goodwin 2009):

1- To consider the service or the product concretely, and provide information based on how it works and how it looks;

2- To do so as quickly as possible in order to enable stakeholders to make decision as soon and as cheaply as possible;

3- To ensure that the design considers possibilities so that it embraces all known routes to complete the design of the product and service, even if it is modified for the short term.

Therefore, MC and AM-enabled MC toolkits were considered as the main service and product of the design framework. Related articles were reviewed and data extracted in order to provide guidelines for selecting the product to deliver MC, and describing the characteristics of the toolkit afterwards. This design framework was created as quickly as possible through the short duration of a PhD. Finally, in order to consider all the possibilities, all the features to be integrated in MC toolkits were collected and studied throughout this research.

9.4.1 The format of the framework

There is no typical or default format for a design framework, however, by examining the recommendations of the authors, it can be inferred that there are at least five types of tools (seeTable 9-1):

Table 9-1 Different formats to present design tools or frameworks

Type of tools/methods	Example	Specifications
Mapping	User Journey Mapping, Blueprints	Representing a process, described step by step as in the classical blueprint (Service Design Tools NA)
Graphs, tables and charts	SWOT, Kano analysis, chart	Communicating information visually mostly for information that is difficult to understand textually (National Center for Education Statistics (NCES) NA)
Flow charts	Task flow	Showing sequence and flow - a temporal or chronological ordering of steps (Nakatsu 2010)
Trees	Mind mappings, taxonomy	Showing all the possible outcomes of an event (BBC 2014, BBC 2014)
Set of cards	Method kits	Summarizing, categorizing and visualizing data in the form of cards (MethodKit 2014)

The design framework was created by considering the stages that design teams need to pass through in order to create a user-centreed AM-enabled MC toolkit. Therefore, a flow chart was chosen for the visualisation of the framework. This flowchart includes sets of commands, decisions or data input that are required to be done sequentially, and is presented in a web-based format to make it more accessible to design teams that would be working with it.

9.4.2 Design of the content

Recommendations from previous literature in this area (see Section 4.17 Current Guidelines for MC Toolkits) were acknowledged and where appropriate, integrated into the design of the framework, which includes two main stages: MC toolkit pre-implementation, and MC toolkit implementation. The pre-implementation stage contains mainly, the feasibility check. Every company needs to consider some factors before MC implementation, which are divided into different types: customer, market, industry, product, and organisational factors. In order to implement a MC toolkit, a suitable product needs to be chosen from within the company's portfolio; therefore, criteria for choosing a customisable product should be considered. This framework is designed for design teams; therefore, it is assumed that all other considerations, necessary for MC implementation, such as market or industry factors, have already taken into account apart from product factors. Factors that are only related to this aspect, when deciding on implementation of MC, are considered for this framework, therefore, this framework helps to find the appropriate product for a MC toolkit. After selecting the right product, the implementation stage of the framework guides the design team in terms of content requirement and structure of the toolkit.

9.4.2.1 MC toolkit pre-implementation

The current task is now the preparation for toolkit pre-implementation such as which product should be chosen, and estimating the benefit and cost for predicting success of the implementation. These steps, with reference numbers from the framework, were explained as follows:

1. First of all, for any design team, three primary requirements (# 25) are needed to continue to the next steps: web design skills, specifically 3D modelling (WebGL, Three.js, etc.) (Ristov et al. 2011), and a strong customer relationship (Cross et al. 2009, Ristov et al. 2011, Wang & Tseng 2014), access to AM.

2. In order to check the feasibility of creating an AM-enabled toolkit, the cost/benefit analysis needs to be done in the pre-implementation of framework. However, this could only be done from the customer's point of view here, due to the availability of the data from literature and studies. One of the determining factors in this analysis is the product of the toolkit (#25).

176

3. Consideration of the product factors that affect the success of MC implementation (#26,27) (Broekhuizen & Alsem 2000):

- Purchasing frequently: If the purchasing frequency is high, the provider has more information over the product options and popular options, and therefore this enables producers to build a 'learning relationship'. This will help to know not only what options need to be essentially included, but also if the company can offer a MC toolkit with enough options to fulfil customers' needs. This frequency also helps to identify which options are bought more by customers so that early evaluation is required to know if the designer team can implement all those options in the toolkit. To match the level of customisation offered with customer's needs is a major success factor of MC.

- Luxury products: These are considered as a positive point to pursue MC of a product. Luxury products by nature tends to be more distinctive, higher priced, and, more importantly unique. Therefore, they are more likely to be customised other than basic products, which fulfil basic needs (Broekhuizen & Alsem 2000). Furthermore, companies that offer luxury products should recognise the importance of delivering a pleasurable shopping experience, which is achievable by MC toolkits.

- Product visibility: Customisation may start on three different levels: style, fit, and functionality. People often want to own a product not only to fulfil their individual needs but also to publicly express them. It is of even more importance for modern customers to express these lifestyles through products and services. However, if a customer would like to customise a product from its functional aspects, then the product is not required to be highly visible. However, if a product is highly visible then it is a good choice for MC; otherwise, the product needs to be highly functional, meaning that the functional values are of primary importance for the customers (Gilmore & Pine 2000, Broekhuizen & Alsem 2000).

- Product adaptability: This factor deals with the cost involved with customisation of the product. In general, the easier products can be tailored to customer needs, the less costly the customisations are.

- First mover: When a product gains a so-called first-mover advantage- the advantage to be the first to be adapted for MC - then it brings high profitability and growth for a company over a long period of time. For example, one of the most sited examples of MC is Dell Computer's online configurators, which was a first mover in its category. They managed to deliver customised personal computers within one week with prices lower than their mass-producing competitors (attribute selection for product configurator design was based on the Gini index). However, this is a recommended criterion not an essential one.

Figure 9-1 The required iteration between product factors and other factors, affecting the success of implementation of MC

Therefore, iterations are required for choosing the right product for implementing MC toolkits. After examining different factors by designers and sales and marketing departments for implementing MC from customers, market, organisational, different aspects etc., the designer team may refer back to their selection and re-examine the chosen product from product factors, and reselect a new one to match more factors other than product factors. This process continues until the right product is chosen. However, for the design team to make their selection they need to go through the product factors. This framework is valid for AM-enabled toolkits, which allow modification of a high level of product attributes. Therefore, in the next stage, the question is about the manufacturability of the product with AM.

- As previously required, AM technology should be available. Although the selection of this type of manufacturing, enables these kinds of toolkits, it imposes some limitations in terms of size, materials, surface finish, etc. Therefore, in this stage, the design team should infer if the chosen product in the previous stage is manufacturable with the company's available AM solutions, or any AM technologies planned to be bought later.

- The whole research is done according to parametric AM-enabled toolkits, or in other words, real customisation of the product to meet each customer's needs and desires more accurately. So, now that the design team is confident that the product can be manufactured with AM, the main intention of the framework must be met, which is the extent of options available for customisations. Therefore, in this stage, the

178

design team need to find out whether the selected product can be customised through providing both high level and hard attributes or not (to fulfil the need of customisation of surface, form, pattern, etc.). Also, the number of options needs to be around 25, recommended based on the findings of this research. In case the options' variety and the quantity are unfulfilled, the team needs to start again from the product selection stage to choose another one.

Furthermore, from the second study, it was found out that the DoF for more complex products tends to be higher, and lower for less complex products from the customer's perspective. Therefore, based on the selected product's complexity, in this stage, the number of options should be adjusted. Therefore, for more complex products, options should be increased to more than 25 and for less complex products, less than 25 is acceptable. In case of lack of fulfilment (due to their AM limitations, tremendous cost effect, etc.), the design team needs to go back to the product selection stage, and choose a product again.

4. After choosing the right product, the next step is to transform functional requirements to design parameters (#28), such as material, surface, parts, technical aspects, etc. These requirements are likely to come from market research data, and will include customers' needs and desires, competitors and competing products, and other marketing rules (Cross et al. 2009).

5. The next step involves examining the created options to assess if they are valid based on current primary research done in this area before MC toolkit implementation. The created options needed to be from high-level attributes, such as surface and size as much as lower level attributes, such as colour or surface decoration. Furthermore, they should include soft product attributes, such as intangible ones as much as hard product attributes, such as physical and tangible ones (Hermans 2012) (#29).

6. Having listed as many options as possible in the previous steps, a filtering exercise should reduce the number of options by applying constraints, such as technological constraints, ease of use for non-designers, brand identity and safety (Hermans 2012, Sinclair, Campbell 2014) (#30).

7. To predict if the MC / creating a MC toolkit for the chosen product will be feasible and profitable, production cost needs to be estimated at this stage. The level of customisation can be decreased or increased based on production cost. In essence, the level of customisation needs to be increased as long as the added-value to the customer and the production cost does not significantly increase (Spahi & Hosni 2007) (#31).

8. At the final stage, estimation of cost and added value need to be examined, if the toolkit implementation increases the added-value more than the sum of the direct and indirect cost, divided by two or not. Obviously, if the benefit is more than the cost, it is worth creating the toolkit for the chosen product and adapted options (Sharma & Sheth 2004, Stojanova et al. 2013) (#32). This estimation is done based on the available data from the studies, and literature review, which is currently only from the customers' perspective.

9.4.2.2 User-centred AM-enabled MC toolkit implementation

The next task is now the preparation for toolkit implementation such as which features should be integrated into it, and in what configuration should they be presented. Within the implementation stage, a number of tasks should be considered, as follows:

1. Since one of the important aspects of the toolkit is the solution space, and therefore, delivery of the options decided, the first stage is devoted to the presentation of the options. From the findings from the studies, the input type is preferred in this order: selection, drop-down menu, slider, drawing and 3D-scan. This user preference was exactly reflected in the framework. (#1)

2. Afterwards, commands and guidelines (#2-8) about the implementation were explained and options were presented, which increase the usability of the solution space. The provided options are in the core of the solutions space, and features such as visualisation option, price feedback, etc. are positioned around it. Therefore, the solution space was dealt with first by providing related guidelines, such as, mechanisms, etc. (#9). For example, the chosen mechanism should provide openness and enough variety (Hermans 2015), and more importantly, should be satisfying to the user, which is reflected in the framework as well (#10). Otherwise, the users need to have access to any options at any time without following any sequence (Hermans 2015) (#11).

3. In the next step (#12, 13), visual feedback as the most important feature of the toolkits was presented with a set of guidelines. The designer should choose the visualisation based on a trade-off between visual appeal, information, and technical constraints such as rendering time (Hermans 2015).

4. In the next stages (#14-22), the most important features from the studies and the workshop was put under spotlight, such as price and guidance. It is important to mention that the guidance was paid attention during the whole framework to provide a smooth experience for customers, according to the second study. At the final stage, this feature is also re-examined to make sure that the manipulations of options are easy enough.

5. At this stage (#23), most of the guidelines needed to implement an operational toolkit have been given, however, the DoF was not exclusively considered in the whole process, which is one of the intriguing aspects of the toolkits. Therefore, based on the result of the second study, the customers should have the ability to customise their toolkit in terms of number of options, or at least to be provided with two platforms or more, which are different in terms of number of options.

6. Customers need to input some feedback to the toolkit provider in order for the provider to improve it . This is enabled by providing them a button on the toolkit to submit feedback. Furthermore, current options can be updated and refined regularly from the resources mentioned (#24).

All these requirements are explained further and shown in different categories in the Quality Function Deployment (QFD) table below (Table 9-2). This is a system dedicated to effectively delivering products and services that satisfy customers (QFD Institute 2010). A QFD table is a design method that helps developers take advantage of users' needs, requirements and designs by integrating them (Punchihewa & Gyi 2009). QFD is based on many different methodologies and different industries' culture and practices (QFD Institute 2010). The first category is the requirements from this thesis's studies (internal). The second category is the acquired requirements from external studies (external) that have been either highly cited (von Hippel & Katz 2002) and/or are mostly-related (Hermans 2015, Sinclair 2012).

The internal requirements have already been divided into three different categories of attributes from the workshop result: the basic, the performance and the excitement. Therefore, the QFD table for the internal requirements are sorted in order of importance, but such information for the external requirement was not available. Furthermore, the external requirements were included if they were complementary and supportive to this research's findings, since their type of recommendations, either user-centred or not, is not available.

	User needs and requirements	Brief explanation of requirement	Box number on the framework
Basics	**Visualisation feedback**	real-time update visualisation (type of visualisation is chosen based on a trade-off) (Internal, Hermans 2015, Sinclair 2012)	8
		The user need to have an ability to try out by trial and error (Internal, Hermans 2015, von Hippel & Katz 2002)	8
		Include basic camera orientations for different visualisation view (Internal)	9
	Price feedback	Price needs to be shown and updated to the user in real-time (Internal + Matt)	11
	Material selection	Material selection comprises of one of the important customisation options (Internal)	12
	Undo	The user should have the chance to undo his/her progress (Internal)	21
	Guidance	Pop-out windows or hovering boxes should be shown to help the user through the customisation process (Internal)	13
		Detailed separate help is required when users seek detailed information (Internal)	14
	Flexible navigation	Users' progress needs to be saved through the customisation process (Internal)	3
	Validation with feedback	Number of feedback occurrences should be included in the toolkit such as dimension feedback (Internal)	4
	Library of modules and producible	Users prefer a starting point over starting from scratch, therefore this can act as a starting point for users (Internal)	15

		Commonly used as well as recommended patterns and parameters are required (von Hippel & Katz 2002)	16
	Camera reset	Camera reset or view reset button needs to be included (Internal)	9
	Click and show option	Selection of each parameter should orient the camera to the appropriate view (Internal)	10
	Need-based or parameter - based	Options (or options that needs high proficiency to be manipulated) need to be provided based on needs (user requirements) other than parameters (product dimensions) (Internal, Randall et al. 2005)	5
Performance	**Technical information**	Extra technical helps is required for more technical products (Internal)	20
	Side by side comparison	These requirements are not included as they belong to the performance group; therefore, it is an optional requirement (Internal)	optional
	Physics providence	These requirements are not included as they belong to the performance group; therefore, it is an optional requirement (Internal)	optional
	Virtual use of product	Final product's beauty and functionality should be evaluated by users before purchasing (Internal, Hermans 2015)	17
Excitement	**Reference object**	To give an illustration to customers of dimension, size, etc. this is included, even if it is an excitement attribute (Internal)	18
	Multiple mechanisms	Users prefer modular and parametric mechanisms over others (Internal, Hermans 2015)	6
	Offline access	These requirements are not included as they belong to the excitement attributes category; therefore, it is an optional requirement (Internal)	optional
Others	**Starting point**	Users prefer a starting point over starting from scratch (Internal)	15
	Complementing with Peer input	If the toolkit requires peer input and support of the community (which is recommended), then it needs to be included (Sinclair 2012)	21

Degree of freedom	Users prefer selection and menu types of option presentation (Internal)	1
	Interfaces with multiple DoF are required (Internal, Hermans)	22
	Complexity of products should be adjusted with using lower level of complexity in terms of presentation of options (Internal)	2
Domain-specific scope	The toolkit should be for a particular product's domain and category, but not too constrained (Hermans 2015)	25
Tailored to specific fabrication method	The requirement is choosing a specific manufacturing method from the beginning (Hermans 2015, von Hippel & Katz 2002)	26
Non-linear navigation	The navigation should support non-sequential input to the toolkit (Internal, Hermans 2015, Sinclair 2012)	7
Expandable or compatible to other systems (Randall et al. 2005, Hermans 2015, Sinclair 2012, von Hippel & Katz 2002)	This requires the system to allow files to be saved in STL format or integration of 3D-party add-ons (not included, as not necessarily a highly preferred option by customers, or at least not yet found out to be so) (Hermans 2015)	optional
Deliver the unexpected	These requirements are not included due to the fact that enough information was not available. (Hermans 2015)	-
User-friendliness	Due to the nature of the requirement, it is not easy to define and then try to meet it, however, the number of toolkit's features help in improving user-friendliness (von Hippel & Katz 2002)	1,2,3,5, 7,9,10, 13,17,19, 21,22
Product themes	The inclusion of product themes was assumed to be fulfilled with library of modules and producibles (Internal, Sinclair 2012)	15
No installation or download	The interface is required to be web-based without installing any add-on or third-party app. (Internal, Sinclair 2012)	24
Including design tools	Design tools are required to ease the manipulation of a product's aspects for naive or professional users (Internal, Sinclair 2012)	19

9.4.3 Key features of the framework

The development of the framework aimed to help in visualising and communicating the design knowledge on user-centred AM-enabled MC toolkits for design teams, to especially fill the gaps between what service providers do and what users expect or need. Figure 9-2 to Figure 9-7 show the pre-implementation and implementation framework. A detailed consideration of them both allows the following key features from the frameworks:

- It illustrates the users' experience and needs in using the AM-enabled MC toolkits

- It provides a means for contrasting the ideal MC toolkit with existing toolkits

- It suggests addressing some of the points to improve an aspect of a toolkit, other aspects can also be improved

- It shows which features have more priority over others to be considered for MC toolkit implementation

- In addition, it provides the main barriers that need to be addressed in order to reduce difficulties for users and to increase uptake of the toolkit.

The final framework was designed and presented in A2 size divided into two sections:

1 (Figures 9-2 – 9-3) Pre-assessment for implementing the toolkits: this includes information about the prerequisite to start the process, selecting the right (customisable) product for the toolkit based on product factors for MC success, AM's limitations, and the variety and quantity of options; creating and adjusting the options; and finally assessing and predicting the success of an AM-enabled MC toolkit by estimating what users gain from using the toolkit, and what they lose.

2 (Figures 9-4 – 9-6) The main guidelines for actual implementation of the toolkit: this includes the selection of user input type, method for presenting the options, technique or method of MC implementation (mechanisms), and detailed description of each and every essential feature of the toolkit (the priority and location). At the end, the point was added to the framework that for every toolkit, there is an optimum number of DoF depending on each customer. For each toolkit based on different types of customers, therefore, the toolkit's number of options (Dof) should be customisable, or at the very least, the toolkit needs to provide two different levels of options for customers to choose (novices: default, professionals: advanced).
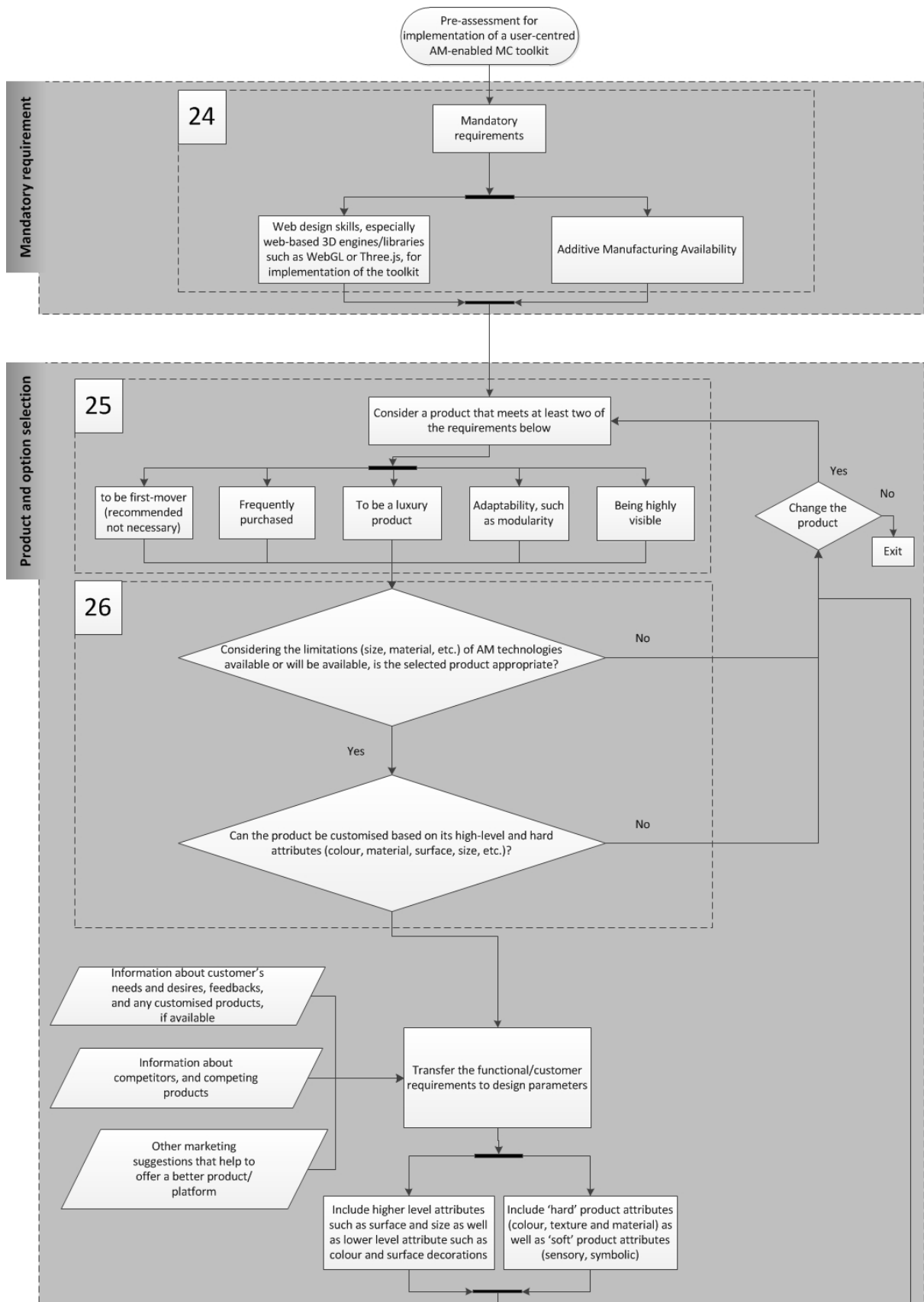
Pre-assessment for implementation of a user-centred AM-enabled MC toolkit

Mandatory requirement

24 — Mandatory requirements

- Web design skills, especially web-based 3D engines/libraries such as WebGL or Three.js, for implementation of the toolkit
- Additive Manufacturing Availability

Product and option selection

25 — Consider a product that meets at least two of the requirements below

- to be first-mover (recommended not necessary)
- Frequently purchased
- To be a luxury product
- Adaptability, such as modularity
- Being highly visible

26 — Considering the limitations (size, material, etc.) of AM technologies available or will be available, is the selected product appropriate? — No

Yes

Can the product be customised based on its high-level and hard attributes (colour, material, surface, size, etc.)? — No

Change the product — Yes / No — Exit

- Information about customer's needs and desires, feedbacks, and any customised products, if available
- Information about competitors, and competing products
- Other marketing suggestions that help to offer a better product/platform

Transfer the functional/customer requirements to design parameters

- Include higher level attributes such as surface and size as well as lower level attribute such as colour and surface decorations
- Include 'hard' product attributes (colour, texture and material) as well as 'soft' product attributes (sensory, symbolic)

Figure 9-2 Pre-assessment section of the framework for designing a AM-enabled web-based MC toolkit (section 1 –continued)

