Personalization Process of 3D Printed Products using Parametric Design

Juan Madrigal[1], Seongwon Jeong[2*]

[1]Department of Mechanical Information Engineering, Student, Seoul National University of Science and Technology, Seoul, Korea

[2]Department of Mechanical Information Engineering, Professor, Seoul National University of Science and Technology, Seoul, Korea

Abstract

Background Personalization is considered one of the latest trends in the market which aims to satisfy the diverse user needs to increase the competitiveness of products. To achieve personalization, designers must involve the users in the process of product design. However, traditional design and manufacturing techniques are found hard to be adapted for constantly changing user requirements. In this study, a personalization process of 3D printed products using parametric design is proposed to reduce the designer's involvement and to give control to the user during the product design process.

Methods First, the definition of personalization, its characteristics, and importance were presented. Second, current personalization processes were analyzed and the key elements for achieving personalization, user involvement methods, and strategies were studied. Third, based on the literature review, an improved personalization process was proposed. Fourth, to validate the efficiency of the new process, a case study for designing a real product was presented. The case study required the development of a parametric design algorithm for lampshade design and an interface so that a number of users could manipulate the design parameters through an experiment. Fifth, interviews were conducted after the experiment to evaluate the design experience of the participants. Sixth, by analyzing the results of the interviews, personalization efficiency and user satisfaction were measured.

Results This thesis proposes an improved personalization process for the design of 3D printed products by using parametric design. The case study validates the achievement of personalization and user satisfaction from the new process. Additionally, parametric design shows that it not only improves the personalization understanding of the designer and users but also enhances the creativity of the users in their designed products. For future works, we would like to test the new personalization process in different types of products, since the design and manufacturing parameters vary from one product to another, which could affect the personalization process efficiency.

Keywords Parametric Design, Personalization, Product Personalization, 3D Printing Products

*Corresponding author: Seongwon Jeong (swjeong@seoultech.ac.kr)

Citation: Madrigal, J., & Jeong, S. (2022). Personalization Process of 3D Printed Products using Parametric Design. *Archives of Design Research, 35*(4), 31-47.

http://dx.doi.org/10.15187/adr.2022.11.35.4.31

Received : Jun. 14. 2022 ; **Reviewed :** Jun. 28. 2022 ; **Accepted :** Aug. 08. 2022
pISSN 1226-8046 **eISSN** 2288-2987

1. Introduction

Personalization is considered one of the key elements in the current Industrial Manufacturing trend, aiming to satisfy the individual needs of the users. It can be defined as “the combined use of technology and user information to tailor” products (Fan & Pole, 2006). Compared to current product variations, personalization entails changes in the basic structure and product features to adapt to the user's needs (Zhang et al., 2021).

The importance of personalization relies on the gradually increasing competitive market and constant changes in the users’ expectations for manufactured goods (Mesa et al., 2019). Manufacturers are using personalization as a strategy to add value to their products and to distinguish themselves from the competition (Torn & Waneker, 2019). Hence, by offering the possibility of personalized features, users tend to feel more valued and consequently, engaged with the product.

For personalization purposes, Additive Manufacturing (AM) allows the realization of highly varied products with the capability of producing them directly from a CAD model into a physical object (Javaid & Haleem, 2019). AM has shown to be an efficient technology to produce single parts with unique features defined by the user specifications.

AM technology, by eliminating limitations of traditional manufacturing processes, enables designers to build complex structures with improved efficacy and to produce highly customized products (Shukla et al., 2018). AM is used for different purposes such as elaboration of mock-ups that help the generation of ideas in the product development, multiple prototyping to assess ergonomics on designs, or, for the production of final goods when designs are highly complicated or under specific user requirements (Kermavnar et al., 2021). In comparison to other manufacturing processes, AM does not require special tooling for product variations (Durakovic, 2018). Thus, small productions of single units can be manufactured without extra cost. Although AM is not a comparatively cost-efficient solution if the geometry is designed for mass production (Khorram et al., 2019), it has a much higher potential for personalization and complex geometries when compared to conventional manufacturing.

