3D Mass Customization Toolkits Design, Part II: Heuristic Evaluation of Online Toolkits

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ABSTRACT

Web-based 3D toolkits create a virtual product environment in Mass Customization (MC) sites, allowing consumers to design their own products or services. A large amount of effort has clearly been expended to build a number of commercial web-based 3D MC systems, but few studies have been conducted to evaluate them, especially their toolkit design. In this paper we take a practical perspective and apply an Online 3D Mass Customization Toolkit Evaluation Model, proposed in our previous study [25], to evaluate four commercial web-based 3D toolkits. This evaluation indicates that current 3D toolkits are still at an early development stage and there are opportunities for improvement. We therefore conclude by identifying a number of open research questions in terms of solution space design, interaction design, enabling technologies and individual differences.

Keywords: 3D toolkit design; toolkit evaluation; 3D modeling technology

1 INTRODUCTION

The key significance of Mass Customization (MC) is to provide personalized service and products to meet each consumer's needs and desires [5][13][19]. To achieve this, consumers are allowed to take part in activities and processes which used to be controlled by the companies [24]. Toolkits therefore have been widely used in industry as a medium between consumers and manufacturers. Since powerful computers, high-speed Internet and sophisticated web browsers facilitate the efficiency of developing customized products, most toolkits nowadays are computer-based and especially web-based. They allow consumers to design their own products or service by trial-and error experimentation, and also deliver immediate feedback of the potential outcome of their design ideas [13][17] [21].

More importantly, the development of geometric modelling provides the means of presenting a virtual 3D product in a mass customization toolkit. Compared with 2D graphic toolkits, 3D toolkits visually create a virtual product environment which provides a more direct interaction experience. Consumers can zoom in/out and rotate 3D models to envision the final products [5][10]. Instead of clicking buttons or moving sliders to customize the product, in certain systems consumers can even directly manipulate 3D models, which gives them a better sense of control. [1] claimed that consumers' experience in a 3D environment is similar to examining the real product in a shop. Other researchers [10] [15] [16] [23] agreed that 3D toolkits create a more satisfying experience for consumers than 2D graphic toolkits, which then helps to increase the propensity of purchase. Therefore, 3D toolkits have been considered as the trend of design communication between consumers and manufacturers [11].

However, the adoption of 3D MC toolkits is still at an early stage. Compared with 2D graphic toolkits, 3D toolkit design requires "greater understanding of customer needs, design options and 3D image representation" [10]. A number of studies showed that poor 3D visualization leads to a higher chance of disorientation or motion sickness [15] [16] [23]. In addition, consumers may have difficulties in understanding 3D virtual models [6]. To achieve effective mass customization it is therefore vitally important that the 3D toolkits are designed to elicit a satisfying consumer experience.

Despite the significant amount of effort that must have collectively gone into building the web-based 3D MC systems, few studies have worked on the evaluation of these systems, especially in terms of toolkit design. Given these considerations, this paper takes a practical perspective and presents four case studies of existing commercial 3D toolkits in the current market. This approach is designed to help us understand the mass customization industry and identify problems and potentials in existing toolkit design which, we believe, will lead us to the right directions for future research.

2 LITERATURE REVIEW

Academic works are currently quiet in establishing a widely-accepted model or criteria to evaluate existing online 3D MC systems, especially in terms of toolkit design. However, a few exceptions have been found devoting research efforts to this area, one of which is the "Human factors framework for usability evaluation of configuration system" [10]. In this framework, factors which may influence user performance and their subjective satisfaction towards the customization task have been considered. From this, they proposed three main components: User/Customer; Design Task and Web Environment; and Web Technology. Specifically, User/Customer considers individual differences in their characteristics, such as preferences, needs, gender, age or experience. Design Task and Web Environment refers to the design procedure and other features of the configuration system, such as hyperlinks, virtual environment or 2D environment etc. Web Technology evaluates the system hardware, software and network, such as the 3D tools used for control, the storage on the server etc. This evaluation model introduced the consumer and technology as two important dimensions for assessing a toolkit. However, it does not provide detailed criteria on how to evaluate them or explanations of how web technology could influence the design of the web environment.

Another benchmark study in this area is [22]'s The Customization 500. In this book, Walcher and Piller compared 500 online customization systems and evaluated them based on a Capabilities Framework, which defines three fundamental capabilities that are required by mass customization, namely: solution space development, robust process design and choice navigation. Accordingly, they identified a number of characteristics to evaluate online customization toolkits: visual features, navigation help, company help and choice options. Meanwhile, subjective evaluations such as Visual Realism, Usability, Creativity, Enjoyment and Uniqueness were also scored.

Applying this framework to 500 online customization systems, their study found that most customization toolkits are lacking in even basic Human-Computer Interaction (HCI) principle. For example, some online toolkits were found to not provide the visualization of final products, while some did not provide a guide for users to help them through the customization process. Also, a majority of toolkits were found to not allow consumers to save their current state and so they can return later to finish their design. These drawbacks certainly affect consumer experience during product customization. As a result, they negatively influence consumer's willingness to buy the product as well as the consumer's loyalty to the brand. Although this study investigated most existing online customization systems, it is more like a business review or yearbook to provide references for companies. In addition, it fails to consider the differences between 3D toolkits and 2D toolkits, so it is not specifically designed for evaluating 3D toolkits.

To fill the gap, [25] proposed an Online 3D Mass Customization Toolkit Evaluation Model to evaluate web-based 3D toolkits, which focuses on four aspects of toolkit design: Enabling Technologies, Interaction Design, Solution Space and Individual Differences. This evaluation model emphasizes the importance of enabling technologies to 3D toolkit design, especially 3D modeling technologies and web technologies, which offer features or limitations to the toolkit design. The interaction design defines the process of customization while the solution space provides the design possibilities. Since each consumer is unique, individual differences are also important to create a satisfying experience for different consumers. This evaluation model provides a comprehensive perspective to toolkit design and especially targets at 3D mass customization toolkits. In addition to general design principles, it also specifies detailed design guidelines (Fig. 1). In this paper we therefore apply this model as the criteria to assess 3D mass customization toolkits on current market.