186

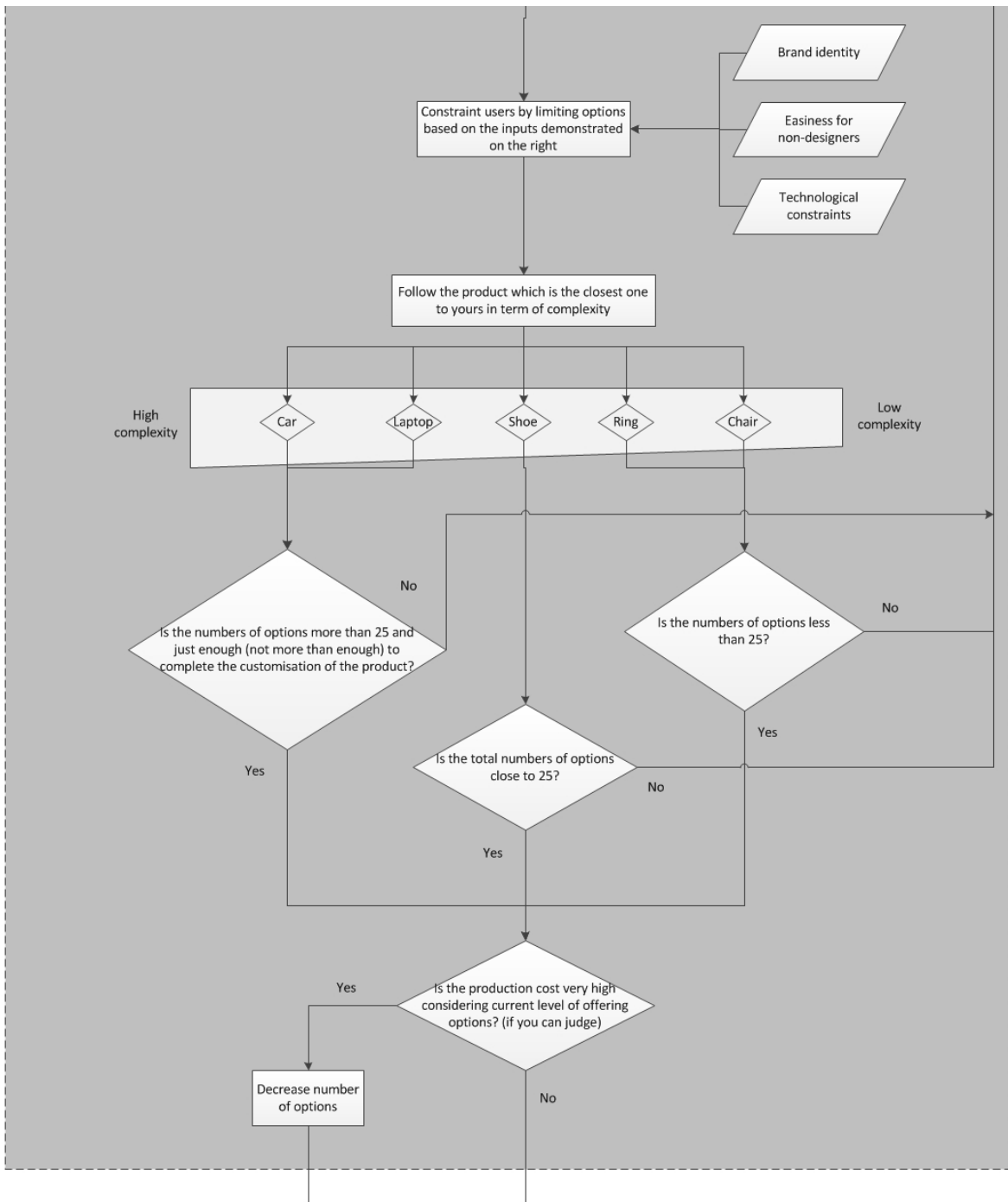Brand identity
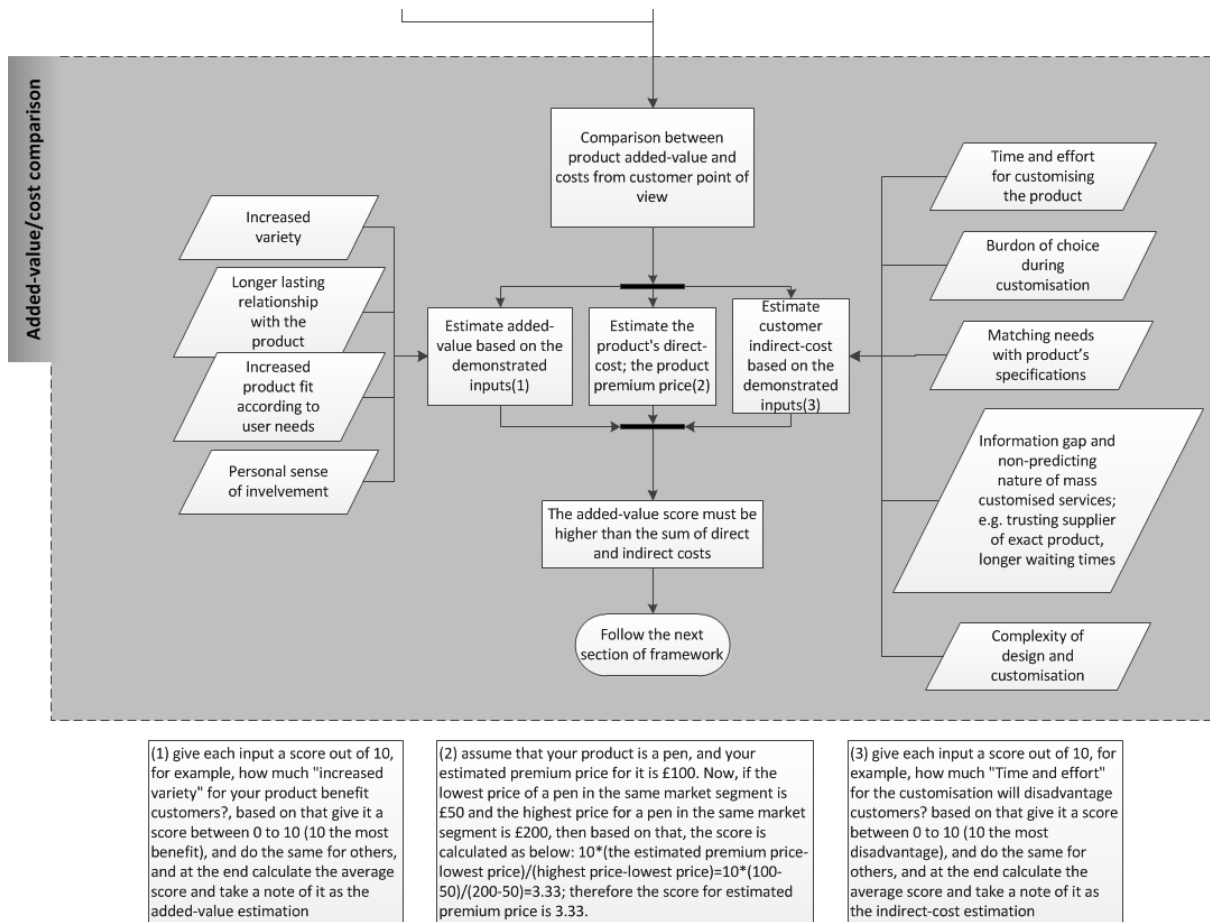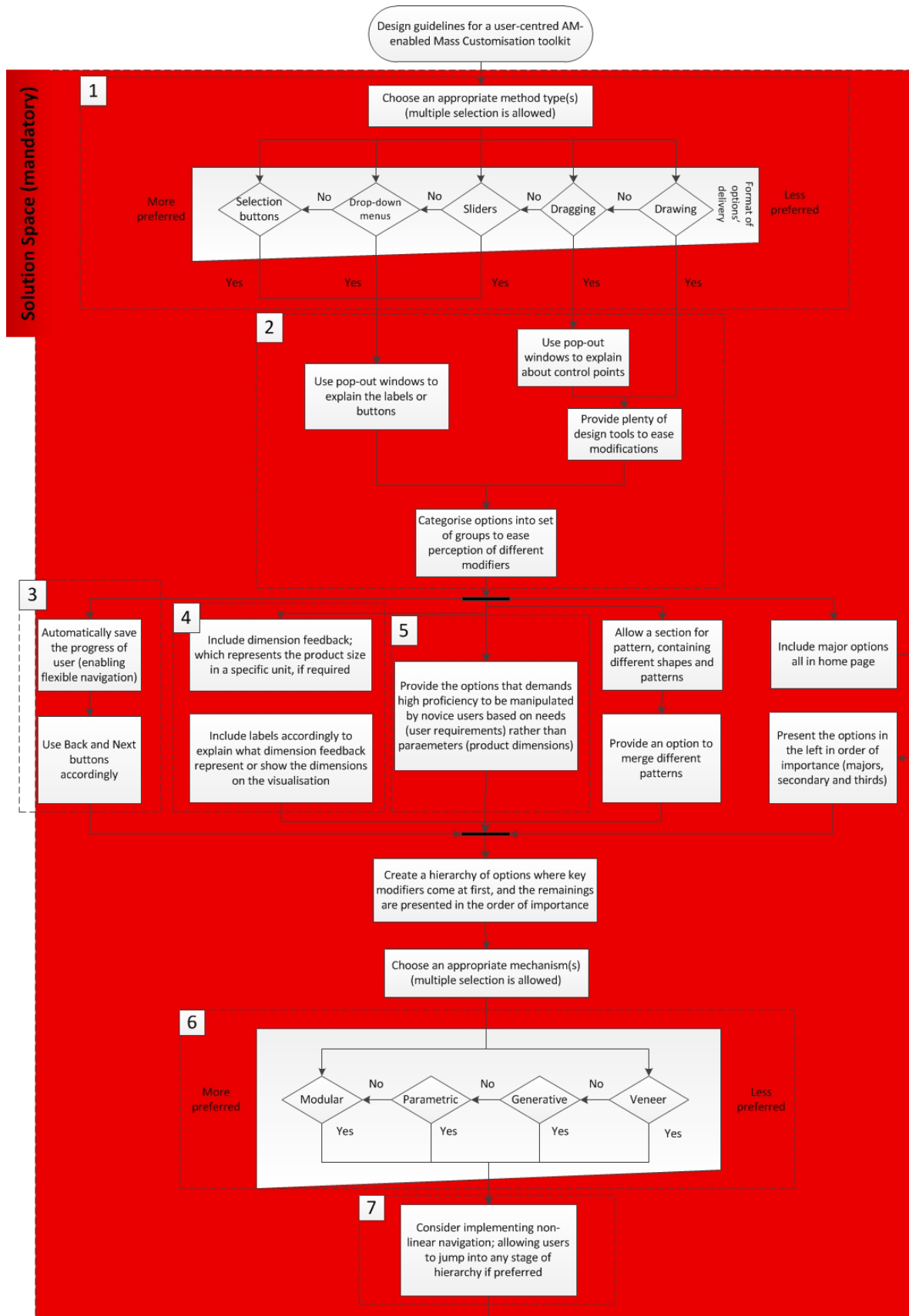
Easiness for non-designers

Technological constraints

Constraint users by limiting options based on the inputs demonstrated on the right

Follow the product which is the closest one to yours in term of complexity

High complexity

Car   Laptop   Shoe   Ring   Chair

Low complexity

Is the numbers of options more than 25 and just enough (not more than enough) to complete the customisation of the product?

No

Yes

Is the total numbers of options close to 25?

Yes

No

Is the numbers of options less than 25?

No

Yes

Is the production cost very high considering current level of offering options? (if you can judge)

Yes

No

Decrease number of options

Figure 9-3 Pre-assessment section of the framework for designing a AM-enabled web-based MC toolkit (section 2 continued)

187

Added-value/cost comparison

Comparison between product added-value and costs from customer point of view

Increased variety

Longer lasting relationship with the product

Increased product fit according to user needs

Personal sense of involvement

Time and effort for customising the product

Burdon of choice during customisation

Matching needs with product's specifications

Information gap and non-predicting nature of mass customised services; e.g. trusting supplier of exact product, longer waiting times

Complexity of design and customisation

Estimate added-value based on the demonstrated inputs(1)

Estimate the product's direct-cost; the product premium price(2)

Estimate customer indirect-cost based on the demonstrated inputs(3)

The added-value score must be higher than the sum of direct and indirect costs

Follow the next section of framework

(1) give each input a score out of 10, for example, how much "increased variety" for your product benefit customers?, based on that give it a score between 0 to 10 (10 the most benefit), and do the same for others, and at the end calculate the average score and take a note of it as the added-value estimation

(2) assume that your product is a pen, and your estimated premium price for it is £100. Now, if the lowest price of a pen in the same market segment is £50 and the highest price for a pen in the same market segment is £200, then based on that, the score is calculated as below: 10*(the estimated premium price-lowest price)/(highest price-lowest price)=10*(100-50)/(200-50)=3.33; therefore the score for estimated premium price is 3.33.

(3) give each input a score out of 10, for example, how much "Time and effort" for the customisation will disadvantage customers? based on that give it a score between 0 to 10 (10 the most disadvantage), and do the same for others, and at the end calculate the average score and take a note of it as the indirect-cost estimation

Figure 9-4 Pre-assessment section of the framework for designing a AM-enabled web-based MC toolkit (section 3)

188

Figure 9-5 Main section of the framework for designing of AM-enabled web-based MC toolkit (section 1 – continued)

8 Choose a visualisation feedback based on a trade-off between the inputs on the right

Information that customer receives from the visualisation

Visual appeal of the product

Technical constraints

9 Create a product visualisation that updates real-time with each modification

Consider including primary camera view options (top view, zoom, rotate, etc.) of the product at the bottom of the screen

Dimensions

3D   2D

Consider including primary camera view options (top view, zoom, rotate etc.) of the product at the bottom of the screen

10 Consider the feature in which the view focuses on the selected option (this will ease manipulation of the selected option)

Present visualisation as closest as possible in the centre of the screen (according to studies)

11 Create a product price feedback that updates with each modification

Allow enough space for price update element

Present it at the bottom right corner of the screen (according to studies)

12 Allow a section for material and colour, containing different colours and materials

Provide variety of materials and colours for different themes and schemes

13 Include pop-out windows for every labels, buttons, and menus

14 Include a separate button for help at the top right corner to open a page to provide extra information

Figure 9-6 Main section of the framework for designing an AM-enabled web-based MC toolkit (section 2 – continued)

190

15 Include a starting point in the toolkit (start from a template/step by step guide)

No → **16** Add library of modules or producibles

No

Yes

Yes

17 Include virtual demonstration of final product's function and beauty

No

Check if it is working properly for different configurations

Yes

18 Add a reference object to the visualisation

19 Include design tools as an advanced options; e.g. mirror, chamfer (optional)

No

No → Allow multiple selection of modifiers

Yes

Yes

20 Does manipulating of the offered options demand technical knowledge or expertise?

Yes → Each technical customisation options requires technical guidance in order to be understandable by every customers

No

21 Provide a button by which users' progress can be saved as STL (for users (optional) later on for production) or automate majority of your repetitive tasks such as CAD modelling

Include a button for users to undo his/her progress

Provide a button so that customers can give feedbacks about the interface

22 Give the ability to users to customise the user interface in terms of number of options or provide at least two user interfaces with different numbers of options

Figure 9-7 Main section of the framework for designing of AM-enabled web-based MC toolkit (section 3-continued)
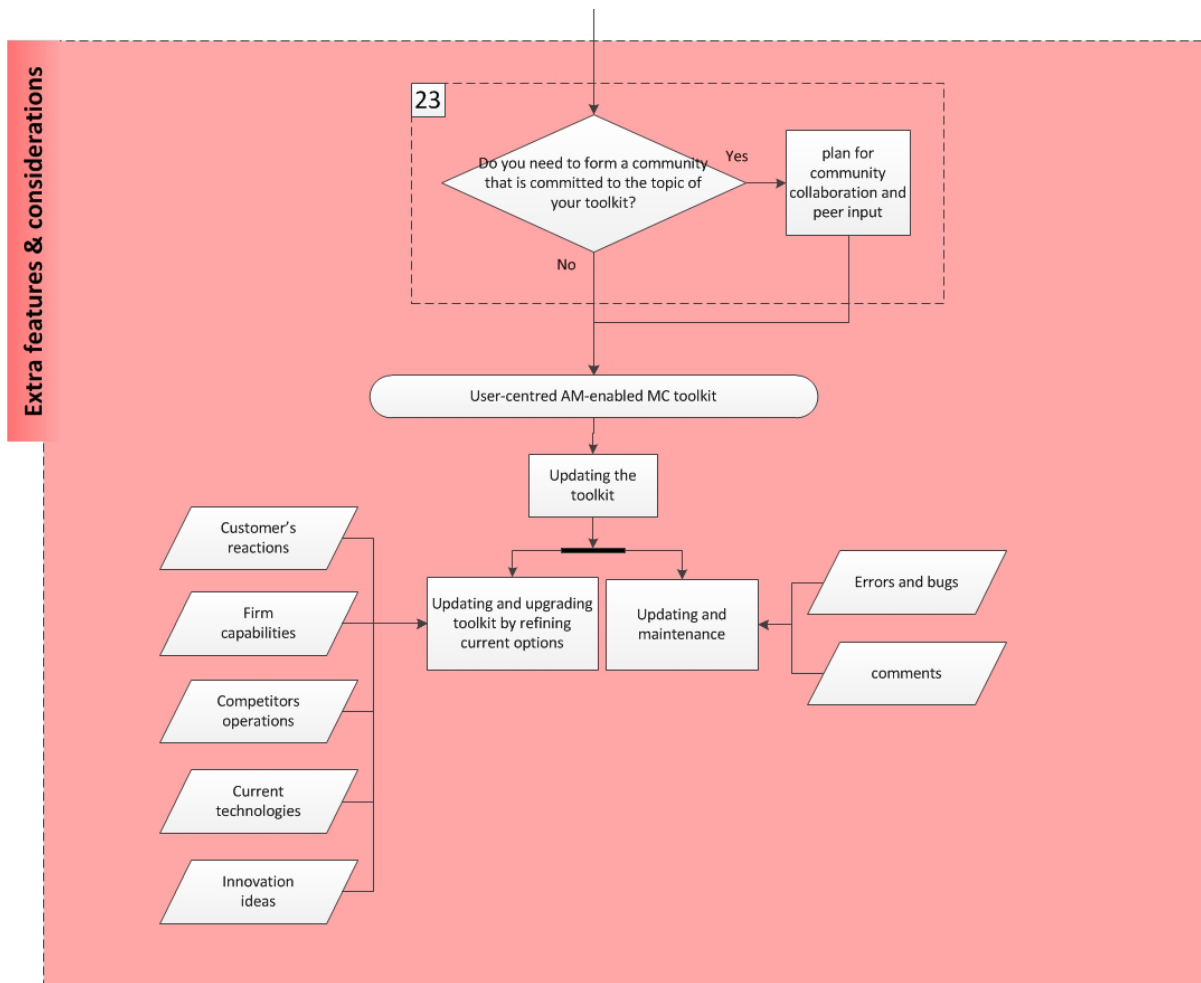
Figure 9-8 Main section of the framework for designing of AM-enabled web-based MC toolkit (section 4)

9.5 Study 3 - Validation of the Design Framework

9.5.1 Introduction

It is not enough to stand up and say, 'Here is the design and it is good because I am an expert.' In order to verify both the general applicability of the design framework, and the features implemented within it, a validation exercise was carried out with representative users, i.e. software developers and designers. Once the designers gave their comments on the framework based on their experience with toolkits and guidelines, then the framework was finalised with the last amendments. Furthermore, the framework format was assessed by the designers and software developers to check its readability, and user-friendliness.

9.5.2 Aim and Objectives

The main purpose of this study was to find out more about the interaction of designers with the framework to extract insights that would help to amend the proposed version and then prepare a final version of it. Participants were asked to attend a session, and to answer a number of questions, in particular:

192

1- What is your experience with similar guidelines or design tools, and how were the current tools perceived or could they be amended based on that?
2- How is the format of the framework presented?
3- What is lacking or contradictory in the framework? How can the framework can be improved?

9.5.3 Study Rationale

The framework is intended to be used without the help of the creator or other specialist in the area of MC toolkits, i.e. it should be usable by any designer or software developer intending to design a user-centred AM-enabled MC toolkit. Participants were asked a number of questions in the session before being shown the framework; they were then requested to use it to create toolkit specifications, and finally were interviewed again. This revealed whether the toolkit was in the right format and understandable by them, as well as revealing amendments and general issues that should be addressed. By addressing the parts that were questioned by participants, amendments could be made, such as more explanation or rearrangements of the components.

9.5.4 Method

9.5.4.1 Participants

Each session was conducted with one participant using the framework alone. Two types of future users of the framework were identified: designers and software developers. In line with recommendations by Goodwin (2009), four expert users were consulted, initially, and due to the repetitiveness of feedback observed after the fourth participant, it was decided the study should be terminated at that stage. The only personal information that was checked was that they were over 18.

9.5.4.2 Material

Since the framework should be used without an expert presented, guidance and usability of the framework were key requirements. A web-based format was chosen as the means of presentation in order to improve the usability, and also the long flow chart was made more user-friendly by splitting it into discrete stages, using animation, transition, and transformation (using CSS) to differentiate each stage.

Prior to the validation sessions, a number of questions suitable for a semi-structured interview were prepared. These formed three stages of inquiry: general background and MC and design questions; general previous guidelines that they have used before; and specific questions on this thesis framework:

Stage	Interview questions
Stage 1 (Background)	May I ask you whether you are a designer or software developer?
	Have you had any experience with MC toolkits before? What product was it for?
	Have you ever created a MC toolkit or configurator in the past? What product was it for?
	What was the most challenging thing when you wanted to design a toolkit in the past?
Stage 2 (Previous guidelines)	Did you use any guidelines for creating one?
	What do you think is missing from the guidelines you used in general? Have you found any issues while following steps?
	If you have used any guidelines for a designing a MC toolkit before, were you able to apply them in your work?
	If you did not use guidelines, how did you create the toolkit you intended?
Stage 3 (Thesis framework)	How about this guideline, do you think you can use it for your design?
	Based on your experiment is there any place in the framework that is contrasting with your thoughts?
	Do you think the framework understandable to a designer or would it require someone to explain it?
	Do you recommend any other format for presenting this framework?

9.5.4.3 Pilot study

One member of the academic staff in the Design School was selected for the pilot study based on the requirements of being a designer or software developer. A date was confirmed with him for the session, which was held in the Design School.

In order to do the final design of the study, a revision was done to the test based on the pilot study, which was performed to find out if there could be any error in the code of the web-based framework or any critical issues that would need to be addressed beforehand. The issues that were found in the pilot study were:

1. There was confusion on what the framework actually does, and what the purpose of it is. The relation between this framework and toolkit was not clear and sometimes those two words were confused with each other.

2. The definition and meaning of some of the terms and phrases were not clear. In a few instances, the flowchart was not understandable due to bad English or unsuitable words.

3. The readability of the flowchart was under question at some points, due to the same geometries and shapes being used for all the stages, whether it was a command, decision, or an input.

4. More information in the form of examples was required to guide the users through the framework and make it more understandable.

5. Some faults, when the framework was being used, were identified. For example, the pointer shape did not change when a decision needed to be made or some buttons were not responsive to the user's clicks.

6. The sequence of the flowchart was not well chosen at some stages, which led to some difficulty for the user to follow the process.

7. There were some spelling and grammar issues.

The amendments consequentially made to the study were as follows:

1. The two terms 'toolkit' and 'framework' were replaced by 'consumer toolkit' and 'design framework' to address the issue. This will explain that the toolkit is a tool for consumers to create a product, and the framework is a tool for designers and software developers to create one of those toolkits for consumers.

2. The English and definition of phrases and words were amended by replacing the words or rewriting the whole phrases and sentences.

3. For each stage of the process, whether it was a command, decision, or input, a specific geometry was used to ease the flow. At the beginning of the website, each geometrical shap was shown with its connecting meaning.

4. More information and examples were added to the process to help users grasp the ideas and logic behind the steps as well as help them to follow the procedure.

5. All the faults and errors of the system were identified and addressed, and the flow was followed several times to find any problematic issues.

6. The sequence of the framework was adapted where possible.

7. All the grammar and spelling issues were corrected accordingly.

9.5.4.4 Procedure

Each participant was sent an email containing the participant's information sheet (Appendix 16 Participant's Information Sheet for Study 3). They were asked to attend a session in either the Design School or an alternative place if more convenient.

In the session, at the beginning, they were asked to sign the consent form (Appendix 15 Permission Letter for Study 3). The questions from stage 1 and 2 were asked, and then the framework was presented for examination and further inquiry. Participants were guided to answer questions from stage 3 while using the framework, but in some cases the questions were addressed at the end of the session. All the sessions were recorded with their permission.

The participants evaluated the framework by going through it step by step, reading each step through, and giving their thoughts generally. It was later identified that they could have been asked to document their decisions and choices as they progressed, which could be more beneficial for a number of reasons. For example, the evaluation would become contextual rather than being general and shallow. This could also have made the evaluation more enjoyable as they progressed through it.

9.5.4.5 Analysis

This study resulted in one set of data, which was from voice recording of interviews. Digital analysis through tools such as NVivo was considered less effective for thematic analysis in this case; because of the type of searching that it is capable of doing (Welsh 2002). This concerns searching through the thematic ideas in order to gain a profound understanding of the data. For this reason, manual techniques were used rather than automated ones. Based on previous consideration of different approaches to qualitative analyses (Robson 2011), detailed in Chapter 8, a thematic analysis approach was used to analyse the collected data due to the similarity of nature of this study with the second study, and previous familiarity of the author with this approach.

9.5.5 Results and Discussion

The study aimed to examine the presence of professional potentials to use the newly designed and prepared design framework for user-centred AM-enabled MC toolkits. Due to the small volume of the data collected, this section combines the result and discussion into one.

According to the study's question, two themes were defined from the importance of the data, and they represent some level of patterned response or meaning within the analysed data. The result of the thematic analysis is presented and discussed next.

9.5.5.1 Participants characteristics

Among the four participants of the study, only one had had previous experience of designing a MC toolkit. Therefore, it was revealed that modifications to the design framework would be required primarily in terms of its design and readability, rather than its technicality. Since most of the participants had not had a chance to use or design a MC toolkit, the collected data was only concerned with stage 3 of the prepared questions of the interview (Table 9-3) (about the actual framework).

Table 9-4 Types and numbers of participants for study 3 (n=4)

Participants	Number
Designer	3
Software Engineer	1

9.5.5.2 Ranking of problematic issues

It is very interesting that some of the data collected in this study was very similar to the second study (Chapter 8), even if they are concerned with two different subjects: MC toolkits and the framework. For example, for the toolkit, the participants mentioned that appropriate and sufficient guidance is very important, this was also mentioned in the feedback for this study. This may indicate that no matter what platform a MC toolkit or design framework, is designed or developed on, there needs to be certain standard or guidelines to meet the user's requirements. This section deals with the results and discussion regarding the issues and their ranking.

Table 9-5 shows the ranking obtained from voice recordings. It not only includes how many participants mention that issue, but also how many times they mention the issue overall.