Various studies indicate that involving the user in the design stage is critical to achieving personalization (Daher et al., 2018) since it helps to identify the expectations and individual needs to consider during product development. In design, this user’s expectations can be defined as requirements. These requirements work as an input in the design process, and usually, they are constantly changing. Traditional CAD design techniques might find these constant variations an inconvenience since the design model would have to be updated every time there is a modification (Stralen, 2018). On the other hand, design techniques such as parametric design (PD), are characterized for updating design models in real-time as parameters are modified (Barrios, 2006). This characteristic can reduce the time for decision-making in the design process for both designer and user. Therefore, it can be said that PD design could play a major role in achieving personalization.

PD is an algorithm-based design, where the relationship between the design elements is defined as parameters and can be modified in order to create complex geometries and structures (Eltaweel & SU, 2017). One of the advantages of PD is the simplicity to create algorithms with simple arithmetical operations. Another advantage is that it allows designers to control and iterate for solutions to their design requirements (Oxman, 2017). By modifying the design parameters, the users can design their own geometries and structures in design-oriented products.

This study focuses on the user's involvement process in the design for personalization, using PD. For this study, the process of personalization was established based on previous studies from different authors. Then, a new personalization process using PD was presented. To evaluate the proposed process, an interface and a PD algorithm were developed, and finally, an experiment was executed to validate the effectiveness of the personalization process.

2. Product Personalization

Personalization is an emerging trend in manufacturing by which manufacturers attempt to maintain a high production efficiency while the users can adapt products to their individual needs (Berry et al., 2013). Through personalization, users can acquire a sense of attachment to the product, extending their product lifetime (Saniuk et al., 2020). Therefore, it is expected to be one of the key drivers for the next transformation of the worldwide economy (Wang et al., 2017).

As shown in Fig. 1, the manufacturing paradigm has changed through the years, from mass production to mass customization, and eventually towards the production of personalized products. While medical and ergonomics industries are pioneering the application of personalization techniques, more industries are expected to adopt this new trend to better serve users and increase their satisfaction levels.

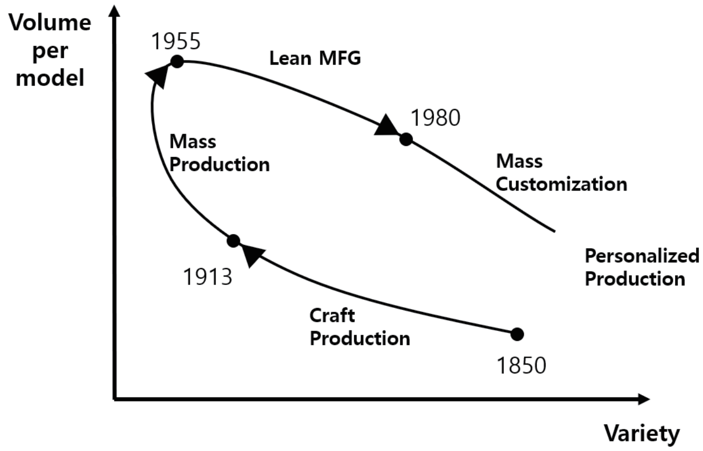

Figure 1 Historical manufacturing paradigm volume–variety relationship (Yoram, 2010).

To achieve personalization, it is crucial to design products from the user's perspective. Compared to customization, personalization satisfies individual needs on a user level, while customization differentiates products for solely market segment purposes (Tseng et al. 2010). Designers must start focusing on a collaborative interaction with users during the design stage since the design is a critical stage to achieving user satisfaction in the personalization process (Konieva et al., 2019). Also, they must consider user's preferences and how users like to interact with the product and between themselves; how to personalize products and services to user needs while making products in a single-unit batch while keeping mass production cost; and how to design systems that can collaborate and adapt to improve product quality, process reliability, system agility, and sustainability of the systems realization ecosystem (Jiao et al., 2021).

Although personalization has certain real-life applications already, the reality is that the implementation of personalization in products is limited by the traditional manufacturing processes. Since personalization aims to satisfy each user's unique and individual needs, it is difficult to achieve production efficiency and cost-effectiveness. However, the emergence of new manufacturing techniques such as AM provides the capability to manufacture personalized final products with low production volumes at a feasible cost (Lacroix et al., 2021). AM eliminates the limitations of traditional methods of manufacturing by enabling designers to build simple and complex structures with a high level of personalization.