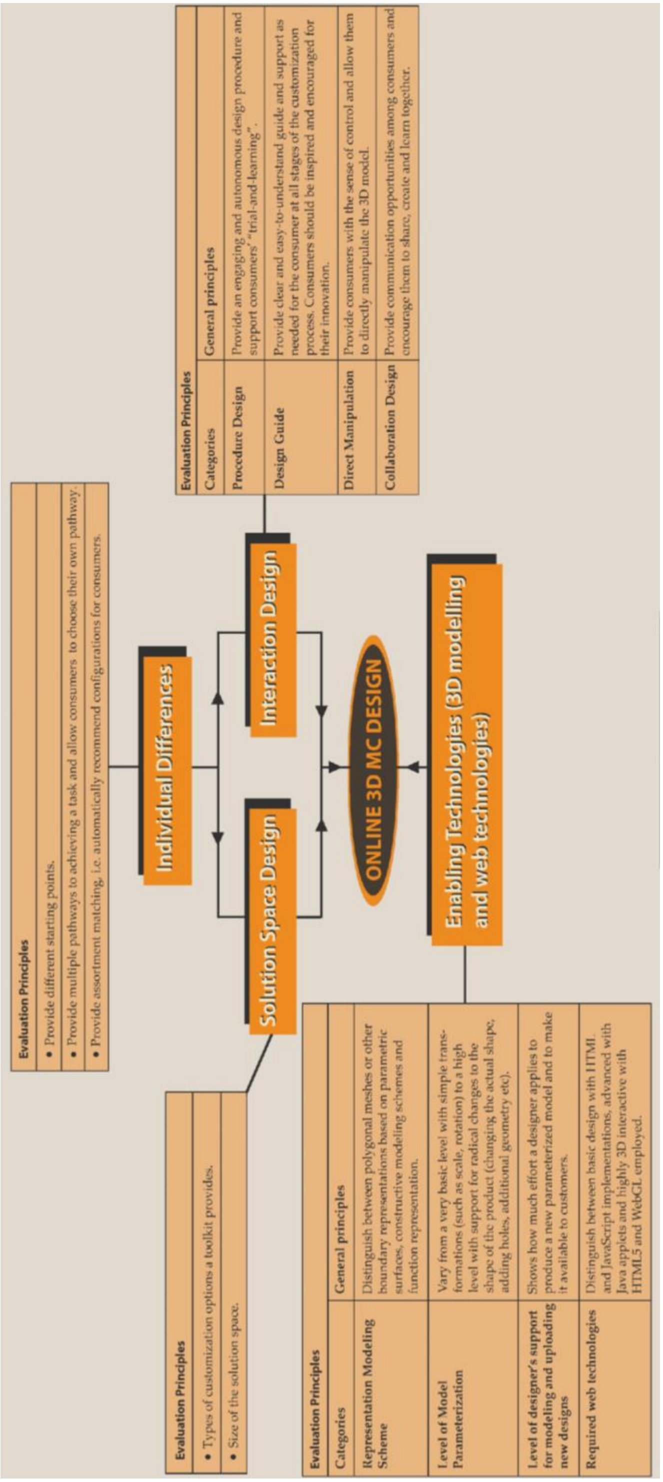

Fig. 1: Evaluation principles of Online 3D Mass Customization Toolkit Evaluation Model

3 HEURISTIC EVALUATIONS OF ONLINE 3D TOOLKITS

In order to better understand the proposed evaluation model for online 3D MC toolkit and the specific principles developed in this study, a heuristic evaluation was applied to four online 3D MC toolkits design. In this section, we will give a detailed explanation and discussion of the methodology we chose and the results of the evaluation.

3.1 Methodology

3.1.1 Heuristic Evaluation

A heuristic evaluation is an inspection technique which aims at identifying usability problems associated with the design of user interfaces by applying a set of pre-defined evaluation principles [14]. In comparison to other evaluation methods requiring user participation, such as observation, interview and questionnaire etc, heuristic evaluation relies on evaluators to inspect a user interface and identify design problems. It is an early stage evaluation technique which can help with the design of user studies at a later stage by providing early insight into problem areas that should be given more focus. More importantly, a number of studies also confirmed that heuristic evaluation helps designers to find important classes of problems that are not always found with user testing [8], [9]. Due to its flexible nature of application, heuristic evaluation has been adapted to a range of specialized domains, including game design [18] and e-commerce website design [7].

In this study, heuristic evaluation was adapted to evaluating online MC toolkit design for a couple of reasons. First, the aim of this study is to conduct preliminary evaluations of online MC toolkit design and identify their design problems. According to Nielsen [14], heuristic evaluation examines the interface and judges its compliance with pre-defined principles. It potentially identifies aspects that user studies would not while also provides a reference point to help design future user studies. Second, heuristic evaluation does not make assumptions about task structure [18], [2], it provided a flexible evaluation mechanism which helps to obtain holistic evaluation results. Third, as reviewed in Section 2 the evaluation model we use in this study covers every aspect of toolkit design, including the influence of enabling technologies, which is a specialized technical area and difficult for general user testing to evaluate. Therefore, heuristic evaluations conducted by skilled evaluators are better suited for this task. Given these consideration, heuristic evaluation was applied in this study.

Despite of the advantages of applying heuristic evaluation to a user study, the biggest limitation is that it relies on experts who have relevant knowledge and experience to execute the evaluation effectively. Therefore, it is not easy to apply the evaluation to a large quantity of mass customization toolkits within a short time, and it is impossible to make the evaluation automatic.

3.1.2 Choice of Four Online Toolkits

Four 3D online MC toolkits have been selected for the evaluation in this section: NikeID (http://www.nike.com/gb/en_gb/c/nikeid, accessed on 2/12/2016), Sandboxr (https://sandboxr.com/, accessed on 2/12/2016), Uformit (https://www.uformit.com/, accessed on 26/11/2016) and Nervous System (http://n-e-r-v-o-u-s.com/, accessed on 26/11/2016). The reason for selecting these specific sites is because they represent different approaches to MC toolkit design: Veneer, Modularity, Parametric and Generative customization [6]. Veneer customization allows consumers to customize products by adding a visual decorative layer to a product. Modularity customization decomposes the product into a set of discrete modules and then assembles them into a customized design. Parametric customization is widely used in 3D toolkits, which allows consumers to customize a product by changing specific parametric values which then change the nature of the product in some way. Generative customization creates 2D or 3D forms based on built-in generation procedure. Different approaches result in huge differences on solution space design, interaction design, and also have different requirements on the supporting technologies. Therefore, in this study we compare four different types of MC toolkits to identify the strengths and weaknesses of existing toolkit design for each approach.

As for selecting a specific website within each MC approach, our criteria are choosing the most popular one and the one which can most represent the approach. For example, NikeID is one of the most popular online customization toolkits (according to http://www.configurator-database.com/, accessed on 18/12/2016) which employs the Veneer approach (Fig. 2). It is provided by footwear manufacturing company Nike, and has set a successful business example for the traditional manufacturing industry to embrace the MC era.

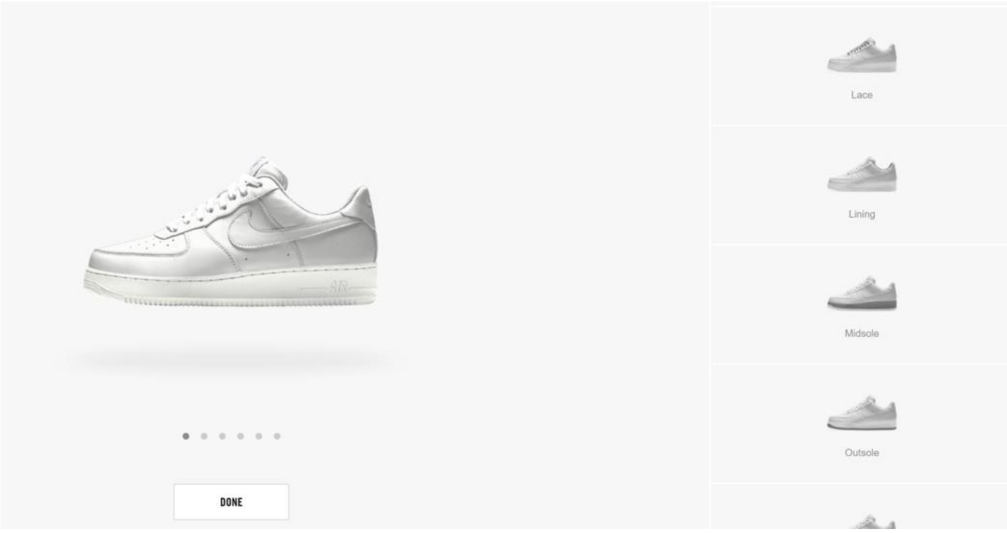

Fig. 2: The customization interface of NikeID.