Table 9-5 Ranking of the framework's issues, obtained by the participants

Rank	Issues	Number of participants mentioned this issue (number of times mentioned)
1	Some items are vague and need clarification/explanation	4 (38)
2	Add examples and guidance	4 (9)
3	The need for rearrangement of the flow	3 (5)
4	Add an introduction about additive manufacturing	3 (3)
5	Allow users to input and store their data	3 (3)
6	Add a heading to each part	2 (4)
7	Use the screen space more effectively	2 (2)
8	Add a summary at the end of each section	2 (2)
9	Use a scoring system for analyzing the feasibility of implementing the MC toolkit	1 (1)
10	Provide prompt/output to users' actions	1 (1)

9.5.5.3 Thematic analysis of issues of the MC toolkit

The issues mentioned in the previous section were categorised into two themes, shown in Figure 9-9. The themes were selected based on two techniques of repetition and theory-related material. Many of the issues regarding guidance were recurring, making guidance one of the themes. Usability is recognised as a theme because of technique of theory-related material.

The figure below, illustrates the ranking of the issues and the association of each issue on the themes.
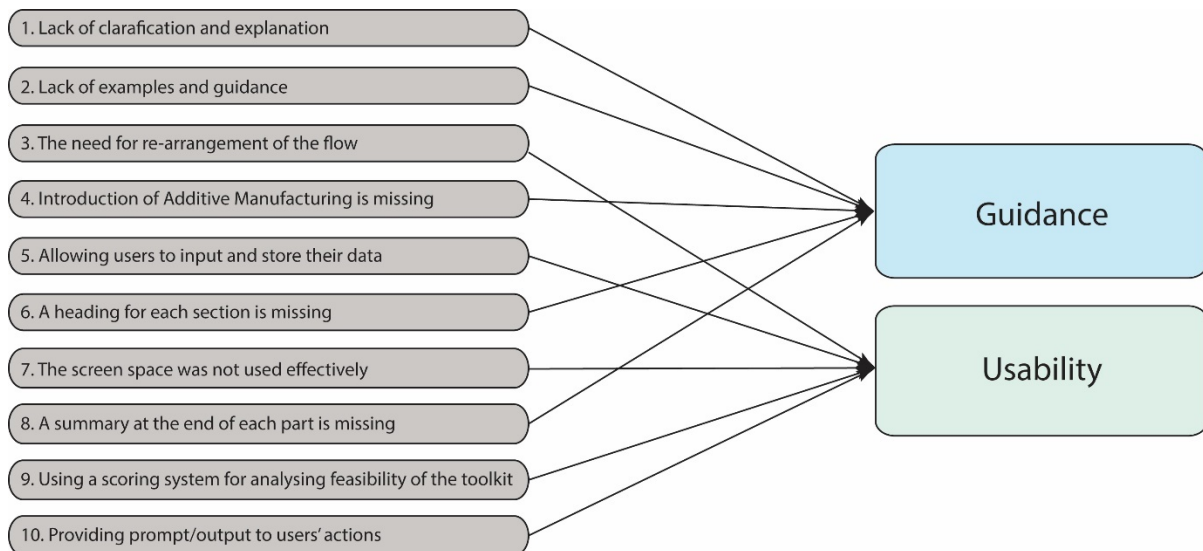
Figure 9-9 The framework's issues and its association with the themes

9.5.5.4 The issues about guidance

Most of the feedback was around the issue of lack of guidance and examples. It is interesting to mention that this was true as well for the second study for the MC toolkit, reflecting that any platform should be accompanied by enough help and guidance as lack of it means that users would not understand and easily progress through the sections, or would probably require a specialist in this area to explain the items to them. Therefore, to solve the problems identified in the diagram below in this study, the framework was divided into two parts, a main section, and a help section.

In the help section, examples and interactive guidance, accompanied by images and videos, were added to ease the use of the tool and make it more fluent. An introduction to AM was also included in this section for familiarising users with the new technique. Furthermore, a heading was created for each section.
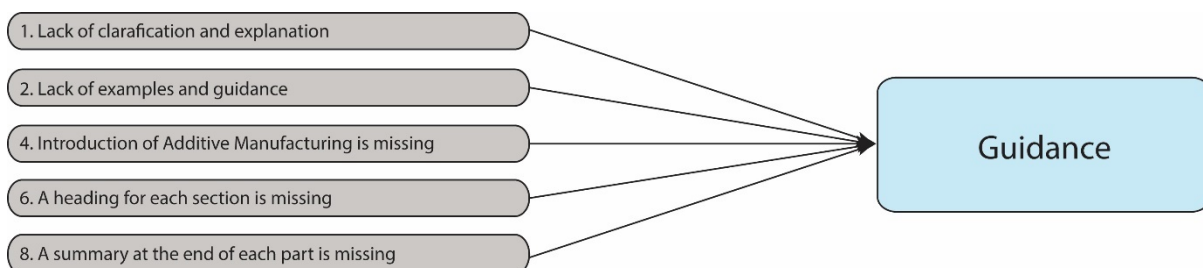
Figure 9-10 The framework's issues that had a major impact on guidance

9.5.5.5 The issue with usability

The second theme that was extracted from the issues was usability of the framework. The issues of this theme were well taken into consideration, as now the framework has been divided into two main parts (using the space more effectively). The

framework requires different data consideration, and even calculations. The interface itself could be used by users to input their data with the aid of check boxes, and the interface takes care of the remaining. Since the study time was limited, the framework was not improved from this aspect to store the data or do the calculations required.
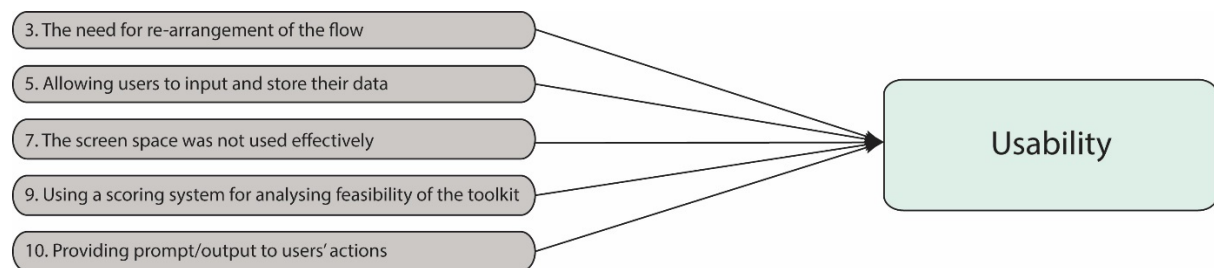
Figure 9-11 The framework's issues that had a major impact on usability

9.5.5.6 Amendments to the framework

Issues regarding the framework were considered as an indication that the tool could be improved; however, implementing even a few of them was estimated to take a long time, and was beyond the scope of this research. It is worth mentioning that if the author noticed any critical issue or fault in the framework during the studies, it was removed for the next study, however, other amendments were undertaken at the end of the study.

The amendments made to the framework were as follows:

- The content of the framework was corrected, and any spelling and grammar faults were removed. Some questions were not clear and were rephrased to express the meaning more clearly

- The sequence of the components was rearranged to be logical, to prevent any confusion or repetition of some elements

- The visualisation of the content was revised in order to divide it into two main parts to use the screen space more effectively and efficiently. One was the questions and commands that needed to be followed. The other was the guidance, which appeared when each step of the flow chart was being reviewed and selected. The main part was presented on the left, and the guidance on the right, demonstrating the level of importance of each part in terms of a left to right reading direction

- The layout of some stages of the framework was tidied up and simplified . The visual design of some stages was also changed by re-programming the CSS

- The guidance was improved by adding examples for some stages, even with visualisations; i.e. photos or videos. Some stages needed calculations, and an

example was also provided to ease completion of the steps. Furthermore, an introduction to AM and Three.js (as two important enablers of web-based MC toolkits) was added to the guidance in the related stage

- Although the system does not perform calculations (the economic feasibility check of toolkit implementation as a part of the pre-assessment in the framework), so was limited in terms of output and feedback. However, it does accept inputs as check marks in the relevant steps to permit the user to progress to the next step, and give him/her the sense of fulfilment.

9.6 Limitation of the Design Framework

Another approach for the framework is generating a scoring system for the choices. In other words, by selecting different choices, the design teams may reach different scores which helps them decide to continue with creating the MC toolkit or not. This was not done because of lack of ranking data in the field of MC toolkits and specifically solution space of AM-enabled MC toolkits. This can also be addressed in future research. The nature of validation in this study is abstract. Therefore, if participants were involved in real project feedback to follow the framework to implement a toolkit, then the result would be different. This framework was a new early visual prototype, which requires testing with a more developed version.

It is important to mention that there are a number of limitations in this framework design, namely lack of DoF information for each product or at least each product category, such as apparel, accessories, clothing, etc. and lack of information to create a scoring system to demonstrate if strong or poor steps or decisions were made throughout the framework. These limitations can be addressed in future research.

9.7 Conclusion

In this chapter, the design framework was proposed and explained in detail. First, key findings from the studies done in this research, which have played an important role in shaping the framework, were explained. This information forms the main skeleton of the framework because it was obtained directly from users. Thereafter, the presentation format of the framework was selected based on different available formats. A static flowchart was deemed difficult to follow and overly long; it was therefore implemented in HTML format with a web-based presentation. Using CSS techniques of transition and transformation, and JavaScript language, the format became more user-friendly, easy-to-follow, and engaging (objective 1).

The guidelines for creating the MC toolkit were divided into two sets of information: pre-assessment for implementing the toolkits, and main guidelines for actual implementation of the toolkit (objective 2), and presented.

This chapter has also presented the last study conducted in this research. The result presented here makes it possible to infer that the design framework has the potential for supporting the specification and design of improved user-centred AM-enabled MC toolkits. Analysis of the data suggests a number of key positive aspects:

- The framework design approach and format were useful to engage participants' (designers and software developers) interest, which would make them consider using the framework as a basis for toolkit improvement.

- The framework enabled participants to obtain a better understanding of the key features of AM-enabled MC toolkits and their content and on-screen layout. In addition, participants were able to obtain more information on: 1) the issues of current MC toolkits that are critical to be addressed in novel MC toolkits, 2) the specifications of MC toolkits to meet the needs of customers, 3) the relevance of considering each individual element of the toolkit and its location on the interface, and 4) their key role to design a better toolkit to provide a better MC experience for users

- The framework is a very effective tool for communicating the needs of MC toolkit users. Furthermore, the format used for presenting the framework was user-friendly and easy-to-follow, according to most of the participants.

However, a number of areas requiring improvement were also noted. The important ones are as follows (objective 3):

- Guidance and help are required when using the framework, in order to guide those who are unfamiliar with the area of MC.

- The screen space should be used more efficiently, and the interactivity should be improved. The framework presentation included lots of space that could be used for demonstrating the guidance, headings, and navigation. There was also a lack of interactivity for users to input their data, either to be stored or calculated. The data could also be summarised for the user at the end to use as a reference.

Chapter 10 : Conclusions and Future Work

10.1 Introduction

The user perspective on the AM-enabled MC toolkits, which intends to fulfil customers' needs and desire more precisely than other types, through availability of customisation options such as surface, size, pattern, etc, was investigated in this research. The investigation led to two main findings: user requirements, and usability insights. A design framework was created to reflect these findings to act as a source of knowledge for designers and software developers. Current guidelines, found in the literature review, were also integrated into the framework wherever it was supportive, and overlapped with this research's findings.

To understand the research area and explore any available knowledge, challenge some of the commonly used guidelines for creating MC toolkits, and also find the gaps in the knowledge, the literature review was first conducted (Chapter 2, Chapter 3, and Chapter 4). Afterwards, a pilot study was undertaken to explore current features of MC toolkits, and to test the study's scenario prior to a more in-depth study. Following that, the first study was conducted to prioritise the features of MC toolkits, which further helped to see which features are more important and need to be used (Chapter 6). Next, the workshop was conducted to find out about the users' expectancy of features at this time, and their preferences on the location of the features on the screen (Chapter 7). The data obtained also helped to validate the findings from the first study.

Gathering all the findings from the study and workshop, the AM-enabled MC toolkit was prototyped for a lampshade, which had both aesthetical and functional aspects for customisation. In a second study, the toolkit was used to validate previous data, find out about the user interaction, as well as the toolkit's usability (Chapter 8). Due to time limitation, the tested toolkit was not developed any further after receiving user feedback. However, in the next step, all the findings from this research along with available supporting guidelines from the literature review were presented in the design framework (Chapter 9), which was then used by a software engineer and designers to be validated and verified (Chapter 9).

Each respective chapter contains the specific findings of the studies and workshop. Hence, this final one considers the research as a whole, and explains the research aim and objectives that have been met. The main contributions to knowledge are also discussed, and the limitations of the research are explained. Suggestions for further work are then made.

The objectives of this chapter are:

1- To specify how answers to each research question has been achieved in this research
2- To express the contribution to original knowledge made by this research
3- To discuss the limitations of this research
4- To suggest potential future work

10.2 Achievement of Research Objectives

The five research questions identified in the introduction to this thesis are listed below along with a discussion on the extent to which these questions have been addressed.

Research question 1 - Which features are most important for user-centred AM-enabled MC toolkits, and in what layout?

Research Objective I was addressed by reviewing and exploring numerous CAD software programs, online sale websites, articles, and MC toolkits to present an exhaustive list of potential features of AM-enabled MC in Table 4-4. This list was then improved and extended with more features by the author's own work. The features were then prioritised with the aid of the first study and workshop, from both importance and expectancy viewpoints, as seen by participants. Those two rankings had many overlaps, and confirmed four essential features for user-centred MC toolkits: visualisation feedback, price update, flexible navigation and material selection.

Furthermore, three non-essential features were also confirmed by selecting manufacturing and assembly method, a reference object, and access to other users' designs. A screen, containing these features, was created for the study and presented in chapter 7, using the results from the workshop, which demonstrated the preferred layout for user-centred MC toolkits (Figure 7-9).

Research question 2 - How many options are appropriate for a user-centred AM-enabled MC toolkit?

This is an intriguing question, which has not been answered completely during this research due to time limitations. It means that this research cannot offer definite information about the preferred number of options for a user-centred AM-enabled MC toolkit for any specific product. However, from the first study, it was discovered that 25 options were preferred most. Interestingly, the average numbers of options preferred by the participants acquired from the second study was calculated as 26. Furthermore, participants expressed that the more complex the product is, the more options the toolkit should provide.

One suggestion from the author is that user-centred AM-enabled MC toolkits should be flexible in terms of DoF, in other words, the customisation toolkit should be customisable itself to allow customers to choose their preferred number of options. To meet this recommendation, the toolkit designer could create two or three versions for different customers. This way, novice customers (or customers who want to reach a design quickly) may choose fewer options, and advanced customers (or those who would like to spend more time exploring options) may use higher numbers of options.

Research question 3 - Which CAD or 3D-enabling system is most suitable for the implementation of AM-enabled MC toolkits?

Research objective III was addressed by comparing two CAD software programs and two 3D-enabling libraries (namely: SolidWorks API, Grasshopper, Processing, and Three.js), which were available and suitable for implementing AM-enabled MC toolkits, and accordingly a table was presented in Chapter 6. The table summarises the characteristics of those four systems in the context of AM-enabled MC toolkits. Although they share some advantages and disadvantages in terms of characteristics, it was determined that Three.js is currently the most suitable system for this purpose.

The main characteristic that led to this inference was 'feature integration'. It was determined from the first study that customers demand features such as price feedback, flexible navigation, etc. Furthermore, it was obvious that CAD software programs are really only aimed at designers (not to be used by novices), but AM-enabled MC toolkits are for consumer design and purchasing (to be used by both novices and advanced users). Therefore, features facilitating the purchasing part are required in MC toolkits, which are almost impossible to be presented on CAD software programs. Other platforms such as Flash may enable implementation of these features, however, it is not a good choice for 3D manipulation, which is the main focus of this research. Another advantage of Three.js, is that when it is programmed and published, it is web-based, which is a fundamental requirement for MC toolkits in general.

Research question 4 - What are the advantages and disadvantages of an AM-enabled MC toolkit from the user's point of view?

The second study was designed mainly to answer this question. Participants were asked to design a lampshade in the prototyped MC toolkit, created from the findings of the first study and workshop. Respectively, research objective II was addressed by testing the toolkits, which led to a number of negative and positive points about the toolkit, presented in Table 8-5 and Table 8-6. These data validate previous findings, and led to user insights, which were helpful for creating the design framework.

Research question 5 - What guidelines do designers and software developers need to take into account when designing user-centred AM-enabled MC toolkits?

Chapter 9 is completely devoted to the development of this framework. Research objective IV was addressed by embedding the findings and insights from this research and supporting guidelines found through the literature review into the framework, and then validating it, which mostly identified required improvements in terms of usability rather than technicality (due to the lack of participants' knowledge in this area). Feedback from the interviews has led to some proposals for further development, which were outside scope of this research, but are listed as future recommended work.

10.3 Contribution to Knowledge

A number of original contributions have been made throughout this research based on the knowledge presented in this thesis, as listed below:

1. The main contribution to knowledge in this thesis is concerning design and implementation of user-centred MC toolkits. It is expected that the novel framework will serve as a guideline for designers and software developers. This framework contributes to the knowledge on user-centred AM-enabled MC toolkits, in terms of content (features) and layout (the feature's location) of MC toolkit features and their configuration. The framework helps its users to know the mandatory requirements, assess the feasibility of creating the toolkit, and then guide him/her to find out about the essential and recommended features, and their configuration on the screen. It helps the user to pre-assess the feasibility of creating a MC toolkit for a product, and then take him/her through the journey of creating one. It tries to accommodate all the points acquired from the research and literature review.

2. A table was produced to discuss the characteristics of four different CAD or 3D-enabled systems in the context of AM-enabled MC toolkits (Table 8-1). It shows how CAD software programs are compared to the fairly new area of 3D-enabling libraries. Three.js was identified as the best available system suited to implementing user-centred MC toolkits.

3. As mentioned before, DoF is an intriguing topic which requires further research, however, this research has made some contribution. It was noted that the product to be designed in a toolkit has a very important effect on the number of options required, which was mentioned by most of the participants during the studies. In addition, the following recommendations can be made:

- MC toolkits should be flexible in terms of DoF, i.e. the toolkit's number of options should be adjustable by customers themselves to fit their own skills and preferences.

- From the users' perspectives that were obtained, a reasonable level of DoF is to have around 25 options available (page 176). However, it was also indicated that the more complex the product is, the more options the toolkit should have.

10.4 Limitations of the Research

The research undertaken for this research has been limited in a number of ways, which are explained below:

One of the important limitations was the number of software developers that were considered to examine the framework, as only one software engineer participated in the last study. However, the feedback from all the participants showed more similarities as the study went on. This implies that all the major issues were raised. These major issues, were mostly concerning the usability and functionality of the framework other than its technicality. In addition, in all the studies, participants were from the UK, a similar study with participants from different part of the world, such as Asia, might possibly provide different results.

A limitation of the second study was that the tested toolkit was for a lampshade. Therefore, the feedback of participants could be different for another kind of product. However, even different toolkits share similar specifications, which were obtained from the first study and the workshop. Furthermore, in the second study's questionnaire, some questions were asked regarding the DoF concerning different product categories, which interestingly support the findings of the first study (obtained for a generic product).

The collected features, although complete, were extracted from currently available resources. However, as expressed in the methodology chapter, a qualitative study could have been done first to try to find out or perhaps create any potential future features. This could lead to some new features, which are not currently available, but might be needed for this toolkit. In other words, the first stage of the UX design approach, the discovery stage, should have been simulated more accurately to obtain user needs more comprehensively.

10.5 Recommendations for Future Work

Although, this thesis has reached its milestones, and achieved its objectives, there are several recommendations to develop it further. These are outlined below:

Three.js was inferred as the most promising system for user-centred AM-enabled MC toolkits, but it lacks many of the design tools that are available in CAD systems, such as SolidWorks. Therefore, the capability of adjusting and further modification of the design in SolidWorks may be investigated. This would allow creation of a sophisticated product in a programming language such as Three.js and it could be sent to SolidWorks for further adjustment or amendments with easy to use design tools such as Loft or Cut-extrude.

The MC toolkit developed and explored in this thesis was for a lampshade. Unfortunately, within the scope of this thesis, other products could not be explored. To reach data that are more comprehensive, further research and development is necessary to create and examine toolkits for different products. Then, the data presented in the framework could be adapted based on the further information acquired.

Further research on DoF is recommended. Future research could obtain more solid data about the required number of options for a user-centred AM-enabled MC toolkit based on different types of product. The findings about the DoF of the lampshade toolkit were not wide enough to make detailed recommendations for other types of products. Furthermore, the association between DoF and various features of the MC toolkit could be further investigated by incorporating a larger number of participants or by using a survey, which could directly or explicitly investigate this issue.

While the framework received limited input from the users, the range of feedback demonstrated the importance of automation and giving outputs to users, such as calculations and summarising the toolkit specifications, specifically for the user. The input data from the users of the framework can also be collected (with their permission) to create a database for further research. This database could even be used to adjust the framework itself.

Finally, this framework addresses if a product is suitable for AM-enabled MC toolkit implementation by considering five requirements. However, what is missing from the framework is the question of about which product categories are more suitable for customisation. In other words, it is reasonable to question which product categories consumers might be more interested in to engage with.

Finally, in the future research, participants should be best informed about MC, and MC toolkits during the process of the studies, and more importantly studies should be performed on specific MC toolkits other than on general ones.

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Appendices

Appendix 1 Presentation Slides for Study 1

Introduction to M.C. Toolkit Criteria

Visual feedback (3D representation)
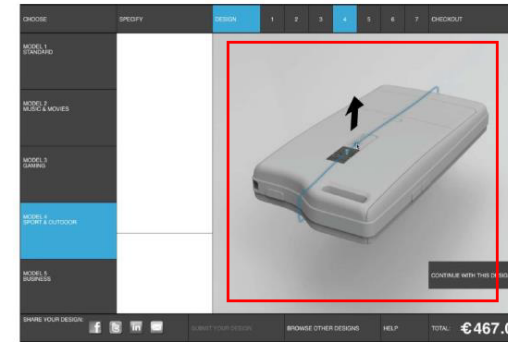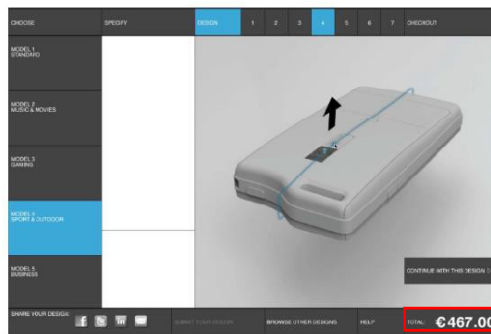
Price Update

The price is updated on each selection (real-time)

Need-based or Parameter-based

Need-based   Parameter-based

Starting point

Template

A blank canvas
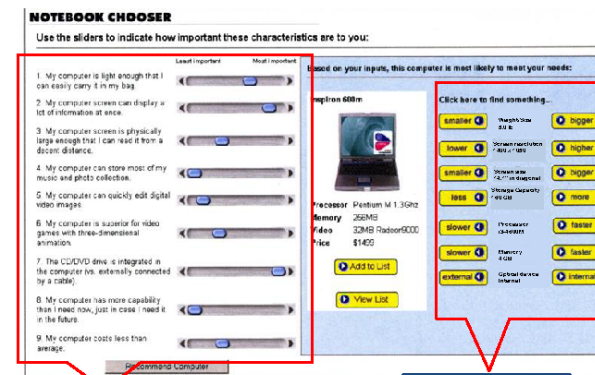
How do user begin the customization process?

6

Mechanisms (a technique to offer and implement M.C.)