3. Personalization Process and User Involvement

There are several design-centered processes for the development of personalized products that have been proposed. Tseng M.M et al. formulated a product ecosystem for personalization based on a design platform and user participation (Tseng et al., 2010). The author proposed that a product ecosystem for personalization must involve three elements: the infrastructure of the product, the components that can be modified, and the soft characteristics of the product. These soft characteristics address user experiences such as the service process, ergonomics, and aesthetics.

Kaneko K. et al, proposed design methods for personalizing products and services (Kaneko et al., 2018). The author analyzed different personalization cases and extracted strategies from the patterns found in his research. According to the study, ten strategies can be applied to successfully achieve personalization. The study presented a design process based on those ten strategies.

Another case is from Ozdemir M. et al. who presented a personalization framework for a saxophone mouthpiece. The authors established a design space where all the ranges of variables were predefined, and each user is able to co-create the product by making changes to predefined variables (Ozdemir & Cascini, 2020). Although this study was limited to saxophone mouthpiece production, the adopted model established by the author shows potential for the personalization of other product families.

It can be observed that the application of personalized processes is currently being applied in many sectors, such as medical and automotive applications (Alfaify et al., 2020), and also, that there are several ways to apply personalization to various products of different natures.

After the analysis of other personalization processes, we present a new personalization process where PD is considered an efficient tool for user involvement during the design process.

4. Parametric Design and Personalization

Current development in CAD tools has changed the traditional way of design in manufacturing. Nowadays, the designer can design through algorithms and scripts to develop more efficient and unique solutions for 3D models (Wassim, 2013). One of the most popular computational design techniques is known as PD. It can be defined as an algorithm-based design, where the relationship between the design elements is defined as parameters and can be modified to create complex geometries and structures (Sun & Huang, 2019).

PD technique has gained popularity among designers in different fields due to its practicality and facility to generate multiple design proposals in a short amount of time (Harding & Sheperd, 2017). PD is characterized by the simplicity to create visual algorithms with simple arithmetical operations, allowing designers to rationalize, control, iterate, analyze, and search for solutions to their design requirements (Tedeschi, 2014).

The generation of various design models in a short time by using PD can be translated as a time reduction when elaborating several design proposals and consequently a reduction in the design costs. It also allows enhancing the creativity of the designer by exploring the relationship between the design parameters in real-time. Additionally, since it is an algorithm-based technique, a PD model can be reused in future solutions, shortening the time of development for new products.

However, PD has some limitations. Since it is not as intuitive as traditional CAD tools, additional training is required for designers to fully utilize PD. Designers who do not have programming knowledge might have difficulties at the beginning of the learning process. Also, without proper planning and identification of parameters, it might be hard to modify the PD algorithm once it is defined. These limitations are highly related to the designer's skills, and it might take some time to improve this ability. Therefore, some designers still prefer traditional design techniques over PD.

5. New Process of Personalization

5. 1. Characteristics of the current personalization process

There are several studies proposing diverse personalization processes. Some of them include the logistic and A/S stages (Tseng et al., 2010; Jin et al., 2018), while others include manufacturing and cost strategies (Zhang et al., 2020). However, all of them have one characteristic in common which is to include the user in the product design process. In order to focus on the design stage of personalization, in this study, Kaneko's model was selected since it represents the conventional way to involve the user in the design process (Kaneko et al., 2018).

Kaneko et al. proposed a design method of a personalization procedure shown in Fig. 2. In this model, the process starts by identifying the target user. Once identified, the personalization provider obtains the user's personal preferences and information from a readout and validates them with the user. If the user approves, then the provider sets the goals of the personalization and defines the requirements. Based on the user's opinion,

the provider generates solutions per the requirements. Once the user finalizes the product features, the provider can release the final solution for product production.
According to the authors, the key element in this procedure is the feedback step, which is when the user can judge whether the proposal suits the user's preferences. However, a repetitive cycle of feedback and modifications might hinder the entire personalization process. This method presents a challenge for designers if the user changes the preferences and requirements multiple times. A modification in requirements of previous stages may alter the initial design and, the process would have to start again from the beginning. These multiple interactions represent a potential increment in time and resources