Sandboxr is an online 3D MC toolkit employing the Modularity approach. It allows consumers to create customized 3D printed figures of video game characters. When Amazon launched a 3D printing service in June 2014, Sandboxr also opened its 3D printing store on Amazon. At present, the Sandboxr customization service covers different characters from a number of video games, including World of Warships, Dungeon Defenders II, etc. Here we chose NU WA from game Smite as an example to analyze (Fig. 3).

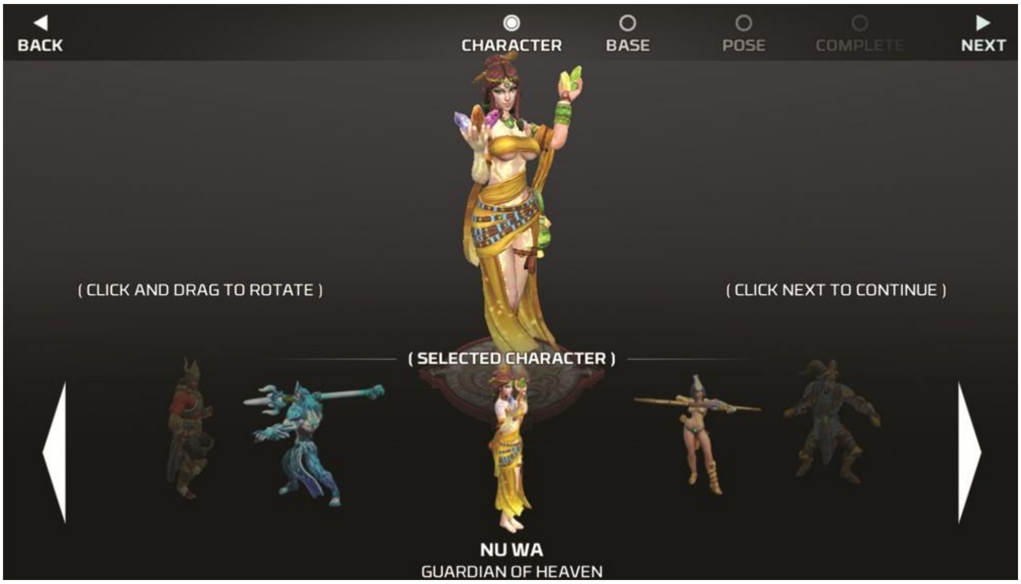

Fig. 3: The interface for NU WA on Sandboxr website.

In comparison to the Veneer and Modularity approaches, Parametric and Generative approaches have more advanced requirements on the design and technical implementation of the toolkit. There are currently not many commercially successful cases. We chose Uformit and Nervous System because they are the best to represent the Parametric approach and Generative approach.

Uformit is an online platform for customized designs of jewelry, art, accessories and ceramics. There are currently a number of products available for customization and purchase online. We chose the toolkit for customizing the Polar Pendant as an example to analyze it (Fig. 4).

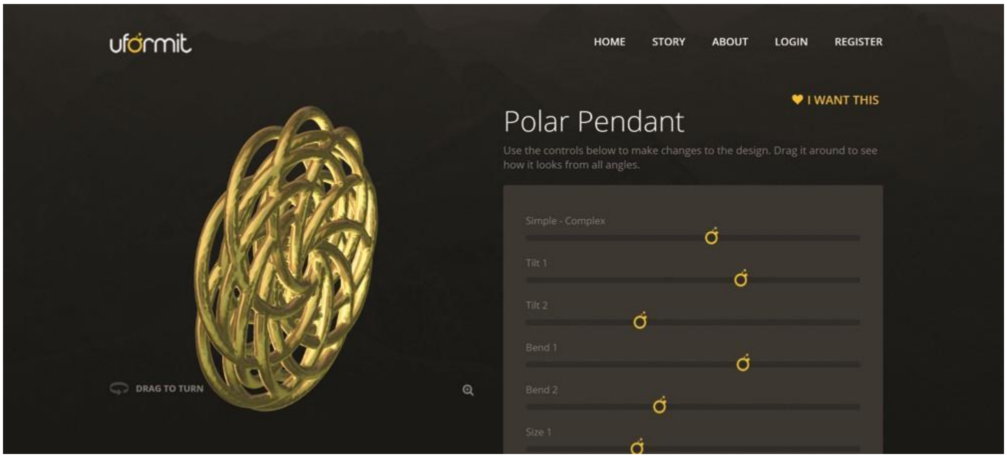

Fig. 4: The interface for Polar Pendant on Uformit website.

Nervous System is a design studio which employs a novel process that applies computer simulation to generate designs and digital fabrications. In addition to selling professionally designed artifacts on its website, Nervous System also provides opportunities for customizing products by using their online apps. Currently, there are six apps on their website, covering a range from cloth, homeware, to jewelry, accessories etc. Here we chose one of the apps – cell cycle as example to demonstrate how Nervous System works (Fig. 5).

Fig. 5: The interface for cell cycle on Nervous System website.

3.2 Results

In this section, the heuristic evaluation results of four online 3D toolkits are explained. They are categorized based on the four dimensions in according to the evaluation model [25]: solution space, interaction design, enabling technologies and individual differences (Fig. 1).

3.2.1 Solution Space

NikeID allows customers to design their own shoes which are then made to their exact specifications for performance, fit or style. On opening the NikeID website, the button ‘customize and buy’ is placed on the right hand side. Consumers can click the button and enter the customization page with a customizable shoe model set by default. Alternatively, consumers can choose a shoe model they want to customize by making decisions among different categories of shoes, for example, shoes for men or women. Under each category, there are different styles of shoe models allowing consumers to choose, such as lifestyle, football or basketball etc. After consumers select the shoe model they want to customize, it will be shown in the interface as well as all the possible customization options.

All the options in the solution space are organized into a set of categories based on different parts of the shoe, such as laces, outsole, base etc. (Please see Fig. 2). For each part of the shoe, there are normally two attributes offered for customization which are material and color. Each attribute has a number of values which allow consumers to choose from. For different shoe models, there are different numbers of options available. For example, Nike's Air Force One shoe gave a choice of 82 different materials, colors and other types of options in total.

However, the variety of option types is very limited. Consumers can only decide the color and material for each part of the shoe rather than changing the actual shape or fit of the shoes. In this sense, NikeID employs a Veneer approach to customization. Besides, most options for customization are aesthetic rather than functional except at the beginning where consumers are allowed to choose the shoe model based on different functions, such as lifestyle shoes, basketball shoes or football shoes etc.