Modularity

To combine and assemble mass produced modules or components to form a customized design (to select from pre-set options)

7

Mechanisms

Parametric
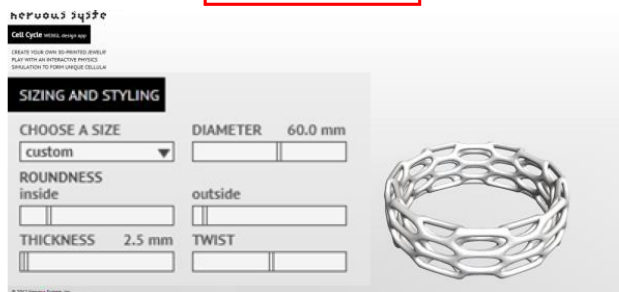
To modify a 3D model by changing or setting parameter values

8

Mechanisms

Generative
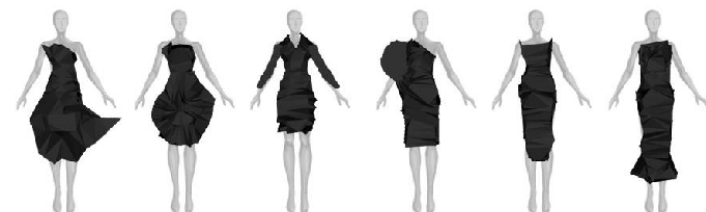
to select from real-time generated original products

9

Mechanisms

Veneer
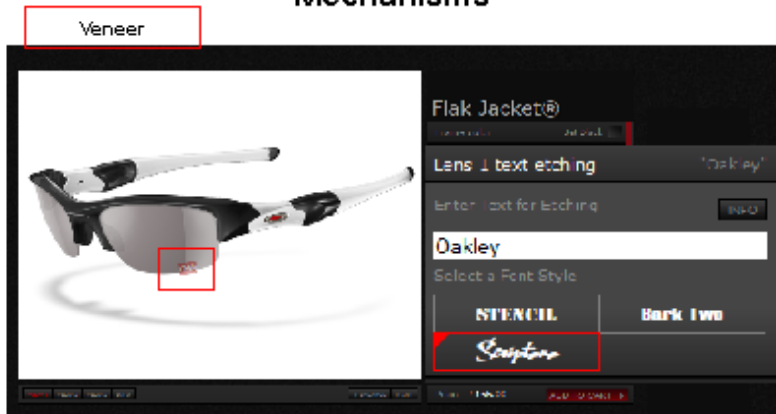
To customize a product by adding a visual, decorative layer to a mass produced product, e.g. etching, image uploading

10

Click and show option (interaction method)

For example: Pop out window shown on the model

Degree of freedom

Engraving

Size

Colour

Shape

Theme
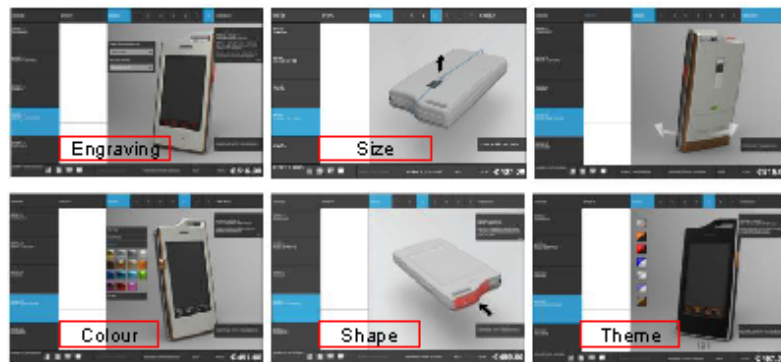
How many options do the users have and how much variety these options provide? change colour, change size, add text, change material

12

Virtual use of product
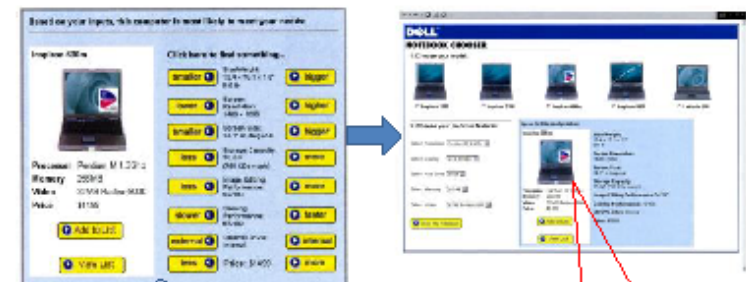
Ability to assess or virtually use final product, or see what happen after changing one or number of variable attribute(s)

13

Guidance (help in using the system)

Technical information

Provide technical information about a variable attribute

Validation with feedback (provide information about compatibility check or/and any physical/technical faults)

Checking valid solutions

Physics providence

Provide information based on physics principles to help user create a physically appropriate result

un-balanced

balanced

Material selection

Selecting manufacturing and assembly method (Production method)

Choose how to manufacture final product or part of the final product

Input type

Selections

Input type

Sliders

Input type

Dropdown menu
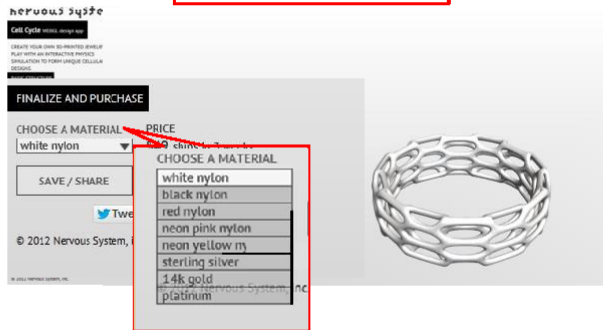
22

Input type

3D scan
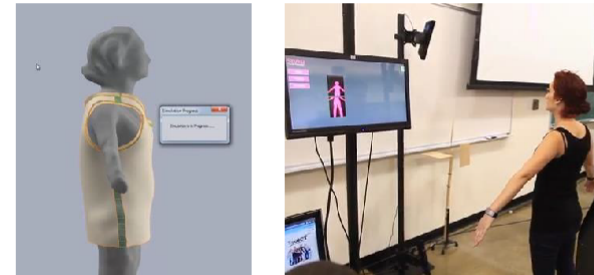
23

Input type

Drawing
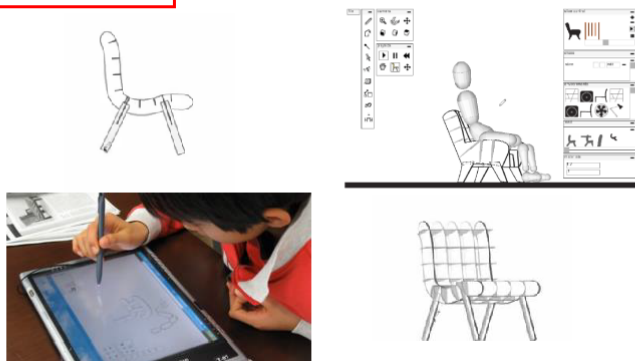
24

Input method

Mouse
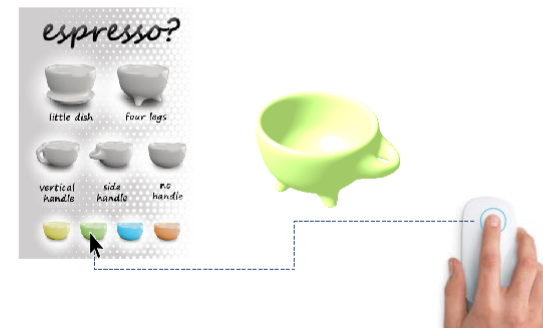
25

Input method

Voice

Green
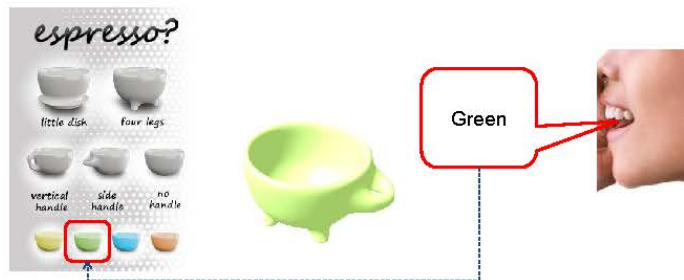
26

Input method

Haptic

27

Input method

Gesture

28

Input method

Touch screen

29

Web-based
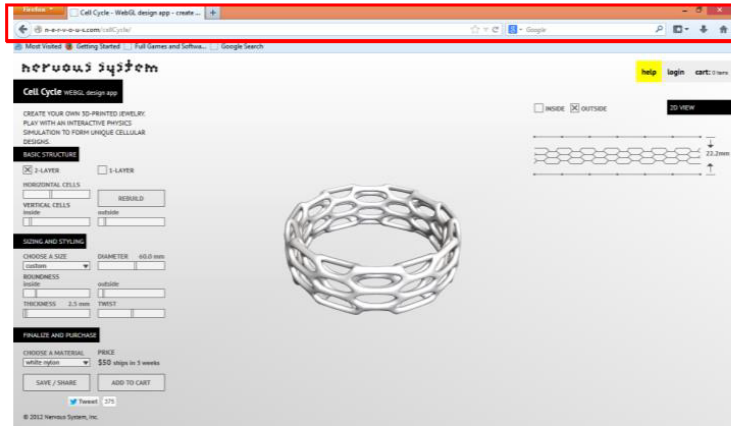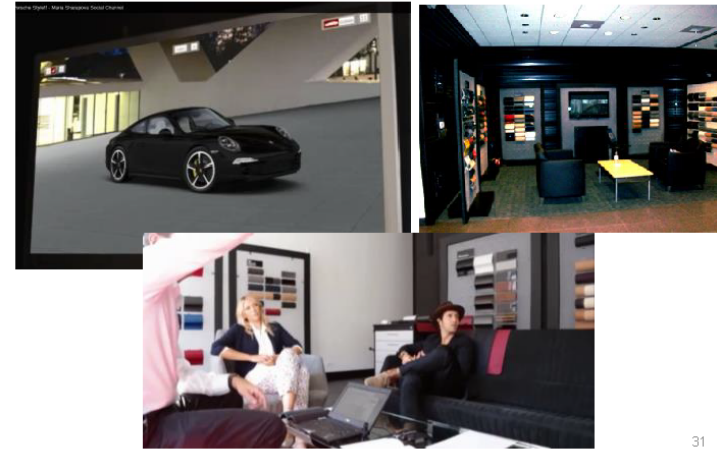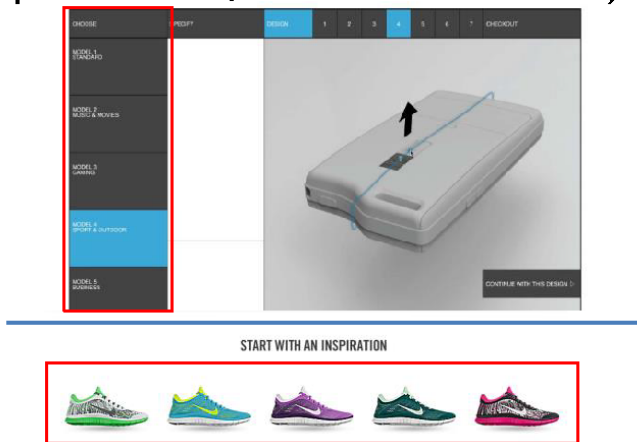
30

Store-based

31

Libraries of modules and producible (from manufacturers)

32

Users' designs access (access to other users' design)

33

Offline access

Can work on local data if internet not working, then updated later

Reference Object

In order to design in appropriate scale, style and human fit
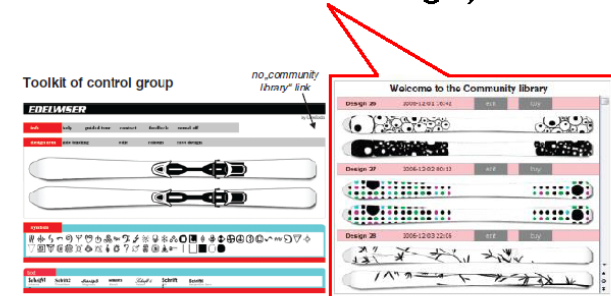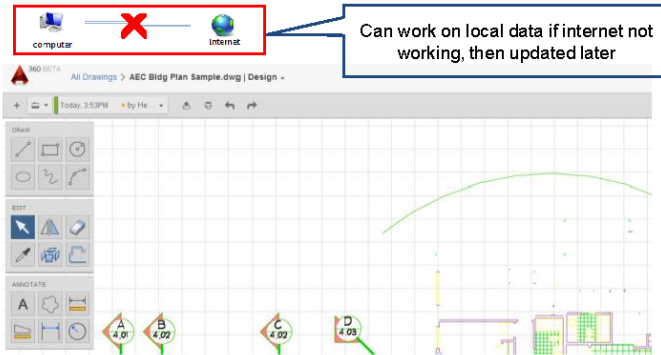
Reference objects
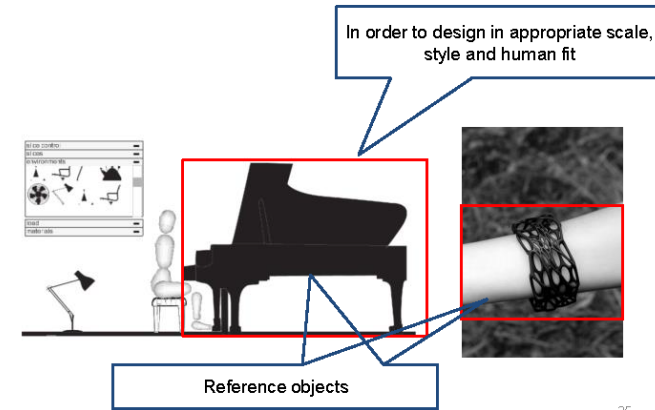
Appendix 2 Online Survey Resource: Survey Monkey

MC Toolkit Study

1. Please rate the importance of the criteria below for a mass customisation toolkit?

	Least needed				Most needed
Visual feedback (3D representation)	○	○	○	○	○
Flexible navigation	○	○	○	○	○
Price update	○	○	○	○	○
Reference object	○	○	○	○	○
Click and show option (interaction method)	○	○	○	○	○
Virtual use of product	○	○	○	○	○
Guidance (help in using the system)	○	○	○	○	○
Technical information	○	○	○	○	○
Validation with feedback	○	○	○	○	○
Physics providence	○	○	○	○	○
Material selection	○	○	○	○	○
Selecting manufacturing and assembly method	○	○	○	○	○
Libraries of modules and producible (from manufacturers)	○	○	○	○	○
Users' designs access	○	○	○	○	○
Offline access	○	○	○	○	○
Side-by-side comparison	○	○	○	○	○

2. Which one do you prefer for mass customization toolkit?

○ Need-based

○ Parameter-based

3. Which one do you prefer for mass customization toolkit?

○ Store-based

○ Web-based

4. Which one do you prefer for mass customization toolkit?

○ Template

○ Blank canvas

5. About how many degree of freedom do you prefer that a mass customization toolkit has?

○ Less than 5

○ 5

○ 10

○ 15

○ 20

○ 25

○ More than 25

Appendix 3 Ethics Clearance Checklist Form for Study 1

Ethics Approvals (Human Participants) Sub-Committee

Loughborough University

Ethical Clearance Checklist

Has the Investigator read the 'Guidance for completion of Ethical Clearance Checklist' before starting this form?	Yes

Project Details

1. Project Title: Mass Customization Toolkit Study

Applicant(s) Details

2. Name of Applicant 1: Hesam Yavari	10. Name of Applicant 2: Ian Campbell
3. Status: PGR student	11. Status: Staff
4. School/Department: Design School	12. School/Department: Design School
5. Programme (if applicable): Click here to enter text.	13. Programme (if applicable): Click here to enter text.
6. Email address: h.yavari@lboro.ac.uk	14. Email address: R.I.Campbell@lboro.ac.uk
7a. Contact address: flat 2, 12 sparrow hill, loughborough	15a. Contact address: Design school, loughborough university
7b. Telephone number: 07408848755	15b. Telephone number: +441509228312
8. Supervisor: No	16. Supervisor: Yes
9. Responsible Investigator: No	17. Responsible Investigator: Yes

Participants

Positions of Authority

18. Are researchers in a position of direct authority with regard to participants (e.g. academic staff using student participants, sports coaches using his/her athletes in training)?	No

1

Vulnerable groups

19. Will participants be knowingly recruited from one or more of the following vulnerable groups?	
Children under 18 years of age	No
Persons incapable of making an informed decision for themselves	No
Pregnant women	No
Prisoners/Detained persons	No
Other vulnerable group Please specify: Click here to enter text	No
If you have selected No to all of Question 19, please go to Question 23.	
20. Will participants be chaperoned by more than one investigator at all times?	Choose an item
21. Will at least one investigator of the same sex as the participant(s) be present throughout the investigation?	Choose an item
22. Will participants be visited at home?	Choose an item

Researcher Safety

23. Will the researcher be alone with participants at any time?	Yes
If Yes, please answer the following questions:	
23a. Will the researcher inform anyone else of when they will be alone with participants?	Yes
23b. Has the researcher read the 'guidelines for lone working' and will abide by the recommendations within?	Yes

Methodology and Procedures

24. Please indicate whether the proposed study:

Involves taking bodily samples (please refer to published guidelines)	No
Involves using samples previously collected with consent for further research	No
Involves procedures which are likely to cause physical, psychological, social or emotional distress to participants	No
Is designed to be challenging physically or psychologically in any way (includes any study involving physical exercise)	No
Exposes participants to risks or distress greater than those encountered in their normal lifestyle	No
Involves collection of body secretions by invasive methods	No
Prescribes intake of compounds additional to daily diet or other dietary manipulation/supplementation	No

2

Involves pharmaceutical drugs	No
Involves use of radiation	No
Involves use of hazardous materials	No
Assists/alters the process of conception in any way	No
Involves methods of contraception	No
Involves genetic engineering	No

Involves testing new equipment	No

Observation/Recording

25a. Does the study involve observation and/or recording of participants?	No
If **Yes**:	
25b. Will those being observed and/or recorded be informed that the observation and/or recording will take place?	Choose an item

Consent and Deception

26. Will participants give informed consent freely?	Yes

Informed consent

27. Will participants be fully informed of the objectives of the study and all details disclosed (preferably at the start of the study but, where this would interfere with the study, at the end)?	Yes
28. Will participants be fully informed of the use of the data collected (including, where applicable, any intellectual property arising from the research)?	Yes

29. For children under the age of 18 or participants who are incapable of making an informed decision for themselves:	
a. Will consent be obtained (either in writing or by some other means)?	N/A
b. Will consent be obtained from parents or other suitable person?	N/A
c. Will they be informed that they have the right to withdraw regardless of parental/guardian consent?	N/A
d. For studies conducted in schools, will approval be gained in advance from the Head-teacher and/or the Director of Education of the appropriate Local Education Authority?	N/A
e. For detained persons, members of the armed forces, employees, students and other persons judged to be under duress, will care be taken over gaining freely informed consent?	N/A

3

235

Deception

30. Does the study involve deception of participants (i.e. withholding of information or the misleading of participants) which could potentially harm or exploit participants?	No
If **Yes:**	
31. Is deception an unavoidable part of the study?	Choose an item
32. Will participants be de-briefed and the true object of the research revealed at the earliest stage upon completion of the study?	Choose an item
33. Has consideration been given on the way that participants will react to the withholding of information or deliberate deception?	Choose an item

Withdrawal

34. Will participants be informed of their right to withdraw from the investigation at any time and to require their own data to be destroyed?	Yes

Storage of Data and Confidentiality

35. Will all information on participants be treated as confidential and not identifiable unless agreed otherwise in advance, and subject to the requirements of law?	Yes
36. Will storage of data comply with the Data Protection Act 1998?	Yes
37. Will any video/audio recording of participants be kept in a secure place and not released for any use by third parties?	Yes
38. Will video/audio recordings be destroyed within ten years of the completion of the investigation?	Yes
39. Will full details regarding the storage and disposal of any human tissue samples be communicated to the participants?	N/A
40. Will research involve the sharing of data or confidential information beyond the initial consent given?	No
41. Will the research involve administrative or secure data that requires permission from the appropriate authorities before use?	No

Incentives

42. Will incentives be offered to the investigator to conduct the study?	Yes†
43. Will incentives by offered to potential participants as an inducement to participate in the study?	No

4

Work Outside of the United Kingdom

44. Is your research being conducted outside of the United Kingdom?	No
If Yes:	
45. Has a risk assessment been carried out to ensure the safety of the researcher whilst working outside of the United Kingdom?	Choose an item
46. Have you considered the appropriateness of your research in the country you are travelling to?	Choose an item
47. Is there an increased risk to yourself or the participants in your research study?	Choose an item
48. Have you obtained any necessary ethical permission needed in the country you are travelling to?	Choose an item

Information and Declarations

Checklist Application Only:
If you have completed the checklist to the best of your knowledge, and not selected any answers marked with an * or †, your investigation is deemed to conform with the ethical checkpoints. Please sign the declaration and lodge the completed checklist with your Head of Department/School or his/her nominee.

Checklist with Additional Information to the Secretary:
If you have completed the checklist and have only selected answers which require additional information to be submitted with the checklist (indicated by a †), please ensure that all the information is provided in detail below and send this signed checklist to the Secretary of the Sub-Committee.

Checklist with Generic Protocols Included:
If you have completed the checklist and you have selected one or more answers in which you wish to use a Generic Protocol (indicated by #), please include the Generic Protocol reference number in the space below, along with a brief summary of how it will be used. Please ensure you are on the list of approved investigators for the Generic Protocol before including it on the checklist. The completed checklist should be lodged with your Head of Department/School or his/her nominee.

Full Application needed:
If on completion of the checklist you have selected one or more answers which require the submission of a full proposal (indicated by a *), please download the relevant form from the Sub-Committee's web page. **A signed copy of this Checklist should accompany the full submission to the Sub-Committee.**

5

237

Space for Information on Generic Proposals and/or Additional Information as requested:

We offer participants £10 high street voucher for the time they spend on the study.

For completion by Supervisor

Please tick the appropriate boxes. The study should not begin until all boxes are ticked.

☑ The student has read the University's Code of Practice on investigations involving human participants

☑ The topic merits further research

☑ The student has the skills to carry out the research or are being trained in the requires skills by the Supervisor

☑ The participant information sheet or leaflet is appropriate

☑ The procedures for recruitment and obtaining informed consent are appropriate

Comments from supervisor:

Click here to enter text.

Signature of Applicant: Hesam Tavari

Signature of Supervisor (if applicable): Click here to enter text.

Signature of Head of School/Department or his/her nominee: Click here to enter text.

Date: Click here to enter text. 17.11.2014

Ethical Clearance Checklist February 2013

Introduction to the Study

Firstly, many thanks for agreeing to take part in this study.

The study forms an important contribution to my research, which is looking at the growing phenomenon of the "consumer designer" and the ways in which Mass Customization Toolkits (commonly known as MC toolkits) might enable highly customised products. The workshop's specific aim is to gain further understanding of the ways in which these toolkit's elements are managed.