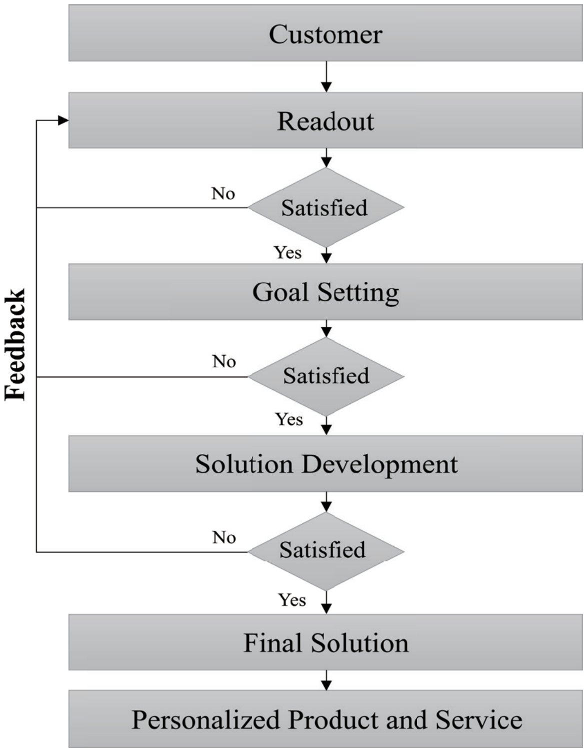

Figure 2 Traditional personalization process.

5. 2. Improved Personalization Process

In this study, the proposed personalization process is based on the proposal made by Kaneko (Kaneko et al., 2018) since it represents clearly the user involvement in the personalization process. Its main difference from the aforementioned model is the simplification of the user's interference during the personalization process by implementing PD techniques and the automation of the product design every time there are changes in the initial requirements.
The model of the new process is shown in Fig. 3 and goes as follows: First, the designer must define the product grammar which includes the features and associations describing the appearance of a product. This is a crucial step since it defines the scope of the entire design algorithm. For example, if the target product to personalize is a bottle, it can't be expected to have a personalized dish as an output. Therefore, there must be a clear idea of the product to personalize. Otherwise, the PD model will become too complex and inefficient.

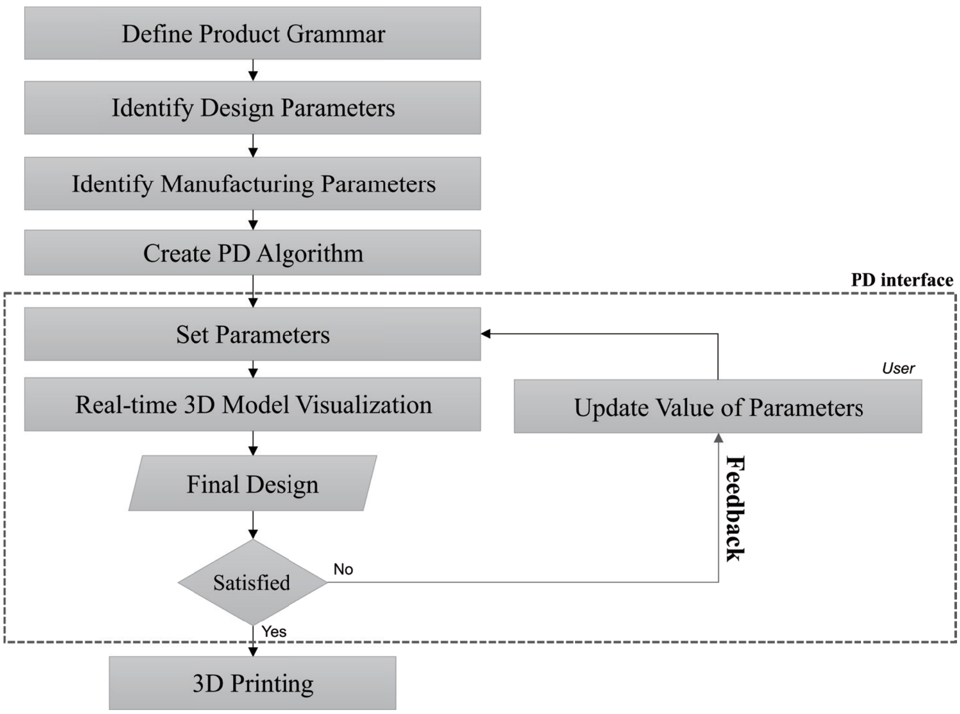

Figure 3 Improved personalization process using PD.