Game characters on Sandboxr have been decomposed into different customizable parts. For example, the character NU WA contains three customizable parts: the game character, the base that a character stands on and the pose the character holds. Each part offers multiple options to allow consumers to choose from (Fig. 6). The toolkit will assemble all the parts together and print as a single piece through a 3D printer. Therefore, Sandboxr employs a modularity approach to mass customization. Although there are only three parts for consumers to customize, the options offered for each part are reasonable, for example, 16 options are provided for customizing the base of the character NU WA, and 9 options are available for her pose. In particular, for some pose options, there is a special time slider provided at the bottom of the toolkit allowing consumers to change parts of the pose in real time, for example, the hand gesture and the direction of the head, which brings more customizable varieties (Fig. 7).

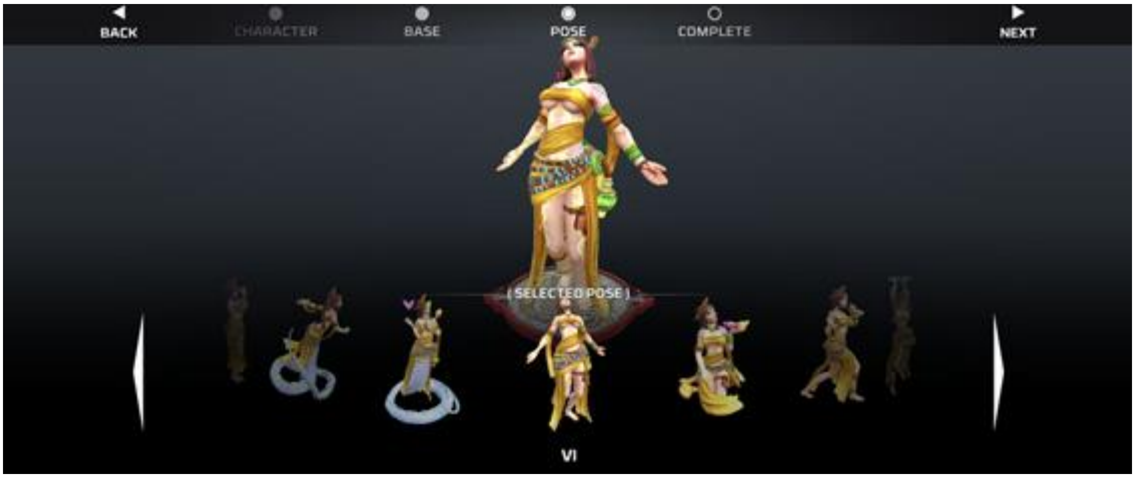

Fig. 6: Sandboxr solution space design.

Fig. 7: Using time slider for more pose options.

On the Uformit website, the Polar Pendant is a geometrically unique design created by a number of intersecting pairs of tori. The toolkit provides ten attributes to change the topology of the structure, for example, consumers can choose the ‘complexity’ which changes the number of torus pairs (Fig. 8 illustrates the effects of changing the shape from simple to complex), the tilt of each torus, the size of each torus and material etc. The sliders potentially offer continuous values to vary between, with range limits set by the designer, while the material offers a clearly discrete selection from a list of options.

Uformit follows a typical parametric approach to MC. The product is defined by a set of parameters which are related to different aspects of the product, such as structure, shape and size etc. As the value of one parameter changes, the 3D model is changed accordingly. All options for this example focus on the aesthetic aspects of the product rather than functional aspects.

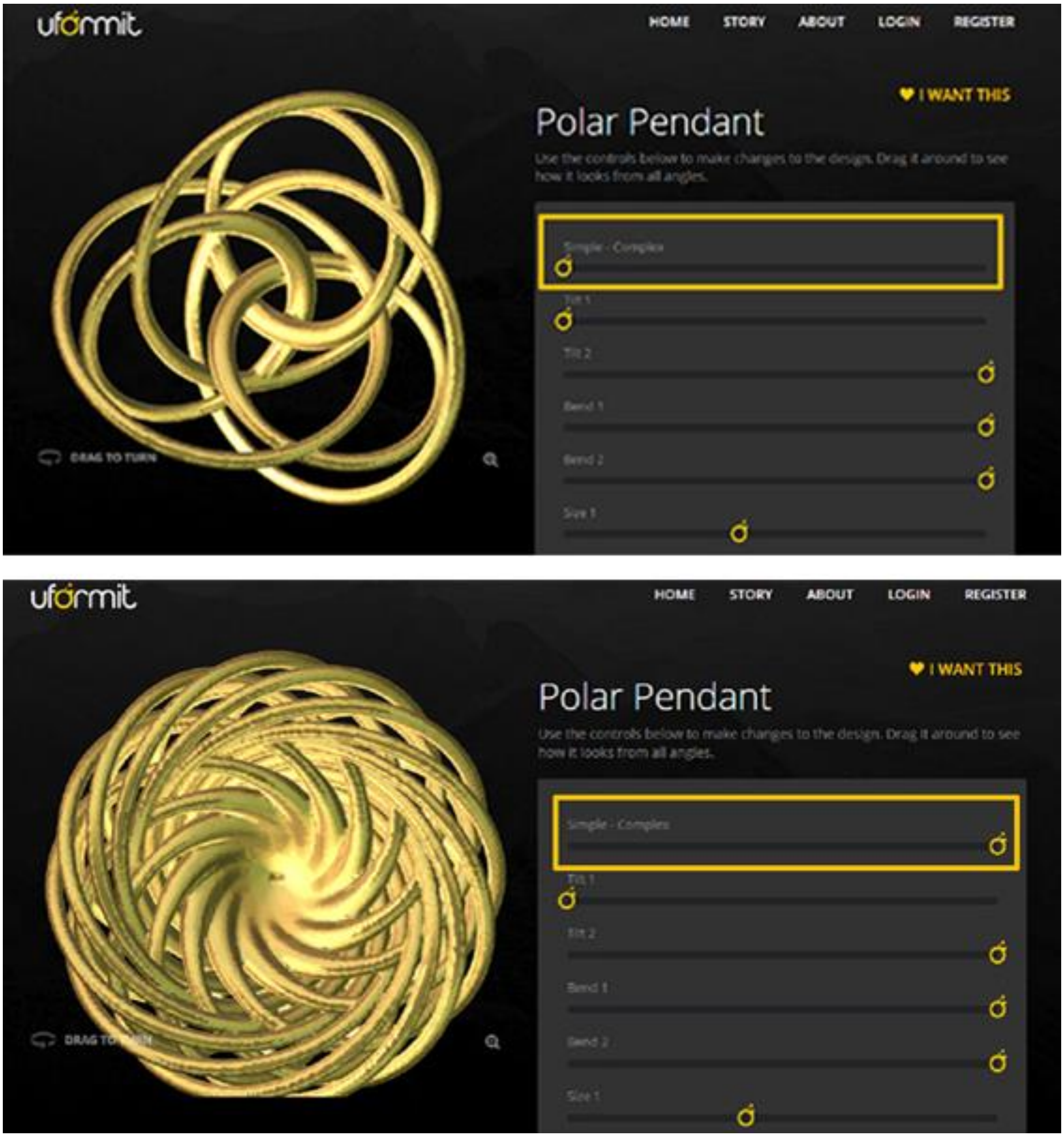

Fig. 8: The effect of changing the first parameter 'Simple - Complex'.