The study's data and/or direct quotes will be anonymised. No participant's name will be mentioned publicly (either in research outputs or elsewhere) without their express, written permission. You may withdraw from the study at any time and will not be required to give reasons for withdrawing. Information regarding data protection is given in an additional document, but if you have any questions please e-mail me at h.yavari@lboro.ac.uk

Approval for this workshop has been granted by Loughborough University's Ethics Committee. If you have questions or complaints about the conduct of this study you should contact me in the first instance at the email address above. If you are unsatisfied with the response you should contact the Director of the School of Design Research, Dr Ian Campbell, at r.i.campbell@lboro.ac.uk; alternatively you may contact Jacqueline Green, the Secretary for the University's Ethics Approvals (Human Participants) Sub-Committee, at:

Research Office, Rutland Building, Loughborough University, Epinal Way, Loughborough, LE11 3TU. Tel: 01509 222423

J.A.Green@lboro.ac.uk

Hesam Yavari, July 2015.

h.yavari@lboro.ac.uk

Appendix 5 Pilot Study Results for Study 1

Pilot study result: Test 1

Participant ranking	Participant 1	Participant 2
1(Highest)	Offline access	Starting point
2	Guidance	Guidance
3	Starting point	Need-based or parameter-based
4	Libraries of modules and producible	Virtual use of product
5	Price update	Technical information
6	Need-based or parameter-based	Degree of freedom
7	Technical information	Click and show option
8	Validation with feedback	Visual feedback
9	Physics providence	Material selection
10	Reference object	Validation with feedback
11	Virtual use of product	Libraries of modules and producible
12	Visual feedback	Physics providence
13	User's design access	Reference object
14	Click and show option	Selecting manufacturing and assembly method
15	Material selection	User's design access
16	Degree of freedom	Offline access
17(lowest)	Selecting manufacturing and assembly method	Price update

Test 2

Input Method

Participant ranking	Participant 1	Participant 2
1(Highest)	Mouse	Mouse
2	Touch screen	Haptic
3	Voice	Touch screen
4	Gesture	Gesture
5	Haptic	Voice

Input type

Participant ranking	Participant 1	Participant 2
1(Highest)	Selection	Selection
2	Drop-down menu	Drop-down Menu
3	Sliders	Sliders
4	Drawing	Drawing
5	3D scan	3D scan

Mechanism

Participant ranking	Participant 1	Participant 2
1(Highest)	Generative	Modularity
2	Modularity	Veneer
3	Parametric	Generative
4	Veneer	Parametric

Survey result: Test 1

MC Toolkit Criteria

1. How do you importance rate this criterion for mass customization toolkit application?

	Definitely not needed				Absolutely essentia
Visual feedback (3D representation)	○	○	○	●	○
Price Update	○	○	○	○	●
Click and show option (interaction method)	○	○	○	●	○
Virtual use of product	○	○	●	○	○
Guidance (help in using the system)	○	○	○	○	●
Technical information	○	○	○	○	●
Validation with feedback (provide information about compatibility check	○	○	○	○	●
Physics providence	○	○	○	○	●
Material selection	○	○	○	●	○
Selecting manufacturing and assembly method (Production method)	○	●	○	○	○
Libraries of modules and producible (from manufacturers)	○	○	○	●	○
Users' designs access (access to other users' design)	○	○	●	○	○
Offline-access	○	○	○	●	○
Reference object	○	○	○	●	○

MC Toolkit Criteria

1. How do you importance rate this criterion for mass customization toolkit application?

Most needs

least needs

Definitely not needed — Absolutely essentia

Criterion	1	2	3	4	5
Visual feedback (3D representation)	○	○	○	○	●
Price Update	○	○	○	○	●
Click and show option (interaction method)	○	○	○	○	●
Virtual use of product	○	○	○	●	○
Guidance (help in using the system)	○	○	○	○	●
Technical information	○	○	○	○	●
Validation with feedback (provide information about compatibility check	○	○	○	○	●
Physics providence	○	○	○	●	○
Material selection	○	○	○	●	○
Selecting manufacturing and assembly method (Production method)	○	○	○	●	○
Libraries of modules and producible (from manufacturers)	○	○	○	●	○
Users' designs access (access to other users' design)	○	○	○	●	○
Offline-access	○	○	○	●	○
Reference object	○	○	○	○	●

1   2   3   4   5

243

Test 2

2. Which one do you prefer for mass customization toolkit?

○ Need-based

✓ Parameter-based

3. Which one do you prefer for mass customization toolkit?

○ Store-based

✓ Web-based

4. Which one do you prefer for mass customization toolkit?

✓ Template

○ Blank canvas

5. About how many degree of freedom do you prefer that a mass customization toolkit has?

○ Less than 5

○ 5

✓ 10

○ 15

○ 20

○ 25

○ More than 25

2. Which one do you prefer for mass customization toolkit?

◉ Need-based

○ Parameter-based

3. Which one do you prefer for mass customization toolkit?

○ Store-based

◉ Web-based

4. Which one do you prefer for mass customization toolkit?

◉ Template

○ Blank canvas

5. About how many degree of freedom do you prefer that a mass customization toolkit has?

○ Less than 5

○ 5

◉ 10

○ 15

○ 20

○ 25

○ More than 25

Appendix 6 Presentation Slides for the Workshop

246

Virtual use of product

Guidance
(help in using the toolkit)

Technical information

Validation with feedback (provide information about compatibility check or/and any physical/technical faults)

249

Technical information

Validation with feedback (provide information about compatibility check or/and any physical/technical faults)

Physics providence

Provide information based on physics principles to help user create a physically proper result

un-balanced

balanced

Material and colour selection

Selecting manufacturing and assembly method
(Production method)

Side-by-Side Comparison

	iPhone 5s	iPhone 6	iPhone 6 Plus
Audio	40	50	80
Video	10	11	14
Wi-Fi	10	11	12
3G	10	14	24
Standby (days)	10	10	16

Libraries of modules and producible
(from manufacturers)

Users' designs access
(access to other users' design)

Offline access

Reference Object

Undo

Camera reset

252

Overview of all MC toolkit features

3D Visualization Feedback	Virtual use of object
Physics providence	Reference object
Libraries of other users' design	Guidance (help in using the system)
Technical information	Direct manipulation
Validation with Feedback	Price Update
Offline access	Libraries of modules and producible
Material selection	Flexible navigation
Side by side comparison	Touch Input
Multiple mechanism	Undo
Having need-based platform	Camera reset
Selecting manufacturing method	

Loughborough University

Tasks

Workshop { Kano analysis
Card Sorting
Wireframing

MC Toolkit

Feedback   Navigation   Guidance

Loughborough University
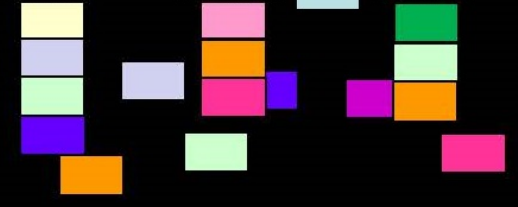
Tasks

Kano analysis diagram

Extreme Delight

Excitement Generators

Performance Payoff

Basic Expectations

Extreme Frustration
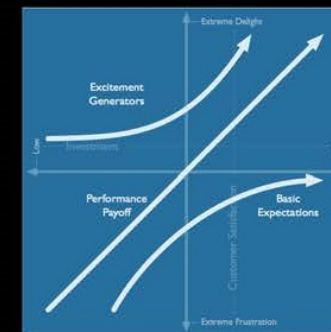
Contact list

Free handsfree

Camera

Loughborough University

Appendix 7 Ethics Clearance Checklist Form for the Workshop

Ethics Approvals (Human Participants) Sub-Committee

Loughborough University

Ethical Clearance Checklist

Has the Investigator read the 'Guidance for completion of Ethical Clearance Checklist' before starting this form?	Yes

Project Details

1. Project Title: Mass Customization Toolkit Workshop

Applicant(s) Details

2. Name of Applicant 1: Hesam Yavari	10. Name of Applicant 2: Ian Campbell
3. Status: PGR student	11. Status: Staff
4. School/Department: Design School	12. School/Department: Design School
5. Programme (if applicable): Click here to enter text.	13. Programme (if applicable): Click here to enter text.
6. Email address: h.yavari@lboro.ac.uk	14. Email address: R.I.Campbell@lboro.ac.uk
7a. Contact address: flat 2, 12 sparrow hill, loughborough	15a. Contact address: Design school, loughborough university
7b. Telephone number: 07408848755	15b. Telephone number: +441509228312
8. Supervisor: No	16. Supervisor: Yes
9. Responsible Investigator: No	17. Responsible Investigator: Yes

Participants

Positions of Authority

18. Are researchers in a position of direct authority with regard to participants (e.g. academic staff using student participants, sports coaches using his/her athletes in training)?	No

1

Ethical Clearance Checklist February 2013

254

Vulnerable groups

19. Will participants be knowingly recruited from one or more of the following vulnerable groups?	
Children under 18 years of age	No
Persons incapable of making an informed decision for themselves	No
Pregnant women	No
Prisoners/Detained persons	No
Other vulnerable group Please specify: Click here to enter text	No
If you have selected No to all of Question 19, please go to Question 23.	
20. Will participants be chaperoned by more than one investigator at all times?	Choose an item
21. Will at least one investigator of the same sex as the participant(s) be present throughout the investigation?	Choose an item
22. Will participants be visited at home?	Choose an item

Researcher Safety

23. Will the researcher be alone with participants at any time?	Yes
If Yes, please answer the following questions:	
23a. Will the researcher inform anyone else of when they will be alone with participants?	Yes
23b. Has the researcher read the 'guidelines for lone working' and will abide by the recommendations within?	Yes

Methodology and Procedures

24. Please indicate whether the proposed study:

Involves taking bodily samples (please refer to published guidelines)	No
Involves using samples previously collected with consent for further research	No
Involves procedures which are likely to cause physical, psychological, social or emotional distress to participants	No
Is designed to be challenging physically or psychologically in any way (includes any study involving physical exercise)	No
Exposes participants to risks or distress greater than those encountered in their normal lifestyle	No
Involves collection of body secretions by invasive methods	No
Prescribes intake of compounds additional to daily diet or other dietary manipulation/supplementation	No

2

255

Involves pharmaceutical drugs	No
Involves use of radiation	No
Involves use of hazardous materials	No
Assists/alters the process of conception in any way	No
Involves methods of contraception	No
Involves genetic engineering	No

Involves testing new equipment	No

Observation/Recording

25a. Does the study involve observation and/or recording of participants?	Yes
If **Yes**:	
25b. Will those being observed and/or recorded be informed that the observation and/or recording will take place?	Yes

Consent and Deception

26. Will participants give informed consent freely?	Yes

Informed consent

27. Will participants be fully informed of the objectives of the study and all details disclosed (preferably at the start of the study but, where this would interfere with the study, at the end)?	Yes
28. Will participants be fully informed of the use of the data collected (including, where applicable, any intellectual property arising from the research)?	Yes

29. For children under the age of 18 or participants who are incapable of making an informed decision for themselves:	
a. Will consent be obtained (either in writing or by some other means)?	N/A
b. Will consent be obtained from parents or other suitable person?	N/A
c. Will they be informed that they have the right to withdraw regardless of parental/guardian consent?	N/A
d. For studies conducted in schools, will approval be gained in advance from the Head-teacher and/or the Director of Education of the appropriate Local Education Authority?	N/A
e. For detained persons, members of the armed forces, employees, students and other persons judged to be under duress, will care be taken over gaining freely informed consent?	N/A

3

Deception

30. Does the study involve deception of participants (i.e. withholding of information or the misleading of participants) which could potentially harm or exploit participants?	No
If **Yes:**	
31. Is deception an unavoidable part of the study?	Choose an item
32. Will participants be de-briefed and the true object of the research revealed at the earliest stage upon completion of the study?	Choose an item
33. Has consideration been given on the way that participants will react to the withholding of information or deliberate deception?	Choose an item

Withdrawal

34. Will participants be informed of their right to withdraw from the investigation at any time and to require their own data to be destroyed?	Yes

Storage of Data and Confidentiality

35. Will all information on participants be treated as confidential and not identifiable unless agreed otherwise in advance, and subject to the requirements of law?	Yes
36. Will storage of data comply with the Data Protection Act 1998?	Yes
37. Will any video/audio recording of participants be kept in a secure place and not released for any use by third parties?	Yes
38. Will video/audio recordings be destroyed within ten years of the completion of the investigation?	Yes
39. Will full details regarding the storage and disposal of any human tissue samples be communicated to the participants?	N/A
40. Will research involve the sharing of data or confidential information beyond the initial consent given?	No
41. Will the research involve administrative or secure data that requires permission from the appropriate authorities before use?	No

Incentives

42. Will incentives be offered to the investigator to conduct the study?	Yes†
43. Will incentives by offered to potential participants as an inducement to participate in the study?	No

4

Work Outside of the United Kingdom

44. Is your research being conducted outside of the United Kingdom?	No
If **Yes**:	
45. Has a risk assessment been carried out to ensure the safety of the researcher whilst working outside of the United Kingdom?	Choose an item
46. Have you considered the appropriateness of your research in the country you are travelling to?	Choose an item
47. Is there an increased risk to yourself or the participants in your research study?	Choose an item
48. Have you obtained any necessary ethical permission needed in the country you are travelling to?	Choose an item

Information and Declarations

Checklist Application Only:
If you have completed the checklist to the best of your knowledge, and not selected any answers marked with an * or †, your investigation is deemed to conform with the ethical checkpoints. Please sign the declaration and lodge the completed checklist with your Head of Department/School or his/her nominee.

Checklist with Additional Information to the Secretary:
If you have completed the checklist and have only selected answers which require additional information to be submitted with the checklist (indicated by a †), please ensure that all the information is provided in detail below and send this signed checklist to the Secretary of the Sub-Committee.

Checklist with Generic Protocols Included:
If you have completed the checklist and you have selected one or more answers in which you wish to use a Generic Protocol (indicated by #), please include the Generic Protocol reference number in the space below, along with a brief summary of how it will be used. Please ensure you are on the list of approved investigators for the Generic Protocol before including it on the checklist. The completed checklist should be lodged with your Head of Department/School or his/her nominee.

Full Application needed:
If on completion of the checklist you have selected one or more answers which require the submission of a full proposal (indicated by a *), please download the relevant form from the Sub-Committee's web page. **A signed copy of this Checklist should accompany the full submission to the Sub-Committee.**

5

Space for Information on Generic Proposals and/or Additional Information as requested:

We offer participants £10 high street voucher for the time they spend on the workshop.

For completion by Supervisor

Please tick the appropriate boxes. The study should not begin until all boxes are ticked.

☑ The student has read the University's Code of Practice on investigations involving human participants

☑ The topic merits further research

☑ The student has the skills to carry out the research or are being trained in the requires skills by the Supervisor

☑ The participant information sheet or leaflet is appropriate

☑ The procedures for recruitment and obtaining informed consent are appropriate

Comments from supervisor: *£10 voucher payment is needed to recruit right number of people.*

Click here to enter text.

Signature of Applicant: *Hessam Tonai*

Signature of Supervisor (if applicable): Click here to enter text.

Signature of Head of School/Department or his/her nominee: Click here to enter text.

Date: Click here to enter text. *15. 05. 2015*

Ethical Clearance Checklist February 2013

Appendix 8 Permission Letter for the Workshop

Data Protection Statement

Data collected in this workshop will be held anonymously and securely. Data collected in this workshop will be held for a period of six years (in compliance with Loughborough University guidelines) after which time it will be permanently deleted.

The recording will be recorded by a phone. Copies of the recording will be supplied to participants in MP3 format, on request. All data and/or direct quotes will be anonymised. No participant's name will be mentioned publicly (either in research outputs or elsewhere) without their express, written permission. At any time after the recording you may request that your responses are excluded from the research and that your personal details are permanently deleted by emailing the workshop holder at the address below.

Analysis of the data collected in this workshop will form part of the author's ongoing research, and it is anticipated that findings will be used in submissions to academic journals or conferences. Analysis of the data will not be used for commercial purposes.

Hesam Yavari, June 2015.

h.yavari@lboro.ac.uk

Appendix 9 Participants Information Sheet for the Workshop

What is the purpose of the study?

The purpose of this study is to find out about the information architecture and layout of these toolkits (websites) from customer point of view. Each website has a specific layout, and these toolkits need a user-friendly structure, and its features are needed to be organized and selected appropriately. This will ensure that the customers have a pleasant experience while customizing their product on these toolkits.

Who is doing this research?

This study is part of a Student PhD research project supported by Loughborough University.

Exclusion criteria

You must be over the age of 18 to take part in this study, and a computer literacy (e.g. having done an online shopping before).

What will I be asked to do and how long will it take?

For around 20 minutes, the content will be presented to you, and for an hour or so you will be asked to sort number of features (website's elements) in two stage, and then put them on a big sheet of paper (representing the website) to make the website in your own. Please note the place of the session is in Design School.

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 workshop 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.

However, once the results of the study have been submitted (expected to be by **30/06/15**), it will not be possible to withdraw your individual data from the research.

Are there any risks in participating?

Overall, potential risks associated with participation in the study are unlikely and of no risk.

Will my taking part in this study be kept confidential?

Yes. Once the images have been sent to the researcher they will be sorted and saved electronically on a computer only accessible to the researcher in a card key locked office in the Design School at Loughborough University. This office is only open to authorised university staff and other research students. All previous copies will be erased.

The data will be retained until the publication of the final PhD - expected to be before September 2018.

I have some more questions; who should I contact?

You may contact Hesam Yavari using the contact details above.

What will happen to the results of the study?

The results of this study will be used to understand what the ideal website for delivering mass customization is in terms of structure and feature selection.

Data gather from this study (i.e. photos collected) may be used to demonstrate and/or comment on the research at future conferences or in publications. Your contribution will always be kept anonymous but if you do not wish to be included you must notify the researcher **before 30/6/15**.

What if I am not happy with how the research was conducted?

If you are not happy with how the research was conducted, please contact Ms Jackie Green, the Secretary for the University's Ethics Approvals (Human Participants) Sub-Committee:

Ms J Green, Research Office, Hazlerigg Building, Loughborough University, Epinal Way, Loughborough, LE11 3TU. Tel: 01509 222423. Email: J.A.Green@lboro.ac.uk

The University also has a policy relating to Research Misconduct and Whistle Blowing which is available online at http://www.lboro.ac.uk/admin/committees/ethical/Whistleblowing(2).htm.

Is there anything I need to bring with me?

You do not need to bring anything with you. You are however welcome and encouraged to bring anything with you that you want to show or discuss in relation to the study.

What do I get for participating?

You will be making a valuable contribution towards the study through this workshop and reflection you may become more aware of the mass customization experience you may have in the future. The participants are also given £10 high street voucher for their time.

Appendix 10 Ethics Clearance Checklist Form for Study 2

Ethics Approvals (Human Participants) Sub-Committee

Loughborough University

Ethical Clearance Checklist

Has the Investigator read the 'Guidance for completion of Ethical Clearance Checklist' before starting this form?	Yes

Project Details

1. Project Title: Mass Customization Toolkit Workshop

Applicant(s) Details

2. Name of Applicant 1: Hesam Yavari	10. Name of Applicant 2: Ian Campbell
3. Status: PGR student	11. Status: Staff
4. School/Department: Design School	12. School/Department: Design School
5. Programme (if applicable): Click here to enter text.	13. Programme (if applicable): Click here to enter text.
6. Email address: h.yavari@lboro.ac.uk	14. Email address: R.I.Campbell@lboro.ac.uk
7a. Contact address: flat 2, 12 sparrow hill, loughborough	15a. Contact address: Design school, loughborough university
7b. Telephone number: 07408848755	15b. Telephone number: +441509228312
8. Supervisor: No	16. Supervisor: Yes
9. Responsible Investigator: No	17. Responsible Investigator: Yes

Participants

Positions of Authority

18. Are researchers in a position of direct authority with regard to participants (e.g. academic staff using student participants, sports coaches using his/her athletes in training)?	No

Vulnerable groups

19. Will participants be knowingly recruited from one or more of the following vulnerable groups?	
Children under 18 years of age	No
Persons incapable of making an informed decision for themselves	No
Pregnant women	No
Prisoners/Detained persons	No
Other vulnerable group Please specify: Click here to enter text	No
If you have selected No to all of Question 19, please go to Question 23.	
20. Will participants be chaperoned by more than one investigator at all times?	Choose an item
21. Will at least one investigator of the same sex as the participant(s) be present throughout the investigation?	Choose an item
22. Will participants be visited at home?	Choose an item

Researcher Safety

23. Will the researcher be alone with participants at any time?	Yes
If Yes, please answer the following questions:	
23a. Will the researcher inform anyone else of when they will be alone with participants?	Yes
23b. Has the researcher read the 'guidelines for lone working' and will abide by the recommendations within?	Yes

Methodology and Procedures

24. Please indicate whether the proposed study:

Involves taking bodily samples (please refer to published guidelines)	No
Involves using samples previously collected with consent for further research	No
Involves procedures which are likely to cause physical, psychological, social or emotional distress to participants	No
Is designed to be challenging physically or psychologically in any way (includes any study involving physical exercise)	No
Exposes participants to risks or distress greater than those encountered in their normal lifestyle	No
Involves collection of body secretions by invasive methods	No
Prescribes intake of compounds additional to daily diet or other dietary manipulation/supplementation	No

2

Involves pharmaceutical drugs	No
Involves use of radiation	No
Involves use of hazardous materials	No
Assists/alters the process of conception in any way	No
Involves methods of contraception	No
Involves genetic engineering	No

Involves testing new equipment	No

Observation/Recording

25a. Does the study involve observation and/or recording of participants?	Yes
If **Yes:**	
25b. Will those being observed and/or recorded be informed that the observation and/or recording will take place?	Yes

Consent and Deception

26. Will participants give informed consent freely?	Yes

Informed consent

27. Will participants be fully informed of the objectives of the study and all details disclosed (preferably at the start of the study but, where this would interfere with the study, at the end)?	Yes
28. Will participants be fully informed of the use of the data collected (including, where applicable, any intellectual property arising from the research)?	Yes

29. For children under the age of 18 or participants who are incapable of making an informed decision for themselves:	
a. Will consent be obtained (either in writing or by some other means)?	N/A
b. Will consent be obtained from parents or other suitable person?	N/A
c. Will they be informed that they have the right to withdraw regardless of parental/guardian consent?	N/A
d. For studies conducted in schools, will approval be gained in advance from the Head-teacher and/or the Director of Education of the appropriate Local Education Authority?	N/A
e. For detained persons, members of the armed forces, employees, students and other persons judged to be under duress, will care be taken over gaining freely informed consent?	N/A

3

Deception

30. Does the study involve deception of participants (i.e. withholding of information or the misleading of participants) which could potentially harm or exploit participants?	No
If Yes:	
31. Is deception an unavoidable part of the study?	Choose an item
32. Will participants be de-briefed and the true object of the research revealed at the earliest stage upon completion of the study?	Choose an item
33. Has consideration been given on the way that participants will react to the withholding of information or deliberate deception?	Choose an item

Withdrawal

34. Will participants be informed of their right to withdraw from the investigation at any time and to require their own data to be destroyed?	Yes

Storage of Data and Confidentiality

35. Will all information on participants be treated as confidential and not identifiable unless agreed otherwise in advance, and subject to the requirements of law?	Yes
36. Will storage of data comply with the Data Protection Act 1998?	Yes
37. Will any video/audio recording of participants be kept in a secure place and not released for any use by third parties?	Yes
38. Will video/audio recordings be destroyed within ten years of the completion of the investigation?	Yes
39. Will full details regarding the storage and disposal of any human tissue samples be communicated to the participants?	N/A
40. Will research involve the sharing of data or confidential information beyond the initial consent given?	No
41. Will the research involve administrative or secure data that requires permission from the appropriate authorities before use?	No

Incentives

42. Will incentives be offered to the investigator to conduct the study?	Yes†
43. Will incentives by offered to potential participants as an inducement to participate in the study?	No

4

Work Outside of the United Kingdom

44. Is your research being conducted outside of the United Kingdom?	No
If **Yes**:	
45. Has a risk assessment been carried out to ensure the safety of the researcher whilst working outside of the United Kingdom?	Choose an item
46. Have you considered the appropriateness of your research in the country you are travelling to?	Choose an item
47. Is there an increased risk to yourself or the participants in your research study?	Choose an item
48. Have you obtained any necessary ethical permission needed in the country you are travelling to?	Choose an item

Information and Declarations

Checklist Application Only:
If you have completed the checklist to the best of your knowledge, and not selected any answers marked with an * or †, your investigation is deemed to conform with the ethical checkpoints. Please sign the declaration and lodge the completed checklist with your Head of Department/School or his/her nominee.

Checklist with Additional Information to the Secretary:
If you have completed the checklist and have only selected answers which require additional information to be submitted with the checklist (indicated by a †), please ensure that all the information is provided in detail below and send this signed checklist to the Secretary of the Sub-Committee.

Checklist with Generic Protocols Included:
If you have completed the checklist and you have selected one or more answers in which you wish to use a Generic Protocol (indicated by #), please include the Generic Protocol reference number in the space below, along with a brief summary of how it will be used. Please ensure you are on the list of approved investigators for the Generic Protocol before including it on the checklist. The completed checklist should be lodged with your Head of Department/School or his/her nominee.

Full Application needed:
If on completion of the checklist you have selected one or more answers which require the submission of a full proposal (indicated by a *), please download the relevant form from the Sub-Committee's web page. **A signed copy of this Checklist should accompany the full submission to the Sub-Committee.**

5

Space for Information on Generic Proposals and/or Additional Information as requested:

We offer participants £10 high street voucher for the time they spend on the workshop.

For completion by Supervisor

Please tick the appropriate boxes. The study should not begin until all boxes are ticked.

☑ The student has read the University's Code of Practice on investigations involving human participants

☑ The topic merits further research

☑ The student has the skills to carry out the research or are being trained in the requires skills by the Supervisor

☑ The participant information sheet or leaflet is appropriate

☑ The procedures for recruitment and obtaining informed consent are appropriate

Comments from supervisor: *£10 voucher payment is needed to recruit right number of people.*
Click here to enter text.

Signature of Applicant: *Hessam Yonai*

Signature of Supervisor (if applicable): Click here to enter text.

Signature of Head of School/Department or his/her nominee: Click here to enter text.

Date: Click here to enter text. *15. 05. 2015*

Ethical Clearance Checklist February 2013

Introduction to the study

Firstly, many thanks for agreeing to take part in this study. Along with previous research, we are going to evaluate the usability of a particular computer system called Lampshade MC Toolkit.

Lampshade MC Toolkit is used to generate customisable lampshade by customers. It is planned to be used like other available MC Toolkits such as Nike iD or mi Adidas, meaning that it accessible online, and can be used to purchase customisable lampshade.

The aim of the study is to find out how easy Lampshade MC Toolkit is to use by people like you. We want you to use it to create your preferred lampshade design. We will give you some standard tasks to do using this system. The aim of this is to allow us to get some information about how Lampshade MC Toolkit supports these activities. We're particularly interested in situations in which MC Toolkit needs extra commands or elements, such as: guidance, navigation or feedback to make the system easier to be used. We are also interested in information about the layout or structure of the system.

To get this information we shall use a question-and-answer technique. This involves three things:

1. We want you to think-out-loud as you do each task telling us how you are trying to solve each task, which commands you think might be appropriate, and why, and what you think the machine has done in response to your commands and why. Think of this as you giving us a running commentary on what you are doing and thinking.

2. Whenever you find yourself in a situation where you are unsure about what to do or what effects commands might have, ask us for advice. If you ask us what you need to know we will suggest things for you to try but if you get really stuck we'll explain exactly what to do.

3. In addition we will ask you questions about what you are trying to do and what effects you expect the commands you do will have. This is simply to find out what problems where are with the system. During out conversations, we want you to voice any thoughts you have about parts of the system which you feel are difficult to use or poorly designed.

While you're doing this we'll be noting down the problems you mention but in case we miss any we are going to voice record our conversation. This recording will be

anonymous and treated in confidence. No participant's name will be mentioned publicly (either in research outputs or elsewhere) without their express, written permission. You may withdraw from the study at any time and will not be required to give reasons for withdrawing. If you have any questions or concerns please e-mail me at h.yavari@lboro.ac.uk

Remember it is not you we're testing, it lampshade MC Toolkit. We are interested in what you think so don't treat this as an examination. Treat it as structured discussion about lampshade MC Toolkit. Please feel free to say whatever you think about the system, and tasks you are given.