Once the product family is defined, the designer can proceed to identify the design parameters. The parameters will vary according to the nature of the product and they will be updated by the user later on. These parameters are mainly related to the structure, surface, dimensions, and aesthetics of the product.

Also, manufacturing parameters must be identified and defined. These will depend on the AM tools that the manufacturer would use to produce the final product. These parameters would be related to the type of materials, platform dimensions, minimum thickness, etc. The major purpose of this step is to avoid going through the whole design process and not being able to manufacture the final product due to the manufacturer's infrastructure.

Once the design and manufacturing parameters are defined, the designer can proceed to create the PD algorithm. This is where the relations between the design and manufacturing parameters will be defined to obtain the personalized product. The algorithm will allow the manufacturer to automate the model's design while parameters' values are modified.

The next steps are part of a section called PD Interface. In this section, the user will be involved in the design process. Initially, there are default parameters defined by the designer while the 3D model output with these parameters can be visualized by the user through the PD interface. As seen in Fig. 3, there is a direct connection between the 3D model and the final design, which means it is possible to visualize the final design even though the values of the parameters are yet to be modified. Therefore, if the user is not satisfied with the predefined value of the parameters, the user can update their values and visualize the 3D model in real-time. This process can be repeated as many times as necessary until the user is satisfied.

The PD interface consists of an interface where the user can visualize a 3D view of the product design and manipulate the parameter values through controls. If the user requires to change the design, he will be able to manipulate the parameters through the interface, and these updated parameters would be sent to the PD algorithm. Every time there is an update in a parameter, the changes will be reflected in the 3D visualizer. This process would be iterated until the user finalizes his preferences on the product.

Once the parameters' values are defined and the user is satisfied with the final design, the 3D model file can be generated, and the manufacturer can proceed to produce the personalized product.

The main characteristics of this personalization process are as follows:

- Giving the user control over the design process through an interface by using PD techniques.
- Reducing the number of interferences that might be caused by changes in users' preferences in the product development stages.
- Automation of the final product visualization whenever there is a change in the design parameters made by the user.
- Generation of a three-dimensional model considering manufacturing parameters for 3D printing using PD.

6. Case Study: Applying the new personalization process to a design example

6. 1. PD Interface and its algorithm

To verify the implementation of the proposed process, an experiment was organized for the design of patterned lampshades. The objective of the experiment was to prove that personalization is easier with PD by evaluating the satisfaction and variety of products generated by the users.

For the product grammar, the product to personalize was a lampshade. Lampshades are a good example of personalization due to their flexibility in varying shapes, geometries, and patterns while they have familiarity with regular users. Personalized lampshades are commonly priced in a higher range when designed by specific requirements and their manufacturing volumes are lower. Therefore, it was chosen for the purpose of this study.

(1) Building the PD Interface

The PD interface for this case study was developed in combination with Python and Grasshopper. The part of the PD interface in charge of the control of the parameters can be seen in Fig. 4a while in Fig. 4b the visualization of the lampshade is shown. The PD interface consisted of two main parts which were the geometry and pattern sections. In each of them, some controls allowed the user to set the value of parameters freely without a specific order or sequence. Also, there was an area that allowed the users to sketch in case of wanting their own shapes for both geometry and pattern over the predefined options. All these changes in values through the PD interface were immediately updated and sent to the PD algorithm in Grasshopper so that the user could visualize the lampshade 3D model in real-time.

Figure 4 a) PD Interface. This screen shows the section to control the parameters. b) Lampshade 3D model visualization.

(2) PD Algorithm

For the development of the PD algorithm, Grasshopper software was used, which is a graphical algorithm editor integrated with Rhinoceros 3D modeling tools. In Fig. 5 it can be appreciated part of the PD algorithm developed for our study.