The cell cycle app on the Nervous System website allows consumers to change a wide range of parameters of the 3D model. Specifically, in addition to employing sliders and option lists to change the "macro" features of the product, such as product type, sizing and material, it also provides three "SCULPT" tools on the bottom left of the toolkit interface – "subdivide cells" "merge cells" and "morph structure" to allow consumers to sculpt the internal structure of the 3D model. This provides consumers with unlimited freedom to create whatever shapes they want. Therefore, the size of the solution space is vast.

3.2.2 Interaction Design

Based on the principles and guidelines of interaction design evaluation in [25] (Fig. 1), the interaction design of the four toolkits is evaluated from the following aspects: Procedure Design, Design Guide, Direct Manipulation, and Collaborative Design.

3.2.2.1 Procedure design

NikeID provides a flexible design procedure. It does not require consumers to follow a fixed order, which means consumers can customize a product at their own pace and along their preferred path. Meanwhile it provides indications to let consumers know which step they are currently in by highlighting it with a tick symbol. However, it is not clear to consumers how many steps are left for them to complete the customization. NikeID allows consumers to take snapshots of different versions of their design and to make comparisons; however, the snapshot only shows the side view of the shoe which is difficult to give consumers a full picture of the whole design (Fig. 9). Besides, the toolkit does not support consumers to properly save their designs and come back later to complete them.

Fig. 9: The 'Compare Your Designs' interface.

Sandboxr takes a different approach to NikeID and employs a pre-designed customization procedure, i.e. consumers have to follow a strict order to customize a game figure. It starts from selecting the game character that consumers would like to customize, then after each step consumers have to click the 'Next' button to go to the next step. If they are not happy with what they have done in the previous step, there is a 'Back' button available for them to go back to the previous step. In particular, a timeline is indicated at the top of the interface to tell consumers which step they are in and how many steps remain until completion. However, it does not allow consumers to save unfinished designs, and it provides no way for consumers to compare different design ideas.

Uformit provides a flexible design procedure by allowing consumers to customize the product in a flexible order. However, there are no indications to tell consumers how many steps they have completed and which step they are currently in. Uformit allows consumers to save their unfinished design to a 'Bookmark Design' collection at any time during the creative process. This allows consumers to look through their different design ideas, select the one they like and then continue customizing it (Fig. 10). Although Uformit does not provide a single window to put consumers' different designs together to compare them, the 'Bookmark Design' to some extent helps consumers to review their designs and make their decision.

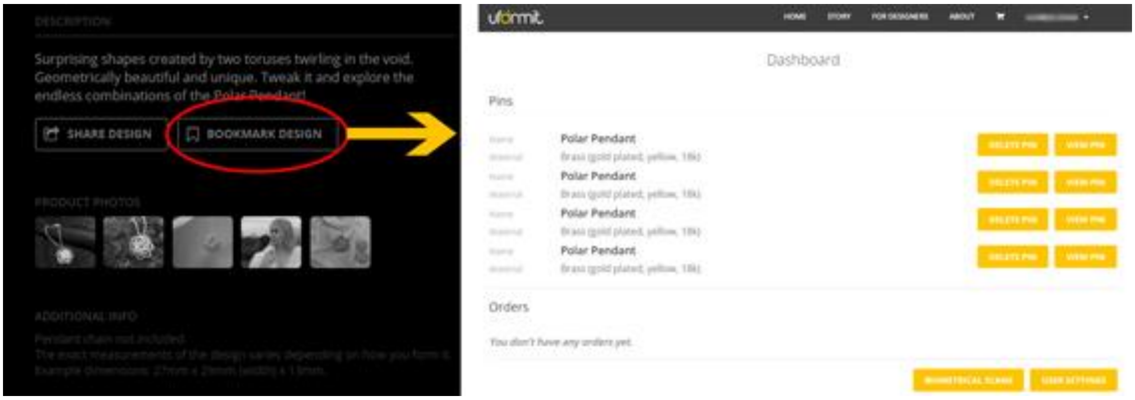

Fig. 10: The screenshot of 'Bookmark Design' interface and the "Dashboard" interface for all added designs.

The Nervous cell cycle app provides a flexible design procedure, but it does not provide enough information to let consumers know which step they are in. Consumers can name their design and save it to a database at any time. They can return later and edit the saved design to complete the order. However, the site does not provide a method for consumers to compare different versions of their designs.

3.2.2.2 Design Guide

NikeID provide a library of pre-configured models that allow consumers to choose one and customize it. It also presents a preset design at the beginning. A 'Need Help' button is also placed in the left corner. If consumers click it, a floating window will show up to explain every interactive part in the interface (Fig. 11).

Fig. 11: The 'Need Help' interface.

On the Sandboxr website, consumers can select a character to customize from the video game's character collection. Sandboxr provides a preset configuration for each character. After entering the toolkit, there are text indications to let consumers know how to interact with the toolkit, for example "click and drag to rotate" and "click next to continue" (Please see Fig. 3).

Uformit provides a preset design at the starting point. However, it does not provide a library of standard modules to allow consumers to select a module that they want to customize. Instead of making choices from a long list, Uformit's technology employs sliders to organize all the options. This helps to provide a visual priority and reduce the confusion of processing excess information. However, it does not provide any real-time help or help menu to support consumer's creativity. In addition, the wording of the parameter names is not clear and can easily cause confusion.

Nervous System also offers a preset design at the starting point of the customization process. Consumers can also choose a module from the library of featured designs or consumer-created design as the starting point which helps to inspire their creativity and focus on the aspects they would like to customize. The cell cycle app on Nervous System does not provide any help menu or real-time support, but another app 'radiolaria' which is more complicated offers a tutorial video for first time consumers, and the 'generative jigsaw puzzle' app provides a flow chart of the design procedure to help consumers understand how to customize the product.

3.2.2.3 Direct manipulation

NikeID allows consumers to customize the product through clicking buttons or selecting the part of the model they wish to customize, which then shows the relevant customization options. The user cannot directly manipulate the shoe model, such as rotate or zoom in/out to see the visual effect of their choices. Instead, they have to click a button to achieve that and a fixed set of different views are provided which can be selected between.

Consumers are free to rotate the 3D model using Sandboxr, but they cannot zoom in/out to get a full picture or get close details of the 3D model. After consumers make the decision at each step, it takes a while for the toolkit to show the outcome. A progress bar will be shown to indicate the loading progress which helps consumers to know how long they need to wait.

Uformit also provides the same freedom to allow consumers to directly rotate the 3D model at any angle and at any direction, but they cannot always zoom in and out either. Besides, the viewing experience is slightly different in different browsers. Some browsers give the user a 'zoom' option. For example, in Google Chrome there is a button to allow consumers to click and get a full image of the 3D model, but there is no 'zoom' button available in Firefox. However, the primary detrimental feature is that after consumers change the value of each parameter, they cannot see the immediate feedback on the 3D model. Depending on the complexity of the consumer's choices and the internet speed, it can take several seconds to update the 3D model.