Approval for this study has been granted by Loughborough University's Ethics Committee. If you have questions or complaints about the conduct of this study you should contact me in the first instance at the email address above. If you are unsatisfied with the response you should contact the Director of the School of Design Research, Dr Ian Campbell, at r.i.campbell@lboro.ac.uk; alternatively you may contact Jacqueline Green, the Secretary for the University's Ethics Approvals (Human Participants) Sub-Committee, at:

Research Office, Rutland Building, Loughborough University, Epinal Way, Loughborough,

LE11 3TU. Tel: 01509 222423

J.A.Green@lboro.ac.uk

Hesam Yavari, August 2015.

h.yavari@lboro.ac.uk

Signature:

Appendix 12 Participant's Information Sheet for Study 2

What is the purpose of the study?

The purpose of this study is to find out about the information architecture, layout and elements of these MC toolkits (websites) from customer point of view. This will ensure that the customers have a pleasant experience while customizing their product on these toolkits.

Who is doing this research?

This study is part of a student PhD research project supported by Loughborough University.

Exclusion criteria

You must be over the age of 18 to take part in this study, and have a computer literacy (e.g. having done an online shopping before).

What will I be asked to do and how long will it take?

At the beginning you will be asked to choose a preferred interface out of three choices, then to create your customised product which is taking around 10 minutes. During these tasks, you will be requested to think loud. Please note the place of the session is in Design School, Loughborough university.

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 workshop please just contact me on h.yavari@lboro.ac.uk. You can withdraw at any time, for any reason and you will not be asked to explain your reasons for withdrawing.

However, once the results of the study have been submitted (expected to be by **30/09/15**), it will not be possible to withdraw your individual data from the research.

Are there any risks in participating?

Overall, potential risks associated with participation in the study are unlikely and of no risk.

Will my taking part in this study be kept confidential?

Yes. Once the images have been sent to the researcher they will be sorted and saved electronically on a computer only accessible to the researcher in a card key locked office in the Design School at Loughborough University. This office is only open to authorised university staff and other research students. All previous copies will be erased.

The data will be retained until the publication of the final PhD - expected to be before September 2016.

I have some more questions; who should I contact?

You may contact Hesam Yavari using the contact details above.

What will happen to the results of the study?

The results of this study will be used to understand what the ideal website for delivering mass customization is in terms of structure and feature selection.

Data gather from this study (i.e. photos collected) may be used to demonstrate and/or comment on the research at future conferences or in publications. Your contribution will always be kept anonymous but if you do not wish to be included you must notify the researcher **before 30/9/15**.

What if I am not happy with how the research was conducted?

If you are not happy with how the research was conducted, please contact Ms Jackie Green, the Secretary for the University's Ethics Approvals (Human Participants) Sub-Committee:

Ms J Green, Research Office, Hazlerigg Building, Loughborough University, Epinal Way, Loughborough, LE11 3TU. Tel: 01509 222423. Email: J.A.Green@lboro.ac.uk

The University also has a policy relating to Research Misconduct and Whistle Blowing which is available online at http://www.lboro.ac.uk/admin/committees/ethical/Whistleblowing(2).htm.

Is there anything I need to bring with me?

You do not need to bring anything with you. You are however welcome and encouraged to bring anything with you that you want to show or discuss in relation to the study.

What do I get for participating?

You will be making a valuable contribution towards the study through this workshop and reflection you may become more aware of the mass customization experience you may have in the future. There is a poll drawn among participants, and the winner will be given his/her customised lampshade.

Appendix 13 The Evaluation Form for Study 2

User's name:		Session start time: Session end time:	Session date:	
Tasks	User's remarks	Observer's comments	No. of errors	Elapsed time
Task 1				
Task 2				

Appendix 14 Ethics Clearance Checklist form for Study 3

Not going to Committee

Ethics Approvals (Human Participants) Sub-Committee

Loughborough University

Ethical Clearance Checklist

Has the Investigator read the 'Guidance for completion of Ethical Clearance Checklist' before starting this form?	Yes

Project Details

1. Project Title: Framework Validation Study

Applicant(s) Details

2. Name of Applicant 1: Hesam Yavari	10. Name of Applicant 2: Ian Campbell
3. Status: PGR student	11. Status: Staff
4. School/Department: Design School	12. School/Department: Design School
5. Programme (if applicable): Click here to enter text.	13. Programme (if applicable): Click here to enter text.
6. Email address: h.yavari@lboro.ac.uk	14. Email address: R.I.Campbell@lboro.ac.uk
7a. Contact address: flat 2, 12 sparrow hill, loughborough	15a. Contact address: Design school, loughborough university
7b. Telephone number: +447408848755	15b. Telephone number: +441509228312
8. Supervisor: No	16. Supervisor: Yes
9. Responsible Investigator: No	17. Responsible Investigator: Yes

Participants

Positions of Authority

18. Are researchers in a position of direct authority with regard to participants (e.g. academic staff using student participants, sports coaches using his/her athletes in training)?	No

1

Ethical Clearance Checklist February 2013

274

Vulnerable groups

19. Will participants be knowingly recruited from one or more of the following vulnerable groups?	
Children under 18 years of age	No
Persons incapable of making an informed decision for themselves	No
Pregnant women	No
Prisoners/Detained persons	No
Other vulnerable group Please specify: Click here to enter text	No
If you have selected No to all of Question 19, please go to Question 23.	
20. Will participants be chaperoned by more than one investigator at all times?	Choose an item
21. Will at least one investigator of the same sex as the participant(s) be present throughout the investigation?	Choose an item
22. Will participants be visited at home?	Choose an item

Researcher Safety

23. Will the researcher be alone with participants at any time?	Yes
If Yes, please answer the following questions:	
23a. Will the researcher inform anyone else of when they will be alone with participants?	Yes
23b. Has the researcher read the 'guidelines for lone working' and will abide by the recommendations within?	Yes

Methodology and Procedures

24. Please indicate whether the proposed study:

Involves taking bodily samples (please refer to published guidelines)	No
Involves using samples previously collected with consent for further research	No
Involves procedures which are likely to cause physical, psychological, social or emotional distress to participants	No
Is designed to be challenging physically or psychologically in any way (includes any study involving physical exercise)	No
Exposes participants to risks or distress greater than those encountered in their normal lifestyle	No
Involves collection of body secretions by invasive methods	No
Prescribes intake of compounds additional to daily diet or other dietary manipulation/supplementation	No

2

275

Involves pharmaceutical drugs	No
Involves use of radiation	No
Involves use of hazardous materials	No
Assists/alters the process of conception in any way	No
Involves methods of contraception	No
Involves genetic engineering	No

Involves testing new equipment	No

Observation/Recording

25a. Does the study involve observation and/or recording of participants?	Yes
If **Yes**:	
25b. Will those being observed and/or recorded be informed that the observation and/or recording will take place?	Yes

Consent and Deception

26. Will participants give informed consent freely?	Yes

Informed consent

27. Will participants be fully informed of the objectives of the study and all details disclosed (preferably at the start of the study but, where this would interfere with the study, at the end)?	Yes
28. Will participants be fully informed of the use of the data collected (including, where applicable, any intellectual property arising from the research)?	Yes

29. For children under the age of 18 or participants who are incapable of making an informed decision for themselves:	
a. Will consent be obtained (either in writing or by some other means)?	N/A
b. Will consent be obtained from parents or other suitable person?	N/A
c. Will they be informed that they have the right to withdraw regardless of parental/guardian consent?	N/A
d. For studies conducted in schools, will approval be gained in advance from the Head-teacher and/or the Director of Education of the appropriate Local Education Authority?	N/A
e. For detained persons, members of the armed forces, employees, students and other persons judged to be under duress, will care be taken over gaining freely informed consent?	N/A

3

Deception

30. Does the study involve deception of participants (i.e. withholding of information or the misleading of participants) which could potentially harm or exploit participants?	No
If **Yes:**	
31. Is deception an unavoidable part of the study?	Choose an item
32. Will participants be de-briefed and the true object of the research revealed at the earliest stage upon completion of the study?	Choose an item
33. Has consideration been given on the way that participants will react to the withholding of information or deliberate deception?	Choose an item

Withdrawal

34. Will participants be informed of their right to withdraw from the investigation at any time and to require their own data to be destroyed?	Yes

Storage of Data and Confidentiality

35. Will all information on participants be treated as confidential and not identifiable unless agreed otherwise in advance, and subject to the requirements of law?	Yes
36. Will storage of data comply with the Data Protection Act 1998?	Yes
37. Will any video/audio recording of participants be kept in a secure place and not released for any use by third parties?	Yes
38. Will video/audio recordings be destroyed within ten years of the completion of the investigation?	Yes
39. Will full details regarding the storage and disposal of any human tissue samples be communicated to the participants?	N/A
40. Will research involve the sharing of data or confidential information beyond the initial consent given?	No
41. Will the research involve administrative or secure data that requires permission from the appropriate authorities before use?	No

Incentives

42. Will incentives be offered to the investigator to conduct the study?	No
43. Will incentives by offered to potential participants as an inducement to participate in the study?	No

4

277

Work Outside of the United Kingdom

44. Is your research being conducted outside of the United Kingdom?	No
If **Yes**:	
45. Has a risk assessment been carried out to ensure the safety of the researcher whilst working outside of the United Kingdom?	Choose an item
46. Have you considered the appropriateness of your research in the country you are travelling to?	Choose an item
47. Is there an increased risk to yourself or the participants in your research study?	Choose an item
48. Have you obtained any necessary ethical permission needed in the country you are travelling to?	Choose an item

Information and Declarations

Checklist Application Only:
If you have completed the checklist to the best of your knowledge, and not selected any answers marked with an * or †, your investigation is deemed to conform with the ethical checkpoints. Please sign the declaration and lodge the completed checklist with your Head of Department/School or his/her nominee.

Checklist with Additional Information to the Secretary:
If you have completed the checklist and have only selected answers which require additional information to be submitted with the checklist (indicated by a †), please ensure that all the information is provided in detail below and send this signed checklist to the Secretary of the Sub-Committee.

Checklist with Generic Protocols Included:
If you have completed the checklist and you have selected one or more answers in which you wish to use a Generic Protocol (indicated by #), please include the Generic Protocol reference number in the space below, along with a brief summary of how it will be used. Please ensure you are on the list of approved investigators for the Generic Protocol before including it on the checklist. The completed checklist should be lodged with your Head of Department/School or his/her nominee.

Full Application needed:
If on completion of the checklist you have selected one or more answers which require the submission of a full proposal (indicated by a *), please download the relevant form from the Sub-Committee's web page. **A signed copy of this Checklist should accompany the full submission to the Sub-Committee.**

Ethical Clearance Checklist February 2013

Space for Information on Generic Proposals and/or Additional Information as requested:

For completion by Supervisor

Please tick the appropriate boxes. The study should not begin until all boxes are ticked.

☑ The student has read the University's Code of Practice on investigations involving human participants

☑ The topic merits further research

☑ The student has the skills to carry out the research or are being trained in the requires skills by the Supervisor

☑ The participant information sheet or leaflet is appropriate

☑ The procedures for recruitment and obtaining informed consent are appropriate

Comments from supervisor: *Standard "Expert Evaluation".*

Click here to enter text.

Signature of Applicant: *Hesam Yonaci*

Signature of Supervisor (if applicable): Click here to enter text.

Signature of Head of School/Department or his/her nominee: Click here to enter text.

Date: Click here to enter text.

Ethical Clearance Checklist February 2013

Appendix 15 Permission Letter for Study 3

Introduction to the study

Firstly, many thanks for agreeing to take part in this study. Along with previous research, we are going to use your input to improve the interfaces for mass customised and personalised products called MC Toolkits (this is a toolkit for consumers).

Our AM-enabled (Additive Manufacturing) web-based MC (Mass Customisation) Toolkit can be used to generate customisable products by customers online and the product can then be manufactured with Additive Manufacturing. It is planned to be used like other available MC Toolkits such as Nike iD or mi Adidas, meaning that it is accessible online, and can be used to purchase customisable products.

After a series of studies on these toolkits, a framework for designers and software developers has been generated for those who would like to create one of these toolkits (this is a framework for designers and software developers). However, this framework has not been validated or assessed by experienced designers in this area or other designers who can benefit from it.

The aim of the study is to find out more about the proposed framework and understand how to improve this framework. Furthermore, the format of the framework needs feedback or comments to be improved as much as possible. Specifications such as practicality, technicality, or usability will be evaluated. We want you to imagine using the framework for your future toolkit design. We will then ask you some prepared questions during the session. The aim of this is to allow us to get the information we need to achieve our goals. We are particularly interested in situations in which the framework needs extra commands or elements, to make the system easier to be used. We are also interested in information about the format, or layout of the system.

While you are doing this we will be noting down the problems you mention but in case we miss any we are going to voice record our conversation. This recording will be anonymous and treated confidential. No participant's name will be mentioned publicly (either in research outputs or elsewhere) without their express, written permission. You may withdraw from the study at any time and will not be required to give reasons for withdrawal. If you have any questions or concerns please e-mail me at h.yavari@lboro.ac.uk

Remember it is not you we are testing, it is the framework. We are very interested in what you think so please do not treat this as an examination. Treat it as a structured conversation about the framework. Please feel free to say whatever you think about the system, and questions you are asked.

Approval for this study has been granted by Loughborough University's Ethics Committee. If you have questions or complaints about the conduct of this study you should contact me in the first instance at the email address above. If you are unsatisfied with my response you should contact my supervisor, Dr Ian Campbell, at r.i.campbell@lboro.ac.uk; alternatively you may contact Jacqueline Green, the Secretary for the University's Ethics Approvals (Human Participants) Sub-Committee, at:

Research Office, Rutland Building, Loughborough University, Epinal Way, Loughborough, LE11 3TU. Tel: 01509 222423

J.A.Green@lboro.ac.uk

Hesam Yavari, Feb 2016.

h.yavari@lboro.ac.uk

Signature:

Appendix 16 Participant's Information Sheet for Study 3

What is the purpose of the study?

The purpose of this study is to find out about the information architecture, layout and elements of the proposed framework for MC toolkits. This will ensure that the customers have a pleasant experience while customizing their product on these toolkits.

Who is doing this research?

This study is part of a student PhD research project supported by Loughborough University.

Exclusion criteria

You must be over the age of 18 to take part in this study, be a designer or a software developer for online sales websites.

What will I be asked to do and how long will it take?

At the beginning you will be asked two sets of questions, then to use the proposed framework, and finally the last set of questions will be asked. Please note the place of the session is in Design School, Loughborough University, or any place at your convenient. The whole sessions should not take more than an hour.

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 workshop please just contact me on h.yavari@lboro.ac.uk. You can withdraw at any time, for any reason and you will not be asked to explain your reasons for withdrawing.

However, once the results of the study have been submitted (expected to be by **30/03/16**), it will not be possible to withdraw your individual data from the research.

Are there any risks in participating?

Overall, potential risks associated with participation in the study are unlikely and of no risk.

Will my taking part in this study be kept confidential?

Yes. Once the images have been sent to the researcher they will be sorted and saved electronically on a computer only accessible to the researcher in a card key locked office in the Design School at Loughborough University. This office is only open to authorised university staff and other research students. All previous copies will be erased.

The data will be retained until the publication of the final PhD - expected to be before September 2016.

I have some more questions; who should I contact?

You may contact Hesam Yavari using the contact details above.

What will happen to the results of the study?

The results of this study will be used to understand what the ideal framework is in terms of layout and content for delivering mass customization toolkit.

Data gather from this study (i.e. photos collected) may be used to demonstrate and/or comment on the research at future conferences or in publications. Your contribution will always be kept anonymous but if you do not wish to be included you must notify the researcher **before 30/3/16**.

What if I am not happy with how the research was conducted?

If you are not happy with how the research was conducted, please contact Ms Jackie Green, the Secretary for the University's Ethics Approvals (Human Participants) Sub-Committee:

Ms J Green, Research Office, Hazlerigg Building, Loughborough University, Epinal Way, Loughborough, LE11 3TU. Tel: 01509 222423. Email: J.A.Green@lboro.ac.uk

The University also has a policy relating to Research Misconduct and Whistle Blowing which is available online at http://www.lboro.ac.uk/admin/committees/ethical/Whistleblowing(2).htm.

Is there anything I need to bring with me?

You do not need to bring anything with you. You are however welcome and encouraged to bring anything with you that you want to show or discuss in relation to the study.

What do I get for participating?

You will be making a valuable contribution towards the study through this workshop and reflection you may become more aware of the mass customization experience you may have in the future.

Appendix 17 Courses Taken during First Year and Second Year

First year:

- Postgraduate Induction Day
- LinkedIn – Can it help?
- Finding Resources for your Literature Review and Beyond – Theory
- Finding Resources for your Literature Review and Beyond - Practice
- Questionnaire Design
- Procrastination: Improving Personal Effectiveness Through Self-Reflection
- Academic Writing Style & Grammar - Exploring Features of an Academic Writing Style
- Reading & Writing Research Articles - Exploring the Abstract
- Introduction to the Design of Surveys and Experiments
- Reading & Writing Research Articles - Exploring Introductions
- Managing Your References Effectively
- Reading and Writing Research Articles - Exploring the Discussion Section
- Academic Writing Style & Grammar - Exploring Noun Phrase Usage in Academic Writing
- Report Writing
- Doing a Systematic Review
- Managing Your Research as a Project
- DesRes Conference

Second year:

- Getting Articles Published for Researchers
- Practising Presentation Skills
- Being Effective as a Researcher
- Tools for Creative Thinking
- Confidence Boost
- Getting the Most out of Supervision
- 3Min Thesis
- DMI conference
- DesRes Conference

- SIDeR Conference

Third year:

- Cafe Academique

Appendix 18 SolidWorks API Code for the Laptop

The SolidWorks API code for customised laptop is as below (in order to implement the code you need to have the excel file associated with this code, otherwise you will receive an error):

```
Sub main()

Dim swApp As SldWorks.SldWorks

Dim swModel As SldWorks.ModelDoc2

Dim swPart As SldWorks.PartDoc

Dim swSktMgr As SldWorks.SketchManager

Dim swFtrMgr As SldWorks.FeatureManager

Dim ftr As SldWorks.Feature

Dim ftr1 As SldWorks.Feature

Dim ftr2 As SldWorks.Feature

Dim ftr3 As SldWorks.Feature

Dim swSegment As Variant

Dim bln As Boolean

Dim Width, Length, Height As Double

Dim spacing1, spacing2 As Double

Dim back_chamfer_width, back_chamfer_angle, chamfer_width, chamfer_angle As Double

Dim front_chamfer_width, front_chamfer_angle As Double

Dim Laptop_width, Laptop_length, radius As Double

'Dim i As Integer

'Dim customer_name As String


'reading the customer data from an excel file

Dim xlApp As Excel.Application

Dim xlWB As Excel.Workbook
```

```vba
Set xlApp = CreateObject("excel.Application")

xlApp.Visible = False


'opening an excel file

Set xlWB = xlApp.Workbooks.Open("C:\Users\Hesam\Dropbox\Works\SW2013\Macro13\Laptop\laptop2.xlsx")

'Set xlWB = xlApp.Workbooks.Open("Z:\SolidWorks\Laptop\laptop.xlsx")



Set swApp = Application.SldWorks


'create a new part document

Set swModel = swApp.NewDocument("C:\ProgramData\SolidWorks\SolidWorks  2013\templates\Part.prtdot", Empty, Empty, Empty)

Set swModel = swApp.ActiveDoc


'select the top plane

bln = swModel.Extension.SelectByID2("Top Plane", "PLANE", 0, 0, 0, False, Empty, Nothing, 0)

Width = xlWB.Sheets("sheet 1").Range("C1").Value

Length = xlWB.Sheets("sheet 1").Range("D1").Value

Height = xlWB.Sheets("sheet 1").Range("E1").Value

'front_chamfer_width = xlWB.Sheets("sheet 1").Range("A2").Value

'front_chamfer_angle = xlWB.Sheets("sheet 1").Range("G2").Value

'chamfer_width = xlWB.Sheets("sheet 1").Range("C2").Value

'chamfer_angle = xlWB.Sheets("sheet 1").Range("H2").Value

'back_chamfer_width = xlWB.Sheets("sheet 1").Range("E2").Value

'back_chamfer_angle = xlWB.Sheets("sheet 1").Range("I2").Value

spacing1 = Width + xlWB.Sheets("sheet 1").Range("F1").Value

spacing2 = Length + xlWB.Sheets("sheet 1").Range("G1").Value

Laptop_width = xlWB.Sheets("sheet 1").Range("B1").Value

Laptop_length = xlWB.Sheets("sheet 1").Range("A1").Value

'radius = Sqrt((Width * Width) / 2 + (Length * Length) / 2) / 2

LCD_length = xlWB.Sheets("sheet 1").Range("H1").Value
```

286

LCD_width = xlWB.Sheets("sheet 1").Range("I1").Value

'customer_name = "Hesam"

'check the chamfers widths

'Dim front_chamfer_angle_degree, chamfer_angle_degree, back_chamfer_angle_degree As Double

front_chamfer_width = xlWB.Sheets("sheet 1").Range("J1").Value

chamfer_width = xlWB.Sheets("sheet 1").Range("K1").Value

back_chamfer_width = xlWB.Sheets("sheet 1").Range("L1").Value

'closing the excel file

xlWB.Close

xlApp.Visible = True

Set xlWB = Nothing

Set xlApp = Nothing

'create keyboard base

Set swSktMgr = swModel.SketchManager

swSegment = swSktMgr.CreateCornerRectangle(-spacing1 + Width, 2 * spacing2, 0, _

spacing1 - Width + 13 * spacing1 + 2 * Width, -4 * spacing2 - spacing2 + Length, 0)

bln = swModel.Extension.SelectByID2("Sketch1", "SKETCH", 0, 0, 0, False, Empty, Nothing, 0)

Set swFtrMgr = swModel.FeatureManager

Set ftr = swFtrMgr.FeatureExtrusion2(True, False, True, 0, 0, 0.3, 0, True, False, False, False, 0, 0, False, False, False, False _

, False, False, True, 0, 0, False)

'create keyboard base extension

'select the top plane

bln = swModel.Extension.SelectByID2("Top Plane", "PLANE", 0, 0, 0, False, Empty, Nothing, 0)

Set swSktMgr = swModel.SketchManager

swSegment = swSktMgr.CreateCornerRectangle(13 * spacing1 + 2 * Width - 3 * spacing1, _

-4 * spacing2 - spacing2 + Length, 0, 13 * spacing1 + 2 * Width + spacing1 - Width, -5 * spacing2 - spacing2 + Length, 0)

bln = swModel.Extension.SelectByID2("Sketch1", "SKETCH", 0, 0, 0, False, Empty, Nothing, 0)

Set swFtrMgr = swModel.FeatureManager

Set ftr = swFtrMgr.FeatureExtrusion2(True, False, True, 0, 0, 0.3, 0, True, False, False, False, 0, 0, False, False, False, False _

, True, False, True, 0, 0, False)

'create laptop body

'select the top plane

bln = swModel.Extension.SelectByID2("Top Plane", "PLANE", 0, 0, 0, False, Empty, Nothing, 0)

Set swSktMgr = swModel.SketchManager

swSegment = swSktMgr.CreateCornerRectangle(-(Laptop_length - 13 * spacing1 - 2 * Width) / 2, (-5 * spacing2 + _

2 * spacing2) / 2 + Laptop_length / 4, 0, Laptop_length - (Laptop_length - 13 * spacing1 - 2 * Width) / 2, _

(-5 * spacing2 + 2 * spacing2) / 2 - Laptop_width / 2, 0)

swModel.ClearSelection2 True

Set swSktMgr = swModel.SketchManager

swSegment = swSktMgr.CreateCornerRectangle(-spacing1 + Width, 2 * spacing2, 0, 13 * spacing1 + 2 * Width + spacing1 - Width, -5 * spacing2 - spacing2 + Length, 0)

bln = swModel.Extension.SelectByID2("Sketch1", "SKETCH", 0, 0, 0, False, Empty, Nothing, 0)

Set swFtrMgr = swModel.FeatureManager

Set ftr = swFtrMgr.FeatureExtrusion2(False, False, True, 0, 0, 0.3, Height, False, False, False, False, 0, 0, False, False, False, False _

, False, False, True, 0, 0, False)

'create laptop body extension

bln = swModel.Extension.SelectByID2("Top Plane", "PLANE", 0, 0, 0, False, Empty, Nothing, 0)

Set swSktMgr = swModel.SketchManager

swSegment = swSktMgr.CreateCornerRectangle(-spacing1 + Width, -4 * spacing2 - spacing2 + Length, _

0, 13 * spacing1 + 2 * Width - 3 * spacing1, -5 * spacing2 - spacing2 + Length, 0)

bln = swModel.Extension.SelectByID2("Sketch1", "SKETCH", 0, 0, 0, False, Empty, Nothing, 0)