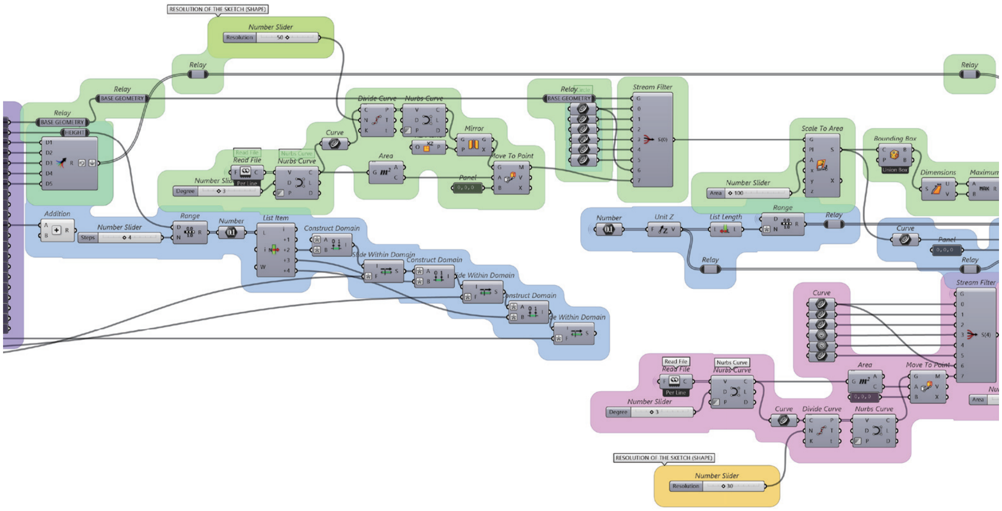

Figure 5 A part of the PD algorithm generated in Grasshopper.

Table Two main categories of parameters for Lampshade Personalization.
The algorithm initially retrieved all the default values that were sent from the PD interface. The first section of the algorithm defined the geometry shape and generated the surface of the lampshade. The user had the option to choose among predefined shapes for the base of the lampshade. In case the user wanted something more unique, the user could draw their own sketch, and, through image processing, a curve could be obtained. Once the surface was generated, the geometry parameters that defined the shape of the lampshade in Table 1 could be modified, allowing the user to generate various forms.

Table 1 Two main categories of parameters for Lampshade Personalization.

Geometry Parameters	Pattern Parameters
	–Scale Pattern Element
–Base's Geometry	–Rotate Pattern Element
–Height	–Number of Rows
–Layer Dimensions	–Number of Columns
–Layer's Vertical Distance	–Horizontal Shifting
–Thickness	–Culling Index
–Twisting Angle	–Shuffling Index
	–Ascending/Descending Pattern

The second section consisted of the pattern configuration. Same as the geometry, the user was able to select among predefined elements for the pattern or to draw their own. The pattern was generated by placing elements on a grid with rows and columns, and the user was able to modify the related parameters in Table 1. Depending on the size of the element, the algorithm automatically limited the maximum number of rows and columns of the grid to avoid design errors.

Finally, the third section was in charge of the visualization of the lampshade. This section showed all the user specifications and the generation of a three-dimensional model for 3D printing. In the case of the manufacturing parameters, the ones that were considered were thickness and maximum dimensions according to the 3D printer tolerances. Once the user finalized the design process and achieve a satisfactory design, by clicking a "Finish" button, the PD algorithm automatically generated a three-dimensional model ready to be exported and prepare for printing.

6. 2. Method of Experiment

One of the main objectives of the study is to prove that personalization can be achieved through PD. Since this is not easy to measure through quantitative analysis, two groups of variables were defined: PD efficiency for Personalization and Personalization efficiency for product design.

In the case of PD efficiency for Personalization, there were two types of variables to be measured which are quantitative variables such as time and number of parameter changes, and user satisfaction which consists of some questions related to the interaction process with the PD interface using the 5-point Likert scale.

For the case of Personalization efficiency for product design, the main variables to measure were the easiness of the personalization process and user satisfaction with their lampshade designs. For this case as well, the 5-point Likert scale was used to evaluate the participants.

The experiment was conducted in two phases. The first phase consisted in testing the interaction PD interface for personalization with two users to obtain some feedback on the parameters and the PD interface manipulation. Once the improvements were made, the second phase was executed, which consisted in testing the PD interface with twenty participants and analyzing whether personalization was achieved through an interview.