The cell cycle app on Nervous System online platform allows consumers to directly manipulate the 3D model and modify its shape and structure. The 3D model is made up of many cells and consumers can type in different values to control the number of cells that appear. Consumers can also use the 'SCULPT' tools on the bottom left of the toolkit to subdivide cells and merge cells, or modify nodes on the morph structure to change the outline of the model (Fig. 12). Feedback of the consumer's customization changes is instant which gives consumers a strong sense of control.

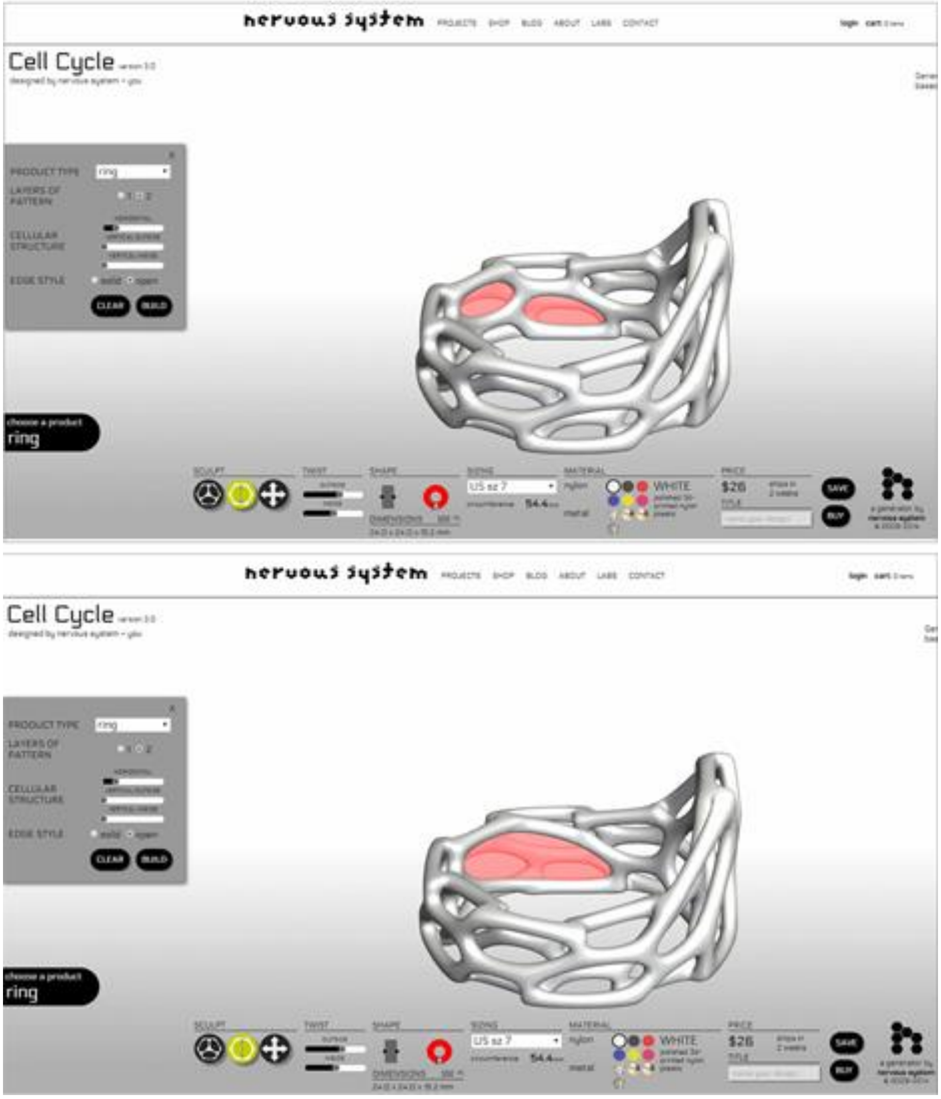

Fig. 12: The effect of two cells merging together when the ‘Merge Cell’ tool (highlighted in green color) is selected.

3.2.2.4 Collaboration design

All four online toolkits allow consumers to share their designs through external social applications, such as Facebook, Flicker and Pinterest. But none of them provides a live online community to allow instant chat between consumers. NikeID allows consumers to comment on a pre-designed shoe module that is provided by the manufacturer. However, it does not allow consumers to comment on each other’s designs. Nervous System provides a gallery of consumer created and saved designs. Similar to NikeID, consumers can download and comment on several licensed designs provided by Nervous System, but they cannot comment on any consumer-created design. Neither Sandboxr nor Uformit provide a gallery of consumers’ designs for them to share ideas or leave comments.

3.2.3 Individual Differences

Among the four toolkits, Sandboxr and Nervous System seem to target all consumers because there is no different interface design provided for consumers with different abilities, knowledge and skills.

NikeID is concerned with consumers' differences in gender and age instead of their differences in knowledge, ability and previous experience. Typically, it provides different pre- configured models for consumers of different ages and from different gender groups to customize, namely different models for men, women, girls or boys. However, for consumers with different skills or experience levels, the same solution space and interaction design is provided.

Uformit takes consumers' different skill level into consideration. It is specifically designed for consumers who are not professional designers. In other words, Uformit provides services to end users who customize a product based on existing models that have been designed by a professional designer. For professional designers, there is another special page on the Uformit website to support them to use the 3D modeling tool Symvol for Rhino (http://uformia.com/products/symvol-for-rhino/) to create a customizable product and upload their design to the Uformit website. Professional designers can either design a product from scratch in Symvol for Rhino or import a design from other 3D tools, though the mass customization features may be limited in this case. Inside Symvol for Rhino, professional designers can bookmark the parameters which they would like consumers to customize. These models can then be uploaded to the Uformit website, product descriptions and payment options added, and the products are made available to consumers. This provides professional designers with two roles where they are not only consumers, but they can also be the sellers who provide original design ideas and receive profit from selling them. This expands the possibilities of a designer, leading to a new future for designers.

3.2.4 Enabling Technologies

The four online 3D toolkits employ different approaches to customizing products, their enabling technologies are therefore different as well. A difficulty for the technical evaluation of toolkits is that very little information is available on their implementation and we have judge from the visual model appearance and toolkit's reaction to parameter changes.

The way that NikeID displays the shoe model is not actually through 3D modeling technology in the web-browser. Instead, static images of the shoes are used from a fixed set of different views to give the impression of a full 3D shoe model. The method of generating these static images could be either through manipulated photographs of actual shoes or 3D models, but this is a separate pre-build process. This approach leads to a limitation as we mentioned in "Direct Manipulation" section that consumers can only get a fixed set of views when they rotate the shoe model. The greatest limitation, however, is that consumers cannot actually modify the shape or fit of the shoe due to the fact that the shoe model is just made of 2D images rather than a real 3D model. Therefore, mass customization on NikeID can only follow the veneer approach and consumers are only allowed to change the superficial attributes of the shoe model, for example, material or color. However, one advantage of employing this method of generating models is that it saves the time of loading a 3D model which usually takes longer than loading pictures, therefore giving consumers a feeling that their interaction is instant.