Set swFtrMgr = swModel.FeatureManager

```vba
Set ftr = swFtrMgr.FeatureExtrusion2(False, False, True, 0, 0, 0.3, Height, False, False, False, False, 0, 0, False, False, False, _

False, True, False, True, 0, 0, False)


'select the top plane

bln = swModel.Extension.SelectByID2("Top Plane", "PLANE", 0, 0, 0, False, Empty, Nothing, 0)


'create the first key of the keyboard

Set swSktMgr = swModel.SketchManager

swSktMgr.InsertSketch True

swSegment = swSktMgr.CreateCornerRectangle(0, 0, 0, Width, Length, 0)

swSktMgr.InsertSketch True


'select the sketch

bln = swModel.Extension.SelectByID2("sketch1", "SKETCH", 0, 0, 0, False, Empty, Nothing, 0)


'create top face of the key for lofting
'create the top plane first

Dim swPoint4 As SldWorks.SketchPoint

Set swSktMgr = swModel.SketchManager

swSktMgr.Insert3DSketch True

Set swPoint4 = swSktMgr.CreatePoint(0, Height, 0)

swSktMgr.Insert3DSketch True

bln = swModel.Extension.SelectByID2("Top Plane", "PLANE", 0, 0, 0, False, 0, Nothing, 0)

bln = swPoint4.Select2(True, 1)

Set swFtrMgr = swModel.FeatureManager

Set swPlane3 = swFtrMgr.InsertRefPlane(1, 0, 4, 0, 0, 0)


'hide plane1

bln = swModel.Extension.SelectByID2("Plane1", "PLANE", 0, 0, 0, False, Empty, Nothing, 0)

swModel.BlankRefGeom

Dim Front_edge, Back_edge, Side_edge_right, Side_edge_left As Double
```

```vba
'here is the formula: for X direction:

' Starting_x + (Key_width /2) + chamfer_width + (key_width - width)/2

' where key_ width = Ending_x - starting_x

Front_edge = (Length / 2) - front_chamfer_width

Back_edge = (Length / 2) + back_chamfer_width

Side_edge_right = (Width / 2) + chamfer_width

Side_edge_left = (Width / 2) - chamfer_width


'create the top rectangle

bln = swModel.Extension.SelectByID2("Plane1", "PLANE", 0, 0, 0, False, Empty, Nothing, 0)

swSktMgr.InsertSketch True

swSegment = swSktMgr.CreateCornerRectangle(Side_edge_left, Front_edge, 0, Side_edge_right, Back_edge, 0)

swSktMgr.InsertSketch True


'select the sketches

bln = swModel.Extension.SelectByID2("Sketch5", "SKETCH", 0, 0, 0, False, 1, Nothing, 0)

'Set ftr1 = swSelMgr.GetSelectedObject6(1, -1)

'Set pProfile(0) = ftr1

bln = swModel.Extension.SelectByID2("Sketch6", "SKETCH", 0, 0, 0, True, 1, Nothing, 0)

'Set ftr2 = swSelMgr.GetSelectedObject6(1, -1)

'Set pProfile(1) = ftr2

'pProfilein = pProfile


'Set swModeler = swApp.GetModeler

Set ftr = swFtrMgr.InsertProtrusionBlend2(False, True, False, 1, 0, 0, 1, 1, _

True, True, False, 0, 0, 0, True, True, True, swGuideCurveInfluence_e.swGuideCurveInfluenceNextGlobal)


'create Axis

bln = swModel.Extension.SelectByID2("Top Plane", "PLANE", 0, 0, 0, False, Empty, Nothing, 0)

bln = swModel.Extension.SelectByID2("Front Plane", "PLANE", 0, 0, 0, True, Empty, Nothing, 0)
```

```vba
bln = swModel.InsertAxis2(True)


'hide axis

bln = swModel.Extension.SelectByID2("Axis1", "AXIS", Width, 0, -2 * spacing2, False, 1, Nothing, 0)

swModel.BlankRefGeom


'create axis

bln = swModel.Extension.SelectByID2("Top Plane", "PLANE", 0, 0, 0, False, Empty, Nothing, 0)

bln = swModel.Extension.SelectByID2("Right Plane", "PLANE", 0, 0, 0, True, Empty, Nothing, 0)

bln = swModel.InsertAxis2(True)


'hide axis

bln = swModel.Extension.SelectByID2("Axis2", "AXIS", Width, 0, -2 * spacing2, False, 1, Nothing, 0)

swModel.BlankRefGeom

bln = swModel.Extension.SelectByID2("Loft1", "BODYFEATURE", 0, 0, 0, False, 4, Nothing, 0)

bln = swModel.Extension.SelectByID2("Axis1", "AXIS", Width, 0, -2 * spacing2, True, 1, Nothing, 0)

bln = swModel.Extension.SelectByID2("Axis2", "AXIS", 13 * spacing1 + 2 * Width, 0, 0, True, 2, Nothing, 0)


'create the first row by using linear pattern

Dim swLinearFtr As SldWorks.Feature

Set swLinearFtr = swFtrMgr.FeatureLinearPattern3(13, spacing1, 2, spacing2, True, True, 1, 2, False, False)


'select the top plane

bln = swModel.Extension.SelectByID2("Top Plane", "PLANE", 0, 0, 0, False, Empty, Nothing, 0)


'create the Delete key of the keyboard

Set swSktMgr = swModel.SketchManager

swSktMgr.InsertSketch True

swSegment = swSktMgr.CreateCornerRectangle(13 * spacing1, spacing2, 0, 13 * spacing1 + 2 * Width, spacing2 + Length, 0)

swSktMgr.InsertSketch True

Side_edge_right = 13 * spacing1 + (2 * Width / 2) + chamfer_width + Width / 2
```

Side_edge_left = 13 * spacing1 + (2 * Width / 2) - chamfer_width - Width / 2

'create the top rectangle

bln = swModel.Extension.SelectByID2("Plane1", "PLANE", Height, Height, Height, False, 0, Nothing, 0)

swSegment = swSktMgr.CreateCornerRectangle(Side_edge_left, spacing2 + Front_edge, 0, Side_edge_right, spacing2 + Back_edge, 0)

'create loft

bln = swModel.Extension.SelectByID2("Sketch7", "SKETCH", 0, 0, 0, False, 1, Nothing, 0)

bln = swModel.Extension.SelectByID2("Sketch8", "SKETCH", 0, 0, 0, True, 1, Nothing, 0)

Set ftr = swFtrMgr.InsertProtrusionBlend2(False, True, False, 1, 0, 0, 1, 1, _

True, True, False, 0, 0, 0, True, True, True, swGuideCurveInfluence_e.swGuideCurveInfluenceNextGlobal)

'select the top plane

bln = swModel.Extension.SelectByID2("Top Plane", "PLANE", 0, 0, 0, False, Empty, Nothing, 0)

'create the Backspace key of the keyboard

Set swSktMgr = swModel.SketchManager

swSktMgr.InsertSketch True

swSegment = swSktMgr.CreateCornerRectangle(13 * spacing1, 0, 0, 13 * spacing1 + 2 * Width, Length, 0)

swSktMgr.InsertSketch True

Side_edge_right = 13 * spacing1 + (2 * Width / 2) + chamfer_width + Width / 2

Side_edge_left = 13 * spacing1 + (2 * Width / 2) - chamfer_width - Width / 2

'create the top rectangle

bln = swModel.Extension.SelectByID2("Plane1", "PLANE", Height, Height, Height, False, 0, Nothing, 0)

swSegment = swSktMgr.CreateCornerRectangle(Side_edge_left, Front_edge, 0, Side_edge_right, Back_edge, 0)

'create loft

bln = swModel.Extension.SelectByID2("Sketch9", "SKETCH", 0, 0, 0, False, 1, Nothing, 0)

bln = swModel.Extension.SelectByID2("Sketch10", "SKETCH", 0, 0, 0, True, 1, Nothing, 0)

Set ftr = swFtrMgr.InsertProtrusionBlend2(False, True, False, 1, 0, 0, 1, 1, _

True, True, False, 0, 0, 0, True, True, True, swGuideCurveInfluence_e.swGuideCurveInfluenceNextGlobal)

'select the top plane

bln = swModel.Extension.SelectByID2("Top Plane", "PLANE", 0, 0, 0, False, Empty, Nothing, 0)

'create the second key of the keyboard (second row)

Set swSktMgr = swModel.SketchManager

swSktMgr.InsertSketch True

swSegment = swSktMgr.CreateCornerRectangle(1.5 * Width + spacing1 - Width, -spacing2 + Length, 0, 2.5 * Width + spacing1 - _

Width, -spacing2, 0)

swSktMgr.InsertSketch True

Side_edge_right = 1.5 * Width + spacing1 - Width + (Width / 2) + chamfer_width

Side_edge_left = 1.5 * Width + spacing1 - Width + (Width / 2) - chamfer_width

'create the top rectangle

bln = swModel.Extension.SelectByID2("Plane1", "PLANE", Height, Height, Height, False, 0, Nothing, 0)

swSegment = swSktMgr.CreateCornerRectangle(Side_edge_left, -spacing2 + Front_edge, 0, Side_edge_right, -spacing2 + Back_edge, 0)

'create loft

bln = swModel.Extension.SelectByID2("Sketch11", "SKETCH", 0, 0, 0, False, 1, Nothing, 0)

bln = swModel.Extension.SelectByID2("Sketch12", "SKETCH", 0, 0, 0, True, 1, Nothing, 0)

Set ftr = swFtrMgr.InsertProtrusionBlend2(False, True, False, 1, 0, 0, 1, 1, _

True, True, False, 0, 0, 0, True, True, True, swGuideCurveInfluence_e.swGuideCurveInfluenceNextGlobal)

swModel.ClearSelection2 True

bln = swModel.Extension.SelectByID2("Loft4", "BODYFEATURE", 0, 0, 0, False, 4, Nothing, 0)

bln = swModel.Extension.SelectByID2("Axis1", "AXIS", 0, 0, 0, True, 1, Nothing, 0)

'create the second row by using linear pattern

Set swLinearFtr = swFtrMgr.FeatureLinearPattern3(12, spacing1, 1, 0, True, False, "Null", "Null", False, False)

'select the top plane

bln = swModel.Extension.SelectByID2("Top Plane", "PLANE", 0, 0, 0, False, Empty, Nothing, 0)

'create the Tab key of the keyboard

Set swSktMgr = swModel.SketchManager

swSktMgr.InsertSketch True

swSegment = swSktMgr.CreateCornerRectangle(0, -spacing2 + Length, 0, 1.5 * Width, -spacing2, 0)

swSktMgr.InsertSketch True

Side_edge_right = (1.5 * Width / 2) + chamfer_width + (0.5 * Width) / 2

Side_edge_left = (1.5 * Width / 2) - chamfer_width - (0.5 * Width) / 2

'create the top rectangle

bln = swModel.Extension.SelectByID2("Plane1", "PLANE", Height, Height, Height, False, 0, Nothing, 0)

swSegment = swSktMgr.CreateCornerRectangle(Side_edge_left, -spacing2 + Front_edge, 0, Side_edge_right, -spacing2 + Back_edge, 0)

'create loft

bln = swModel.Extension.SelectByID2("Sketch13", "SKETCH", 0, 0, 0, False, 1, Nothing, 0)

bln = swModel.Extension.SelectByID2("Sketch14", "SKETCH", 0, 0, 0, True, 1, Nothing, 0)

Set ftr = swFtrMgr.InsertProtrusionBlend2(False, True, False, 1, 0, 0, 1, 1, _

True, True, False, 0, 0, 0, True, True, True, swGuideCurveInfluence_e.swGuideCurveInfluenceNextGlobal)

'select the top plane

bln = swModel.Extension.SelectByID2("Top Plane", "PLANE", 0, 0, 0, False, Empty, Nothing, 0)

'create the | key of the keyboard

Set swSktMgr = swModel.SketchManager

swSktMgr.InsertSketch True

swSegment = swSktMgr.CreateCornerRectangle(1.5 * Width + spacing1 - Width + 12 * spacing1, -spacing2 + Length, 0, _

13 * spacing1 + 2 * Width, -spacing2, 0)

swSktMgr.InsertSketch True

Side_edge_right = 1.5 * Width + spacing1 - Width + 12 * spacing1 + _

((13 * spacing1 + 2 * Width - (1.5 * Width + spacing1 - Width + 12 * spacing1)) / 2) + chamfer_width + _

((13 * spacing1 + 2 * Width - (1.5 * Width + spacing1 - Width + 12 * spacing1)) - Width) / 2

Side_edge_left = 1.5 * Width + spacing1 - Width + 12 * spacing1 + _

((13 * spacing1 + 2 * Width - (1.5 * Width + spacing1 - Width + 12 * spacing1)) / 2) - chamfer_width - _

((13 * spacing1 + 2 * Width - (1.5 * Width + spacing1 - Width + 12 * spacing1)) - Width) / 2

'create the top rectangle

bln = swModel.Extension.SelectByID2("Plane1", "PLANE", 0, 0, 0, False, Empty, Nothing, 0)

swSktMgr.InsertSketch True

swSegment = swSktMgr.CreateCornerRectangle(Side_edge_left, -spacing2 + Front_edge, 0, Side_edge_right, -spacing2 + Back_edge, 0)

swSktMgr.InsertSketch True

'create loft

bln = swModel.Extension.SelectByID2("Sketch15", "SKETCH", 0, 0, 0, False, 1, Nothing, 0)

bln = swModel.Extension.SelectByID2("Sketch16", "SKETCH", 0, 0, 0, True, 1, Nothing, 0)

Set ftr = swFtrMgr.InsertProtrusionBlend2(False, True, False, 1, 0, 0, 1, 1, _

True, True, False, 0, 0, 0, True, True, True, swGuideCurveInfluence_e.swGuideCurveInfluenceNextGlobal)

'select the top plane

bln = swModel.Extension.SelectByID2("Top Plane", "PLANE", 0, 0, 0, False, Empty, Nothing, 0)

'create the third key of the keyboard (third row)

Set swSktMgr = swModel.SketchManager

swSktMgr.InsertSketch True

swSegment = swSktMgr.CreateCornerRectangle(1.9 * Width + spacing1 - Width, -2 * spacing2 + Length, 0, 2.9 * Width + _

spacing1 - Width, -2 * spacing2, 0)

swSktMgr.InsertSketch True

Side_edge_right = 1.9 * Width + spacing1 - Width + _

(Width / 2) + chamfer_width

Side_edge_left = 1.9 * Width + spacing1 - Width + _

(Width / 2) - chamfer_width

'create the top rectangle

bln = swModel.Extension.SelectByID2("Plane1", "PLANE", 0, 0, 0, False, Empty, Nothing, 0)

swSktMgr.InsertSketch True

swSegment = swSktMgr.CreateCornerRectangle(Side_edge_left, -2 * spacing2 + Front_edge, 0, Side_edge_right, -2 * spacing2 + Back_edge, 0)

swSktMgr.InsertSketch True

'create loft

bln = swModel.Extension.SelectByID2("Sketch17", "SKETCH", 0, 0, 0, False, 1, Nothing, 0)

bln = swModel.Extension.SelectByID2("Sketch18", "SKETCH", 0, 0, 0, True, 1, Nothing, 0)

Set ftr = swFtrMgr.InsertProtrusionBlend2(False, True, False, 1, 0, 0, 1, 1, _

True, True, False, 0, 0, 0, True, True, True, swGuideCurveInfluence_e.swGuideCurveInfluenceNextGlobal)

bln = swModel.Extension.SelectByID2("Loft7", "BODYFEATURE", 0, 0, 0, False, 4, Nothing, 0)

bln = swModel.Extension.SelectByID2("Axis1", "AXIS", 0, 0, 0, True, 1, Nothing, 0)

'create the third row by using linear pattern

Set swLinearFtr = swFtrMgr.FeatureLinearPattern3(11, spacing1, 1, 0, True, False, "Null", "Null", False, False)

'select the top plane

bln = swModel.Extension.SelectByID2("Top Plane", "PLANE", 0, 0, 0, False, Empty, Nothing, 0)

'create the CapsLk key of the keyboard

Set swSktMgr = swModel.SketchManager

swSegment = swSktMgr.CreateCornerRectangle(0, -2 * spacing2 + Length, 0, 1.9 * Width, -2 * spacing2, 0)

swSktMgr.InsertSketch True

Side_edge_right = (1.9 * Width / 2) + chamfer_width + (0.9 * Width) / 2

Side_edge_left = (1.9 * Width / 2) - chamfer_width - (0.9 * Width) / 2

```vba
'create the top rectangle

bln = swModel.Extension.SelectByID2("Plane1", "PLANE", 0, 0, 0, False, Empty, Nothing, 0)

swSktMgr.InsertSketch True

swSegment = swSktMgr.CreateCornerRectangle(Side_edge_left, -2 * spacing2 + Front_edge, 0, Side_edge_right, -2 * spacing2 + Back_edge, 0)

swSktMgr.InsertSketch True



'create loft

bln = swModel.Extension.SelectByID2("Sketch19", "SKETCH", 0, 0, 0, False, 1, Nothing, 0)

bln = swModel.Extension.SelectByID2("Sketch20", "SKETCH", 0, 0, 0, True, 1, Nothing, 0)

Set ftr = swFtrMgr.InsertProtrusionBlend2(False, True, False, 1, 0, 0, 1, 1, _

True, True, False, 0, 0, 0, True, True, True, swGuideCurveInfluence_e.swGuideCurveInfluenceNextGlobal)



'select the top plane

bln = swModel.Extension.SelectByID2("Top Plane", "PLANE", 0, 0, 0, False, Empty, Nothing, 0)



'create the Enter key of the keyboard

Set swSktMgr = swModel.SketchManager

swSegment = swSktMgr.CreateCornerRectangle(1.9 * Width + spacing1 - Width + 11 * spacing1, -2 * spacing2 + Length, 0, _

13 * spacing1 + 2 * Width, -2 * spacing2, 0)

swSktMgr.InsertSketch True

Side_edge_right = 1.9 * Width + spacing1 - Width + 11 * spacing1 + _

(13 * spacing1 + 2 * Width - (1.9 * Width + spacing1 - Width + 11 * spacing1)) / 2 + chamfer_width + _

(13 * spacing1 + 2 * Width - (1.9 * Width + spacing1 - Width + 11 * spacing1) - Width) / 2

Side_edge_left = 1.9 * Width + spacing1 - Width + 11 * spacing1 + _

(13 * spacing1 + 2 * Width - (1.9 * Width + spacing1 - Width + 11 * spacing1)) / 2 - chamfer_width - _

(13 * spacing1 + 2 * Width - (1.9 * Width + spacing1 - Width + 11 * spacing1) - Width) / 2



'create the top rectangle

bln = swModel.Extension.SelectByID2("Plane1", "PLANE", 0, 0, 0, False, Empty, Nothing, 0)

swSktMgr.InsertSketch True
```

```vbnet
swSegment = swSktMgr.CreateCornerRectangle(Side_edge_left, -2 * spacing2 + Front_edge, 0, Side_edge_right, -2 * spacing2 + Back_edge, 0)

swSktMgr.InsertSketch True
```

'create loft

```vbnet
bln = swModel.Extension.SelectByID2("Sketch21", "SKETCH", 0, 0, 0, False, 1, Nothing, 0)

bln = swModel.Extension.SelectByID2("Sketch22", "SKETCH", 0, 0, 0, True, 1, Nothing, 0)

Set ftr = swFtrMgr.InsertProtrusionBlend2(False, True, False, 1, 0, 0, 1, 1, _

True, True, False, 0, 0, 0, True, True, True, swGuideCurveInfluence_e.swGuideCurveInfluenceNextGlobal)
```

'select the top plane

```vbnet
bln = swModel.Extension.SelectByID2("Top Plane", "PLANE", 0, 0, 0, False, Empty, Nothing, 0)
```

'create the forth key of the keyboard (forth row)

```vbnet
Set swSktMgr = swModel.SketchManager

swSegment = swSktMgr.CreateCornerRectangle(0.25 * Width + 2 * spacing1, -3 * spacing2 + Length, 0, 1.25 * Width + _

2 * spacing1, -3 * spacing2, 0)

swSktMgr.InsertSketch True

Side_edge_right = 0.25 * Width + 2 * spacing1 + _

(Width / 2) + chamfer_width

Side_edge_left = 0.25 * Width + 2 * spacing1 + _

(Width / 2) - chamfer_width
```

'create the top rectangle

```vbnet
bln = swModel.Extension.SelectByID2("Plane1", "PLANE", 0, 0, 0, False, Empty, Nothing, 0)

swSktMgr.InsertSketch True

swSegment = swSktMgr.CreateCornerRectangle(Side_edge_left, -3 * spacing2 + Front_edge, 0, Side_edge_right, -3 * spacing2 + Back_edge, 0)

swSktMgr.InsertSketch True
```

'create loft

```vbnet
bln = swModel.Extension.SelectByID2("Sketch23", "SKETCH", 0, 0, 0, False, 1, Nothing, 0)
```

298

```
bln = swModel.Extension.SelectByID2("Sketch24", "SKETCH", 0, 0, 0, True, 1, Nothing, 0)

Set ftr = swFtrMgr.InsertProtrusionBlend2(False, True, False, 1, 0, 0, 1, 1, _

True, True, False, 0, 0, 0, True, True, True, swGuideCurveInfluence_e.swGuideCurveInfluenceNextGlobal)

bln = swModel.Extension.SelectByID2("Loft10", "BODYFEATURE", 0, 0, 0, False, 4, Nothing, 0)

bln = swModel.Extension.SelectByID2("Axis1", "AXIS", 0, 0, 0, True, 1, Nothing, 0)


'create the third row by using linear pattern

Set swLinearFtr = swFtrMgr.FeatureLinearPattern3(10, spacing1, 1, 0, True, False, "Null", "Null", False, False)


'select the top plane

bln = swModel.Extension.SelectByID2("Top Plane", "PLANE", 0, 0, 0, False, Empty, Nothing, 0)


'create the Left Shift key of the keyboard

Set swSktMgr = swModel.SketchManager

swSegment = swSktMgr.CreateCornerRectangle(0, -3 * spacing2 + Length, 0, 0.25 * Width + 2 * spacing1 - spacing1 + _

Width, -3 * spacing2, 0)

swSktMgr.InsertSketch True

Side_edge_right = ((0.25 * Width + 2 * spacing1 - spacing1 + Width) / 2) + chamfer_width + (0.25 * Width + 2 * spacing1 - spacing1 + _

Width - Width) / 2

Side_edge_left = ((0.25 * Width + 2 * spacing1 - spacing1 + Width) / 2) - chamfer_width - (0.25 * Width + 2 * spacing1 - spacing1 + _

Width - Width) / 2


'create the top rectangle

bln = swModel.Extension.SelectByID2("Plane1", "PLANE", 0, 0, 0, False, Empty, Nothing, 0)

swSktMgr.InsertSketch True

swSegment = swSktMgr.CreateCornerRectangle(Side_edge_left, -3 * spacing2 + Front_edge, 0, Side_edge_right, -3 * spacing2 + Back_edge, 0)

swSktMgr.InsertSketch True


'create loft
```

```
bln = swModel.Extension.SelectByID2("Sketch25", "SKETCH", 0, 0, 0, False, 1, Nothing, 0)

bln = swModel.Extension.SelectByID2("Sketch26", "SKETCH", 0, 0, 0, True, 1, Nothing, 0)

Set ftr = swFtrMgr.InsertProtrusionBlend2(False, True, False, 1, 0, 0, 1, 1, _

True, True, False, 0, 0, 0, True, True, True, swGuideCurveInfluence_e.swGuideCurveInfluenceNextGlobal)



'select the top plane

bln = swModel.Extension.SelectByID2("Top Plane", "PLANE", 0, 0, 0, False, Empty, Nothing, 0)



'create the Right Shift key of the keyboard

Set swSktMgr = swModel.SketchManager

swSegment = swSktMgr.CreateCornerRectangle(0.25 * Width + 2 * spacing1 + 10 * spacing1, -3 * spacing2 + Length, 0, _

13 * spacing1 + 2 * Width, -3 * spacing2, 0)



swSktMgr.InsertSketch True

Side_edge_right = 0.25 * Width + 2 * spacing1 + 10 * spacing1 + _

((13 * spacing1 + 2 * Width) - (0.25 * Width + 2 * spacing1 + 10 * spacing1)) / 2 + chamfer_width + _

((13 * spacing1 + 2 * Width) - (0.25 * Width + 2 * spacing1 + 10 * spacing1) - Width) / 2

Side_edge_left = 0.25 * Width + 2 * spacing1 + 10 * spacing1 + _

((13 * spacing1 + 2 * Width) - (0.25 * Width + 2 * spacing1 + 10 * spacing1)) / 2 - chamfer_width - _

((13 * spacing1 + 2 * Width) - (0.25 * Width + 2 * spacing1 + 10 * spacing1) - Width) / 2



'create the top rectangle

bln = swModel.Extension.SelectByID2("Plane1", "PLANE", 0, 0, 0, False, Empty, Nothing, 0)

swSktMgr.InsertSketch True

swSegment = swSktMgr.CreateCornerRectangle(Side_edge_left, -3 * spacing2 + Front_edge, 0, Side_edge_right, -3 * spacing2 + Back_edge, 0)

swSktMgr.InsertSketch True



'create loft

bln = swModel.Extension.SelectByID2("Sketch27", "SKETCH", 0, 0, 0, False, 1, Nothing, 0)

bln = swModel.Extension.SelectByID2("Sketch28", "SKETCH", 0, 0, 0, True, 1, Nothing, 0)
```

```
Set ftr = swFtrMgr.InsertProtrusionBlend2(False, True, False, 1, 0, 0, 1, 1, _

True, True, False, 0, 0, 0, True, True, True, swGuideCurveInfluence_e.swGuideCurveInfluenceNextGlobal)
```