6. 2. 1. Pre-experiment

For this phase, two participants were invited to experiment with the design PD interface. Both participants were given a short explanation of the purpose of the study and how the interface work.

The whole experiment per participant took around 30 min and each of them generated an output. After they finalized, they were asked to give feedback on the PD interface and design visualization to improve the personalization experience.

6. 2. 2. Main Experiment

For the second phase, participants were selected without considering specific requirements or characteristics since the study aimed to target common consumers. Participants were in the range of 20 to 30 years old and had different educational backgrounds. Among the participants, twelve of them had experience with some sort of design, and eight of them had never used design software.

First, a computer was set with two monitors; one monitor displayed the PD interface, and the other one the design software. Before starting the experiment there was a short introduction given to the participants to understand the purpose of the study and a brief explanation of the PD interface was given. After that, the participants were able to design their personalized lampshade without any indication or special instructions within 30 minutes. The beginning and end of the experiment were registered for each participant. Once the experiment was finished, the participant was asked some predefined questions about their experience and their design output was saved.

6. 3. Analysis of the results

6. 3. 1. Parametric design efficiency for personalization

As for the quantitative analysis, the average time per design was 10 minutes and 9 seconds, and the average total number of changes in parameters per participant was 33, meaning that within ten minutes participants could visualize more than thirty-three different lampshades until reaching the one that satisfied their preferences. Twenty lampshade designs were generated by the participants. Six of the final designs of the participants are shown in Fig. 6. It can be seen that the designs vary one from each other in both shape and pattern, reflecting the core purpose of personalization.

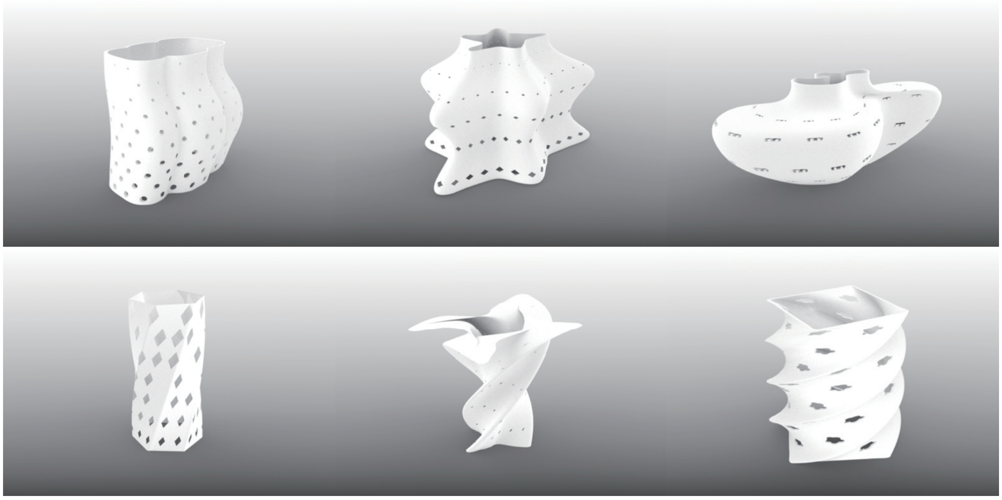

Figure 6 Lampshade designs created by the participants.

Regarding the user satisfaction with PD for personalization, 93% of the participants found that the PD interface helps to create the lampshade of their preference. Although most participants considered the sketching tool important, it is still necessary to include the predefined elements in the design, because at least half of the participants used them. By analyzing the number of changes per parameter, it was observed that Dimension per layer, base geometry and pattern shape were the most modified parameters.

Through these results, it was observed that within a short time, the user can generate various design outputs by the manipulation of the parameter's values without the intervention of the designer and, that the satisfaction level with the final product is higher when control over the design of the product is given to the user. Therefore, PD can be considered an effective technique for personalization.

6. 3. 2. Personalization efficiency for product design

As for the easiness to achieve personalization, more than half of the participants answered that former design experience is not required to design their own lampshade; however, some of them mentioned that it would help them achieve better and more creative designs if they had some sort of prior knowledge. These results might change based on the UX design of the PD interface, which is not included in the scope of this study. Overall, 80% of the participants found the design process of the lampshade easy.