Sandboxr employs traditional textured polygonal meshes as their geometric model representation. The model parameterization is limited to size selection with customization reduced to swapping pre-modeled parts of figurines. However, some figurines are provided with animated poses controlled by a single slider in the interface representing the motion's time parameter. A designer needs to model all the required parts of the new figurine and to design its motion in an animation system. From the Web technology point of view, the toolkit is quite advanced. It provides 3D model inspection via WebGL.

Uformit employs the function representation of geometric models with a high parameterization level. The number of user-controlled parameters of the model is not limited, topological changes in the model are supported by the nature of the representation. However, parameters are not dependent on each other and adding dependencies and constraints would further improve the parameterization level of the toolkit.

As explained above, designers can select parameters, which will be available to the user, during the process of creating the original product model in the Symvol for Rhino CAD system. The designed model, including the selected parameters, is saved and then can be uploaded to the Uformit Web site, where the appropriate customization interface with sliders for each parameter control is generated automatically for the uploaded model. Uformit has further extended the Web technology presented in [20]. It is an advanced toolkit from this point of view as it uses several Web scripting languages and WebGL for 3D model representation.

Nervous System uses polygonal meshes to represent geometric models. It provides a very high level of parameterization with support of arbitrarily changing model topology through the generative modeling process. Each app has to be generated from scratch by generative modeling software tools rather than traditional CAD design tools. Here, the designer has to closely work with or to be a software developer to properly implement the generative procedures in software. Nervous System is also a very advanced toolkit from the Web technology point of view, incorporating several scripting languages and WebGL.

In summary, the parameters under all four categories are tabularized in Tab. 1. A scheme is introduced to rate the four mass customization toolkits to indicate how far the toolkit design meets the requirements of the evaluation model. The meaning of the given numerical ranks is explained in each row of the table, where appropriate.

Categories	**Parameters**	**NikeID**	**Sandboxr**	**Uformit**	**Nervous System**
Solution Space	**Type of Options**	Veneer	Modularity	Parametric	Generative
	Size of Solution Space (1-A few choices; 2-Many choices; 3-Unlimited choices)	2	1	3	3
Interaction Design	**Procedure Design** (This parameter includes 6 design guidelines. The number given represents how many guidelines the toolkit follows)	4	3	4	3
	Design Guide (This parameter includes 6 design guidelines. The number given represents how many guidelines the toolkit follows)	3	2	2	3/4 (some apps provide help button, some not)
	Direct Manipulation (This parameter includes 2 design guidelines. The number given represents how many guidelines the toolkit follows)	1	0.5 (consumer can rotate the 3D product but cannot zoom in/out)	0.5 (consumer can rotate the 3D product but cannot zoom in/out)	2

	Collaboration Design (This parameter includes 4 design guidelines. The number given represents how many guidelines the toolkit follows)	1.5 (consumers can comment on licensed designs, but not on any consumer-created design)	0	0	1.5 (consumers can comment on licensed designs, but not on any consumer-created design)
Enabling Technologies	**3D Modelling Technologies**	No 3D modeling technology applicable	Traditional textured polygonal meshes	Function representation of geometric models with a high parameterization level	Polygonal meshes, procedurally generated
	Web Technologies	HTML	WebGL	Several Web scripting languages and WebGL	Several scripting languages and WebGL
Individual Differences	(This parameter includes 4 design guidelines. The number given represents how many guidelines the toolkit follows)	0	0	1	0

Tab. 1: Rating of four mass customization toolkits under four evaluation categories (the meaning of the given numerical ranks is explained in each row of the table, where appropriate)

3.3 Discussion

In this section, we analyzed and compared four online 3D toolkits based on the evaluation model proposed in [25]. The four online toolkits represent four different approaches to mass customization. NikeID employs a veneer approach which only allows consumers to change the visual decorative features (e.g. color) rather than the structure and shape of the product. Sandboxr applies a modularity approach which allows consumers to select different parts i.e. modules of the product and assemble them to design a final product. Uformit is based on parametric modeling technology where consumers can change the parametric value of a product and therefore modify either the visual features or the structure or shape of a product. Nervous System is a generative design studio that creates computer simulations or algorithms to generate designs.

The differences between the four toolkits results in different solution spaces. NikeID and Sandboxr provide option lists that allow consumers to choose the design they want. In particular, all the options in NikeID and Sandboxr are pre-determined by designers or manufacturers, which means designers or manufacturers retain the ultimate control over the design of the product. Uformit and Nervous System on the contrary offer more design freedom and creativity to consumers. Uformit allows consumers to change the parametric features of a product by moving sliders, which offers continuous values to vary between, though with range limits still set by the designer. In addition to sliders and option lists, Nervous System provides a set of tools that allow consumers to directly manipulate and modify the structure of the 3D model in real time.

The generative approach taken by Nervous System means that each of their designs is the output of a computer program. Each application on the Nervous System website therefore needs programmers to write code for their implementation, which is not easy or flexible for generating more designs in a short time. In comparison, Uformit provides a platform for professional designers to upload their designs or to generate new designs using the specific supported software. This potentially encourages more original designs from designers, expands the possibilities of a designer, and is feasible for commercial application.

Regarding the interaction design, the four toolkits manage to follow some of the guidelines identified in the evaluation model (Fig. 1), but also fail to follow others. In particular, we can see three websites (NikeID, Uformit, Nervous System) employ a flexible design procedure which allows consumers to customize the product in their preferred order and speed. However, only one website (NikeID) provides visual indications to let consumers be aware of their position in the whole procedure. Two websites (Uformit and Nervous System) allow consumers to save their unfinished design and come back to edit it later. But except for NikeID that allows consumers to take snapshots of the side view of the 3D model and compare them, none of the four toolkits provide consumers with a direct way to compare their different designs. This to some extent fails to support consumers 'trial-and-error learning process. As most consumers do not know what they actually want at the beginning of the customization process, offering a preview of the comparisons of different designs can help them make their decisions.

The four toolkits provide different levels of direct manipulation to consumers. They all allow consumers to rotate the 3D model as they wish, but none of them support real-time zoom in/out to let consumers see the full image or close-up details of the 3D model. Two toolkits (NikeID and Nervous System) can provide instant feedback after consumers make their customization choices. Depending on the complexity of the 3D model, Uformit and Sandboxr may take a little time to show the effect on the 3D model. Sandboxr applies a progress bar to make it clear for consumers about the current loading progress and how long it takes to complete loading the 3D model.

In terms of creating the collaborative co-design environment for consumers, only Nervous System provides a gallery of consumer created designs and allows consumers to comment on a few licensed designs. The other toolkits do not support any co-design or interactions between consumers. However, they do encourage consumers to share their works through external social websites such as Facebook or Twitter. This to some extent could be because of copyright concerns, which are becoming an issue for MC. The question here is who should own the copyright of a design if it is created based on another design provided by a different consumer? What is the role of the professional designer who provides the customizable design for consumers to modify? These questions are starting to attract research attention in academia [26]. In addition, protecting an individual's privacy when consumers share their designs and leave comments online is also a potential issue for MC. Therefore, creating a collaborative co-design environment is not only a technical or interaction design issue, but also a legislation issue.