'select the top plane

```
bln = swModel.Extension.SelectByID2("Top Plane", "PLANE", 0, 0, 0, False, Empty, Nothing, 0)
```

'create the fifth key of the keyboard (fifth row)

```
Set swSktMgr = swModel.SketchManager

swSegment = swSktMgr.CreateCornerRectangle(0, -4 * spacing2 + Length, 0, Width, -4 * spacing2, 0)

swSktMgr.InsertSketch True

Side_edge_right = (Width) / 2 + chamfer_width

Side_edge_left = (Width) / 2 - chamfer_width
```

'create the top rectangle

```
bln = swModel.Extension.SelectByID2("Plane1", "PLANE", 0, 0, 0, False, Empty, Nothing, 0)

swSktMgr.InsertSketch True

swSegment   =   swSktMgr.CreateCornerRectangle(Side_edge_left,   -4   *   spacing2   +   Front_edge,   0,
Side_edge_right, -4 * spacing2 + Back_edge, 0)

swSktMgr.InsertSketch True
```

'create loft

```
bln = swModel.Extension.SelectByID2("Sketch29", "SKETCH", 0, 0, 0, False, 1, Nothing, 0)

bln = swModel.Extension.SelectByID2("Sketch30", "SKETCH", 0, 0, 0, True, 1, Nothing, 0)

Set ftr = swFtrMgr.InsertProtrusionBlend2(False, True, False, 1, 0, 0, 1, 1, _

True, True, False, 0, 0, 0, True, True, True, swGuideCurveInfluence_e.swGuideCurveInfluenceNextGlobal)

bln = swModel.Extension.SelectByID2("Loft13", "BODYFEATURE", 0, 0, 0, False, 4, Nothing, 0)

bln = swModel.Extension.SelectByID2("Axis1", "AXIS", 0, 0, 0, True, 1, Nothing, 0)
```

'create the third row by using linear pattern

```
Set swLinearFtr = swFtrMgr.FeatureLinearPattern3(4, spacing1, 1, 0, True, False, "Null", "Null", False, False)
```

'select the top plane

bln = swModel.Extension.SelectByID2("Top Plane", "PLANE", 0, 0, 0, False, Empty, Nothing, 0)

'create the Space key of the keyboard

Set swSktMgr = swModel.SketchManager

swSegment = swSktMgr.CreateCornerRectangle(4 * spacing1, -4 * spacing2 + Length, 0, 13 * spacing1 + 2 * Width _

- 6 * spacing1, -4 * spacing2, 0)

swSktMgr.InsertSketch True

Side_edge_right = 4 * spacing1 + ((13 * spacing1 + 2 * Width - 6 * spacing1) - 4 * spacing1) / 2 + chamfer_width + _

((13 * spacing1 + 2 * Width - 6 * spacing1) - 4 * spacing1 - Width) / 2

Side_edge_left = 4 * spacing1 + ((13 * spacing1 + 2 * Width - 6 * spacing1) - 4 * spacing1) / 2 - chamfer_width - _

((13 * spacing1 + 2 * Width - 6 * spacing1) - 4 * spacing1 - Width) / 2

'create the top rectangle

bln = swModel.Extension.SelectByID2("Plane1", "PLANE", 0, 0, 0, False, Empty, Nothing, 0)

swSktMgr.InsertSketch True

swSegment = swSktMgr.CreateCornerRectangle(Side_edge_left, -4 * spacing2 + Front_edge, 0, Side_edge_right, -4 * spacing2 + Back_edge, 0)

swSktMgr.InsertSketch True

'create loft

bln = swModel.Extension.SelectByID2("Sketch31", "SKETCH", 0, 0, 0, False, 1, Nothing, 0)

bln = swModel.Extension.SelectByID2("Sketch32", "SKETCH", 0, 0, 0, True, 1, Nothing, 0)

Set ftr = swFtrMgr.InsertProtrusionBlend2(False, True, False, 1, 0, 0, 1, 1, _

True, True, False, 0, 0, 0, True, True, True, swGuideCurveInfluence_e.swGuideCurveInfluenceNextGlobal)

'select the top plane

bln = swModel.Extension.SelectByID2("Top Plane", "PLANE", 0, 0, 0, False, Empty, Nothing, 0)

'create the fifth key of the keyboard (fifth row)

Set swSktMgr = swModel.SketchManager

```
swSegment = swSktMgr.CreateCornerRectangle(13 * spacing1 + 2 * Width - 6 * spacing1 + spacing1 - Width, -4 * _

spacing2 + Length, 0, 13 * spacing1 + 2 * Width - 6 * spacing1 + spacing1 - Width + Width, -4 * spacing2, 0)

swSktMgr.InsertSketch True

Side_edge_right = (13 * spacing1 + 2 * Width - 6 * spacing1 + spacing1 - Width) + ((Width) / 2) + chamfer_width

Side_edge_left = (13 * spacing1 + 2 * Width - 6 * spacing1 + spacing1 - Width) + ((Width) / 2) - chamfer_width


'create the top rectangle

bln = swModel.Extension.SelectByID2("Plane1", "PLANE", 0, 0, 0, False, Empty, Nothing, 0)

swSktMgr.InsertSketch True

swSegment = swSktMgr.CreateCornerRectangle(Side_edge_left, -4 * spacing2 + Front_edge, 0, Side_edge_right, -4 * spacing2 + Back_edge, 0)

swSktMgr.InsertSketch True


'create loft

bln = swModel.Extension.SelectByID2("Sketch33", "SKETCH", 0, 0, 0, False, 1, Nothing, 0)

bln = swModel.Extension.SelectByID2("Sketch34", "SKETCH", 0, 0, 0, True, 1, Nothing, 0)

Set ftr = swFtrMgr.InsertProtrusionBlend2(False, True, False, 1, 0, 0, 1, 1, _

True, True, False, 0, 0, 0, True, True, True, swGuideCurveInfluence_e.swGuideCurveInfluenceNextGlobal)

bln = swModel.Extension.SelectByID2("Loft15", "BODYFEATURE", 0, 0, 0, False, 4, Nothing, 0)

bln = swModel.Extension.SelectByID2("Axis1", "AXIS", 0, 0, 0, True, 1, Nothing, 0)


'create the third row by using linear pattern

Set swLinearFtr = swFtrMgr.FeatureLinearPattern3(6, spacing1, 1, 0, True, False, "Null", "Null", False, False)


'select the top plane

bln = swModel.Extension.SelectByID2("Top Plane", "PLANE", 0, 0, 0, False, Empty, Nothing, 0)


'create the left,down and right arrow keys of the keyboard (six row)

Set swSktMgr = swModel.SketchManager

swSegment = swSktMgr.CreateCornerRectangle(13 * spacing1 + 2 * Width - 3 * spacing1 + spacing1 - Width, -5 * _

spacing2 + Length, 0, 13 * spacing1 + 2 * Width - 3 * spacing1 + spacing1 - Width + Width, -5 * spacing2, 0)
```

```vbnet
swSktMgr.InsertSketch True

Side_edge_right = (13 * spacing1 + 2 * Width - 3 * spacing1 + spacing1 - Width) + ((Width) / 2) + chamfer_width

Side_edge_left = (13 * spacing1 + 2 * Width - 3 * spacing1 + spacing1 - Width) + ((Width) / 2) - chamfer_width


'create the top rectangle

bln = swModel.Extension.SelectByID2("Plane1", "PLANE", 0, 0, 0, False, Empty, Nothing, 0)

swSktMgr.InsertSketch True

swSegment = swSktMgr.CreateCornerRectangle(Side_edge_left, -5 * spacing2 + Front_edge, 0, Side_edge_right, -5 * spacing2 + Back_edge, 0)

swSktMgr.InsertSketch True


'create loft

bln = swModel.Extension.SelectByID2("Sketch35", "SKETCH", 0, 0, 0, False, 1, Nothing, 0)

bln = swModel.Extension.SelectByID2("Sketch36", "SKETCH", 0, 0, 0, True, 1, Nothing, 0)


Set ftr = swFtrMgr.InsertProtrusionBlend2(False, True, False, 1, 0, 0, 1, 1, _

True, True, False, 0, 0, 0, True, True, True, swGuideCurveInfluence_e.swGuideCurveInfluenceNextGlobal)

bln = swModel.Extension.SelectByID2("Loft16", "BODYFEATURE", 0, 0, 0, False, 4, Nothing, 0)

bln = swModel.Extension.SelectByID2("Axis1", "AXIS", 0, 0, 0, True, 1, Nothing, 0)


'create the fifth row by using linear pattern

Set swLinearFtr = swFtrMgr.FeatureLinearPattern3(3, spacing1, 1, 0, True, False, "Null", "Null", False, False)


'create trackpad (touchpad)
'select the top plane

bln = swModel.Extension.SelectByID2("Top Plane", "PLANE", 0, 0, 0, False, Empty, Nothing, 0)

Set swSktMgr = swModel.SketchManager

swSegment = swSktMgr.CreateCornerRectangle(((13 * spacing1 + 2 * Width) / 2) - Laptop_length / 8, -4 * spacing2 - spacing2 + Length _

- 0.5, 0, ((13 * spacing1 + 2 * Width) / 2) + Laptop_length / 8, ((-5 * spacing2 + 2 * spacing2) / 2 - Laptop_width / 2) + 0.5, 0)

swSktMgr.InsertSketch True

bln = swModel.Extension.SelectByID2("Sketch37", "SKETCH", 0, 0, 0, False, Empty, Nothing, 0)
```

```
Set swFtrMgr = swModel.FeatureManager

Set ftr = swFtrMgr.FeatureCut3(True, False, True, 0, 0, Height - 0.25, 0, False, False, False, False, 0, 0, False, False, False, _

False, False, False, True, True, True, False, 3, 0.25, False)
```

'create LCD

'create plane

'create 3 points for plane creation

```
Dim swPlane1, swPlane2 As SldWorks.RefPlane

Dim swPoint1, swPoint2, swPoint3 As SldWorks.SketchPoint

swSktMgr.Insert3DSketch True

Set swPoint1 = swSktMgr.CreatePoint(0, Height, -(-5 * spacing2 + 2 * spacing2) / 2 - Laptop_length / 4)

swSktMgr.Insert3DSketch True
```

'hide plane

```
Dim swLine1 As SldWorks.SketchLine

swSktMgr.Insert3DSketch True

Set swLine1 = swSktMgr.CreateLine(0, 0, 0, 0, 0.94 * Laptop_width, -0.34 * Laptop_width)

swSktMgr.Insert3DSketch True

bln = swModel.Extension.SelectByID2("Axis1", "AXIS", Width, 0, -2 * spacing2, True, 0, Nothing, 0)

bln = swLine1.Select2(True, 1)
```

'create the first plane with two condition, coincident and coincident (4)

```
Set swPlane1 = swFtrMgr.InsertRefPlane(4, 0, 4, 0, 0, 0)

bln = swPoint1.Select2(True, 0)

bln = swPlane1.Select2(True, 1)
```

'create the second plane with two conditions, coincident and parallel (1, 4)

```
Set swPlane2 = swFtrMgr.InsertRefPlane(4, 0, 1, 0, 0, 0)
```

'Hide two planes and the sketched line

```
bln = swModel.Extension.SelectByID2("3Dsketch1", "SKETCH", 0, 0, 0, False, Empty, Nothing, 0)
```

```
swModel.BlankSketch

bln = swModel.Extension.SelectByID2("3Dsketch2", "SKETCH", 0, 0, 0, False, Empty, Nothing, 0)

swModel.BlankSketch

bln = swModel.Extension.SelectByID2("Plane2", "PLANE", 0, 0, 0, False, Empty, Nothing, 0)

swModel.BlankRefGeom

bln = swModel.Extension.SelectByID2("Plane3", "PLANE", 0, 0, 0, False, Empty, Nothing, 0)

swModel.BlankRefGeom


'create LCD

'select the plane1

bln = swModel.Extension.SelectByID2("Plane3", "PLANE", 0, 0, 0, False, Empty, Nothing, 0)


'create the LCD rectangle

Set swSktMgr = swModel.SketchManager

swSegment = swSktMgr.CreateCornerRectangle((Laptop_length - 13 * spacing1 - 2 * Width) / 2, _

((-5 * spacing2 + 2 * spacing2) / 2 + Laptop_length / 4) * 0.342, 0, -Laptop_length + (Laptop_length - 13 * spacing1 - 2 * Width) / 2, _

((-5 * spacing2 + 2 * spacing2) / 2 + Laptop_length / 4) - ((-5 * spacing2 + 2 * spacing2) / 2 - Laptop_width / 2) _

+ ((-5 * spacing2 + 2 * spacing2) / 2 + Laptop_length / 4) * 0.342, 0)


'select the sketch

bln = swModel.Extension.SelectByID2("sketch1", "SKETCH", 0, 0, 0, False, Empty, Nothing, 0)


'extrude the sketch

Set swFtrMgr = swModel.FeatureManager

Set ftr = swFtrMgr.FeatureExtrusion2(True, False, False, 0, 0, Height, 0, False, False, False, False, 0, 0, False, _

False, False, False, False, False, True, 0, 0, False)


'create the LCD screen

'select plane1

bln = swModel.Extension.SelectByID2("Plane3", "PLANE", 0, 0, 0, False, Empty, Nothing, 0)

Set swSktMgr = swModel.SketchManager
```

```
swSegment = swSktMgr.CreateCornerRectangle(-(13 * spacing1 + 2 * Width) / 2 + LCD_length / 2, _

 ((-5 * spacing2 + 2 * spacing2) / 2 + Laptop_length / 4) * 0.342 + 2, 0, -(13 * spacing1 + 2 * Width) / 2 -
LCD_length / 2, _

 ((-5 * spacing2 + 2 * spacing2) / 2 + Laptop_length / 4) * 0.342 + LCD_width + 2, 0)
```

```
bln = swModel.Extension.SelectByID2("Sketch1", "SKETCH", 0, 0, 0, False, Empty, Nothing, 0)

Set swFtrMgr = swModel.FeatureManager

Set ftr = swFtrMgr.FeatureCut3(True, False, True, 0, 0, Height - 0.25, 0, False, False, False, False, 0, 0, False,
False, False, _

False, False, False, True, True, True, False, 0, 0, False)

swModel.ClearSelection2 True
```

```
'create hinge for LCD
```

```
'select the plane1
```

```
bln = swModel.Extension.SelectByID2("Right Plane", "PLANE", 0, 0, 0, False, Empty, Nothing, 0)
```

```
'create the left,down and right arrow keys of the keyboard (six row)
```

```
Set swSktMgr = swModel.SketchManager

Set swSegment = swSktMgr.CreateCircleByRadius((-5 * spacing2 + 2 * spacing2) / 2 + Laptop_length / 4, Height,
0, Height / 3)
```

```
'select the sketch
```

```
bln = swModel.Extension.SelectByID2("sketch1", "SKETCH", 0, 0, 0, False, Empty, Nothing, 0)
```

```
'extrude the sketch
```

```
Set swFtrMgr = swModel.FeatureManager

Set ftr = swFtrMgr.FeatureExtrusion2(True, False, False, 0, 0, Laptop_length / 10, 0, False, False, False, False, 0,
0, False, _

False, False, False, True, False, True, 0, 0, False)
```

```
'create the second hinge
```

```
bln = swModel.Extension.SelectByID2("Boss-Extrude6", "BODYFEATURE", 0, 0, 0, False, 4, Nothing, 0)

bln = swModel.Extension.SelectByID2("Axis1", "AXIS", 0, 0, 0, True, 1, Nothing, 0)
```

Set swLinearFtr = swFtrMgr.FeatureLinearPattern3(2, 13 * spacing1 + 2 * Width - Laptop_length / 10, 1, 0, True, False, "Null", "Null", False, False)

End Sub

Appendix 19 Creating the AM-enabled MC Toolkit with Three.js

The method of manipulation of the lampshade is based on manipulation of faces and vertices. Therefore, a fairly strong background in mathematics and some cases physics is required by software developers to handle the programming of the toolkit with three.js, specially the meshes. For example, knowing about triangular arithmetic (Sinus and cosines) is essential. The approach to programming of the scene is as below:

1. Creating the scene, and choosing the renderer

2. Creating a simple light and camera

3. Creating the object for direct manipulation and required manipulators (the term used here as a reference to arrows, points, and lines, demonstrated on the lampshade in Figure 8-13)

4. Setting the manipulators in the correct position around the object

5. Using events for mouse inputs and defining functions for them accordingly (functions for events handling)

6. In each function from previous step, an update is needed for the location of a manipulator. An update is also required for the manipulators, which are influenced by the effect of the updated manipulator. In other words, a first update is needed for the manipulator location, which influences the object vertices and faces, and a second one for other manipulators, which change their location since the main object has changed

7. In the 'Render' function, the effect of each manipulator on the object should be defined

8. Finally setting all the geometries and objects to be updated each time when the scene is rendered simply by few lines of codes in the 'Animate' function.

Therefore, it can be seen that functions for events handling are mainly for updating the manipulators, and 'Render' function is for updating the object.

In this toolkit, a lightshade is the object, and 3 sets of diamonds, 23 cubes, and 5 lines are included as manipulators.

In making this system, many 'manipulators' (Figure 8-13) play a role in the scene, namely, diamonds, cubes, and lines. For example, when the user is dragging a diamond as a manipulator to increase a circle's diameter, other manipulators should align themselves to new locations in order to be usable in the next steps.
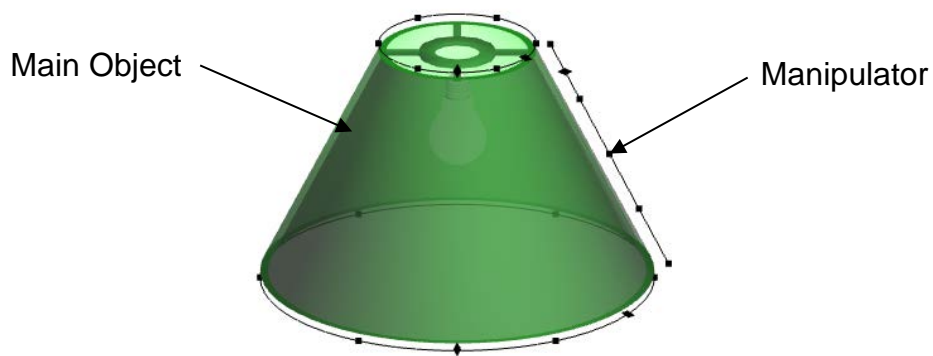

Main Object   Manipulator

Figure 0-1 A view of the toolkit's main object (lightshade) and manipulator system (diamonds, cubes and lines)

Diamonds do the whole transformations, for example, a diamond can change the top radius of a lampshade (Figure 8-14), and cubes do the partial transformations. For example, a cube can change a section of the lampshade's top circle locally (Figure 8-15).
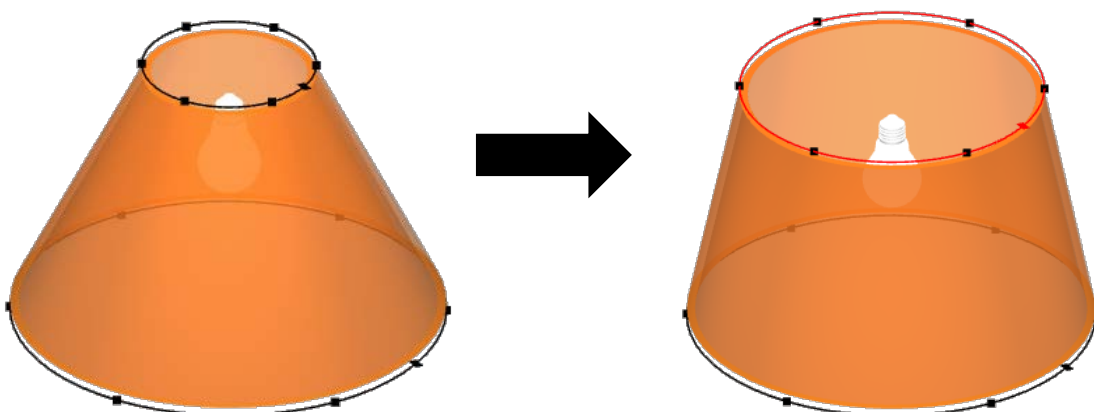

Figure 0-2 Whole transformation of radius of the top edge of the lightshade with the help of a diamond (highlighted in red)
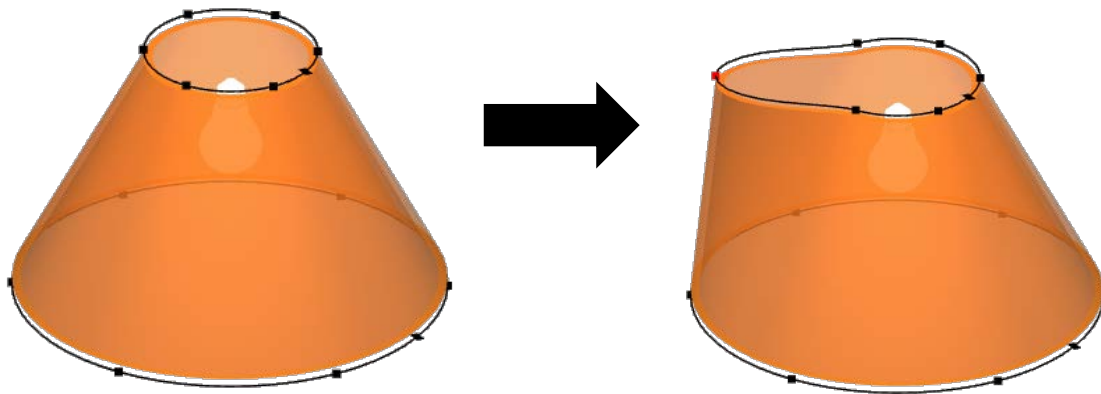
Figure 0-3 Partial transformation of radius of the top edge of the lightshade with the help of a cube (highlighted in red)

The manipulators were designed to allow whole and partial manipulation in three main directions. As the number of parameters increase, linking these manipulators with the actual object gets more difficult. Especially when a manipulator may move or change the actual object in a way that another one does the same, synchronising and therefore their movements is challenging. Therefore, the complexity of the code was where two parameters are related based on the similar manipulation they do on the object. For example, one manipulator does the job of adjusting a diameter, and another manipulator may have a similar job. Therefore, they do a similar task, but in different views/selection types and this was challenging for the author.

Most parts of the code were related to moving each vertex by a manipulator. It can be interpreted that the more mathematics knowledge the software developer has, the more complex patterns s/he can create.

Based on the findings of the first study and the workshop, the toolkit is required to provide some references for customers to allow checking the aspect ratio, harmony and size of the lightshade. Therefore, a light bulb was added to the Solution Space. It was also suggested by the author that the object must have some thickness to be 3D printed, so the object was amended to be a solid, a closed area of 4 surfaces. This also made the object more realistic when participants tried to customize their lightshade. Finally, due to roughness of circles (becoming jagged) when they are moved, more vertices were added to the lightshade. They were increased to 96 segments in the radial direction and 44 segments in the height direction to allow smooth transition when modified. In addition, the starting size of the lightshade was amended to 25 cm (height) x 20 cm (mean diameter) to represent a typical lightshade. A new equation was derived for the new lightshade with new manipulators as follows:

$$y = \left(\frac{dragged\ length}{2 * number\ of\ vertices\ to\ be\ moved\ on\ one\ side\ ^2}\right)(x)^2 \qquad \text{Equation 8-1}$$

This equation shows how the object is tuned when a manipulator is dragged. This was done by calculating y for the number of vertices, which were affected by dragging a manipulator (Figure 8-16). In Figure 8-16, the manipulated surface of the lampshade is not shown, and only the moved vertices and line were shown.
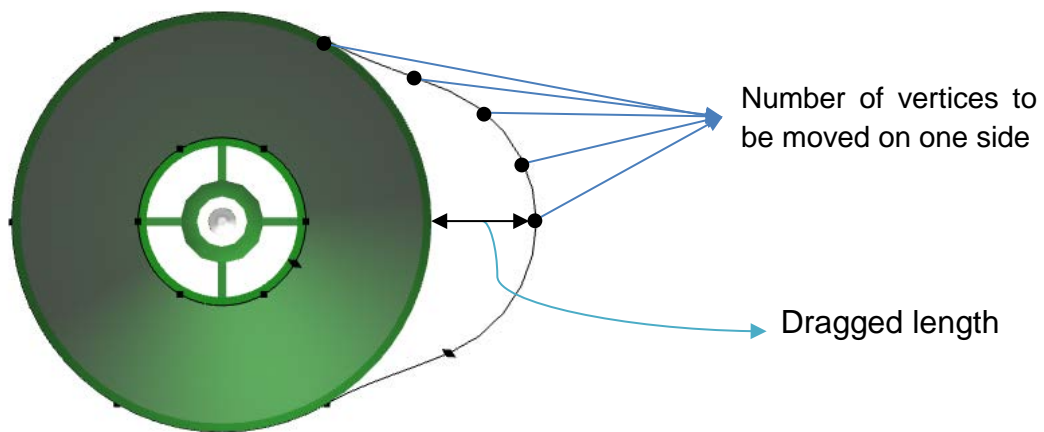

Number of vertices to be moved on one side

Dragged length

Figure 0-4 The 'dragged length'