Regarding user satisfaction, most of the participants liked the final lampshade they created. To understand to what extent the participants' preference for personalized products exceeded that for mass-produced goods, the question of whether they would prefer a personalized product over a predefined product without considering the price was asked. 67% of the participants chose personalized products since they like to design their own shape, and because it has more personal value while the rest of the participants preferred to just acquire something already designed since they consider they have no good taste for design or just do not like spending time designing. Based on this. it can be assumed that the users prefer personalized products when the price is not a factor to consider.

6. 3. 3. Participant's opinion on the experiment

After the experiment, participants provided some feedback that could improve the design experience from their perspective. Some of the comments were as follow:

- Addition of more predefined shapes.
- Multiple shapes to define the surface of the lampshade.
- Provide recommendations for pattern designs.
- Show the lampshade scale compared to in-house furniture and physical environments like a living room or a bedroom to be able to visualize the product’s size.
- Visualization of the shadow of the lampshade.

By analyzing the feedback from the participants, we noted that is important that the users can evaluate the performance of the product in a virtual environment in order to design more consciously. Visualizing the lampshade in an environment such as a living room or bedroom, for example, would help them make a better choice in their designs according to the participants. Additionally, certain participants mentioned it would be helpful if a designer provided recommendations of pattern designs and more predefined shapes so they can have different references for their designs. Since some users do not have experience with design or have difficulty starting a design from the scratch, it seems like this would help them to get inspiration. It was also mentioned that it would be good to add more functions to generate the surface of the lampshade by combining geometries, meaning that the level of personalization could be increased.

These recommendations surely would enhance the personalization experience and help to produce more diverse results from the users. Their implementation wouldn’t represent a major problem since the PD algorithm can constantly grow and be modified without starting the design process from the beginning. This is one of the advantages of using PD for personalization since it can adapt well to dynamic changes in the design requirements and constant improvements.

6. 4. Discussion

For this experiment, the product to personalize with PD was limited to lampshades; however, PD can be applied to products of different kinds by following the personalization process presented in this study. There are examples of products that have applied PD for personalization in diverse industries such as fashion (Jeong et al., 2021), car grills (Park & Ahn, 2018), and eyewear (Bai et al., 2021). The main challenge to be considered for personalization is the definition of parameters. The type and method to define the parameters will decide the level and efficiency of personalization.

PD technique is ideal for products that require the generation of multiple design models where they share characteristics such as parts, dimensions, form, and structure (Sun and Huang, 2019). Although PD enhances personalization, depending on the product type, personalization efficiency can differ from the results presented in this study. Thus, it would be ideal to test the proposed personalization model with more products other than lampshades and evaluate the efficiency and user satisfaction.

Regarding the manufacturing method, AM was chosen since it adapts well to the dynamic changes of personalized products. In our case study, we only considered the parameters of thickness and maximum and minimum dimensions of the 3D printer, since the rest of the parameters could be defined in the 3D printing software. However, more parameters can be included in the PD algorithm such as speed, quality of printing, and infill, among others, even generating the printing file directly from the algorithm. This can be defined by the designer considering the designer's experience and the manufacturer's capability.

The personalization process presented in this study is focused on AM and PD, but for future works, it would be meaningful to analyze the adaptation of the personalization process to other manufacturing methods and to evaluate its manufacturability efficiency.

7. Conclusion

After discussing the characteristics of personalization, and its importance in the current manufacturing trends, this study presented a new product personalization process for 3D printed products considering PD. To evaluate the efficiency of the personalization process, a study case for designing a personalized lampshade was developed. The study case consequently validated the achievement of personalization and user satisfaction from it. PD showed that it not only improves the personalization understanding of the designer and users but also enhances the creativity of the users in their product design, allowing them to make creative designs without the need for professional design experiences.

For future works, we would like to test the new personalization process in different types of products, since the design and manufacturing parameters vary from one product to another and this could affect the personalization process's efficiency.

Additionally, it would be good to include the visualization of the performance of the design product in the PD interface. If we want to make the design process more realistic, the user should be able to change the environment and the setting of the design product. For example, in the case of lampshade design, the user should be able to move the lampshade around a room or office and, change the color and intensity of the light source. If the user can visualize the final product in a live-time simulation, they can make a more conscious and better choice of characteristics in their designs.

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