Instead of letting consumers design from scratch, all of the four toolkits provide a preset design as the starting point. This helps to make the process more understandable and accessible for consumers. NikeID also provide a library of standard modules for consumers to select which help them to focus on the attributes they actually want to customize. Unfortunately, none of the four toolkits provide real-time help or guidance. However, NikeID does provide a 'Need Help' button to explain each interactive part of the interface. Uformit puts a little question mark next to some attributes and, when the mouse moves over the question mark button, an explanation will show to tell consumers what the attribute means. For one Nervous System app, an introduction video is provided before consumers enter the customization interface. To some extent whether or not to provide help or guide consumers through the customization process largely depends on the complexity of the toolkits and the target consumer groups. However, the complexity of the toolkits is normally decided by the toolkit designers or manufactures who already have some knowledge about the product and mass customization. They may be not sensitive to consumer's confusion and questions. Therefore, we argue that providing guidance and support at all stages of the customization process without distracting consumer's attention is necessary.

Providing an adaptive approach to toolkit design ensures the usability and accessibility of toolkits for consumers with different skills, experience and knowledge. However, the toolkits we have examined in this study fail to consider this aspect of toolkit design. The one possible exception is

Uformit, which provides different interfaces and tools for ordinary consumers and professional designers. However, this does not provide an adaptive approach to integrate all different approaches in one toolkit, which means different consumers must access through different interfaces to meet their requirements. The Uformit online toolkit can only be accessed by ordinary consumers who wish to co-design their product. For professional designers who want to submit their original design for other consumers to customize, they must use particular modeling software to build their customizable product and then access Uformit through an alternative interface to upload their designs. To some extent this violates the true meaning of a toolkit being adaptive to individual differences and does not consider individual differences among the actual consumer group. However, mass customization is currently still at an early stage of development. Technical limitations and the lack of proper design strategies means that an adaptive approach to toolkit design is currently still just a theory. It is expected that future toolkits will meet different consumer's needs and requirements.

4 CONCLUSION AND FUTURE WORK

In this paper, we have applied an evaluation model to assessing four representative online 3D toolkits – NikeID, Sandboxr, Uformit and Nervous System. It reveals that despite a fair amount of efforts that have been devoted to theoretical research, current 3D toolkits are still at an early development stage and a number of research questions need to be addressed as directions for future research.

The evaluation model employed in this paper attempts to provide a comprehensive understanding of 3D toolkit design from four aspects: consumer, solution space, consumer-toolkit interaction and technological support (Fig. 1). Specifically, individual difference, solution space, interaction design, 3D modeling technology and web technology constitute the key dimensions for evaluating 3D MC toolkits. Previous research has found that individual differences in knowledge, skill, creative talent and previous experience require different design strategies for solution space design and interaction design [3], [13]. Despite a number of studies suggesting how to adapt toolkit design to different consumers, few efforts have actually been made to apply them into practice. Therefore, research questions that we suggest should be considered in terms of individual differences include:

- In addition to knowledge, skill, creative talent and previous experience, what other individual factors would influence toolkit design? For example, gender? Age? Income?
- What is the best way to discover individual differences, especially for new customers? An explicit approach, for example, could directly ask the consumer's gender or preferences but would violate the interaction flow and also give the consumer a feeling of being investigated.
- Given a set of identified differences, how should the toolkit adapt itself to best suit these?

Solution space design is understood as all the possible designs a toolkit can provide. Specifically, the size of the solution space and the types of options are two main concerns. The size of the solution space has attracted lots of research attention in recent years which leads to two different opinions: some researchers argue that the more options the solution space provides, the more enjoyable and creative the experience can be [4], [12], while others are cautious about the 'mass confusion' caused by overloaded customizable options [13]. Here we argue that the size of the solution space is not a single dimension. It is influenced by a number of factors, such as the type of product and the approaches of customization. For example, the size of the solution space for customising a laptop would be different from the size of the solution space for customizing a cup. Similarly, the number of options for customizing the aesthetic aspect of a product may be different from the number of options for customizing the functional aspect of a product because the function of a product may be restricted from a practical purpose as well as safety or legal concerns. Given these considerations, we suggest that future research questions which should be considered for solution space design include:

- What are the factors that influence the size of the solution space?
- What are the efficient ways of organising options for different customization approaches, i.e. Veneer, Modularity, Parametric and Generative approaches to avoid mass confusion?

- What auxiliary information should be provided to help consumers understand each customizable option, e.g. how to interact with it and what effects it will bring to customizing the product?
- Considering individual differences, what is the best way to adapt the solution space design to different consumer's needs and preferences?

Interaction design refers to the process of the consumer interacting with the website and customizing the product. In the evaluation model, guidelines from aspects of procedure design, design guide, direct manipulation and collaboration design have been considered and applied to evaluating four representative 3D toolkits. The results of evaluating the interaction design of four toolkits agree with [22]'s research conclusion that most MC toolkits are lacking in basic HCI principles. Therefore, we suggest the following research questions for future research in interaction design for MC:

- What HCI principles should be followed by mass customization toolkit design?
- What support can be provided to the consumers to help them understand the process of interaction and customizing the product?
- What are the effective ways to encourage consumer's interaction and creativity while customizing the product?
- Considering individual differences, what different interactive strategies can be applied to difference consumers or consumer groups?

The design of a toolkit is closely related to technical development. In particular, 3D toolkit design is a special area which is quite different from 2D toolkit design in terms of the visual representation of products and the way consumers interact with the toolkits. Therefore, 3D toolkits bring different experiences to consumers when compared to 2D toolkits, which also have higher requirements for the technical support, especially for the development of 3D modelling and web technologies. Different technologies bring different capabilities and restrictions to toolkit design, many of which can only be improved by technical breakthroughs in the future. Therefore, future research questions in terms of enabling technologies include:

- What are the most intuitive interface elements for an MC model and how can they be supported by the modelling representation scheme? From a technical standpoint, one of the easiest ways to technically provide access to a model's parameters is through slider interface elements, but this is not necessarily the most intuitive from the user's standpoint.
- How can MC interfaces make better use of established and emerging technologies and portable devices, including touchscreen, gestures, or VR?
- How could a collaborative interface be presented for MC, reflecting requirements and views of different audiences? This would allow a professional designer and client to look at the same artefact but see them in different ways and interact with them through a different interface in different ways.
- Given recent advances in multi-material 3D printing hardware and supporting model representation schemes, how can a viable and intuitive interface be made for multi- material products and how can these be made available for MC?

This study helps us understand the current state of MC research especially in terms toolkit design in academia. However, most current studies take a theoretical approach rather than an empirical approach to propose their research findings. In other words, researchers draw their conclusions based on their knowledge in related areas (e.g. HCI, psychology etc.) or their analysis of a few online MC toolkits rather than actually observing consumers using toolkits to customize a product or testing their findings on consumers. Therefore, in the future, we expect to conduct user studies to test what we find in this study and conduct empirical studies to discover the answers to the research questions we proposed above. In the end, we hope to construct comprehensive and systematic design guides for online 3D mass customization toolkit design.

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