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Jonathan D. Ashley
University of Arkansas, Fayetteville

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The Effect of Incorporating End-User Customization
into Additive Manufacturing Designs

A thesis submitted in partial fulfillment
of the requirements for the degree of
Master of Science in Mechanical Engineering

by

Jonathan Ashley
University of Arkansas
Bachelor of Science in Mechanical Engineering, 2015

December 2018
University of Arkansas

This thesis is approved for recommendation to the Graduate Council.

____
David C. Jensen, Ph.D.
Thesis Director

____
Zhenghui Sha, Ph.D.
Committee Member

____
Wenchao Zhou, Ph.D.
Committee Member

Abstract

In the realm of additive manufacturing there is an increasing trend among makers to create designs that allow for end-users to alter them prior to printing an artifact. Online design repositories have tools that facilitate the creation of such artifacts. There are currently no rules for how to create a good customizable design or a way to measure the degree of customization within a design. This work defines three types of customizations found in additive manufacturing and presents three metrics to measure the degree of customization within designs based on the three types of customization. The goal of this work is to ultimately provide a consistent basis for which a customizable design can be evaluated in order to assist makers in the creation of new customizable designs that can better serve end-user. The types of customization were defined by doing a search of Thingiverse's online data base of customizable designs and evaluating commonalities between designs. The three types of customization defined by this work are surface, structure, and personal customization. The associated metrics are used to quantify the adjustability of a set of online designs which are then plot against the daily use rate and each other on separate graphs. The use rate data used in this study is naturally biased towards hobbyists due to where the designs used to create the data resides. A preliminary analysis is done on the metrics to evaluate their correlation with design use rate as well as the dependency of the metrics in relation to each other. The trends between the metrics are examined for an idea of how best to provide customizable designs. This work provides a basis for measuring the degree of customization within additive manufacturing design and provides an initial framework for evaluating the usability of designs based on the measured degree of customization relative to the three types of defined customizations.

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1. INTRODUCTION

There is a growing trend in the online additive manufacturing community, specifically the maker community, to produce customizable designs in virtual space through the use of tool kits provided by the host website for end-users to alter and print. These designs include scalable cell phone cases and vases with variable dimensions and patterns. Whereas, the cell phone case allows the end-user to alter the design to fit their specific phone model, the vase is adjustable to the extent that it can be physically impossible to make and loses all functionality. The goal of this work is to define the types of customization in additive manufacturing designs and develop a quantification of the resulting degree of customization.

Product designers have several methods to meet a diverse range of user needs and preferences. One of the ways companies try to increase a product's appeal is by providing a family of variations customers can choose between [1-5]. Some modular product designs allow users to select a combination of different modules to build a complete product tailored to them [6-10]. Additive manufacturing increases product diversity by giving a user the ability to customize the design throughout its life. While we have methods to evaluate the modularity or value of families of designs, it is less clear how to value the customization enabled through additive manufacturing.

Similar to the principles of Universal Design, this democratization of design requires that the tools users employ to implement the customization are accessible and intuitive [11]. Therefore, the user should not be responsible for defining the limits of a design's customizability, and the design should be customizable to an acceptable degree by the end user. This design information should be transmitted with the design and delineated by the original designer.

Some research shows that customization increases the perceived value of a product to the users [12-16]. Therefore, the broader goal of this work is to define the value provided by a design's customization. Towards that goal, this work defines three types of customization found in additive manufacturing designs and develops metrics to evaluate the adjustability of each type. The metrics developed in this work are able to evaluate the degree to which a product is customizable within a defined set of manufacturing and design boundaries. In this work we define these metrics and apply them to a set of different customizable designs. Furthermore, the metrics are evaluated to explore how they can be used for design analysis.

2. BACKGROUND

This work builds upon previous work on design for product customization in the field of design science which encompasses other fields (e.g. marketing, engineering, psychology). The goal of product design is always to successfully meet a consumer's needs [17] with needs being somewhat subjective based on the product being designed. Customization enables the creation of a range of products that better meets a diverse set of consumers' needs [3, 5, 10, 18]. While there are numerous papers on design for customization as well as end-user customization, none focus on design for end-user customization in an additive manufacturing market place. This work is intended to develop a way to find the value for end-user customizable design in additive manufacturing and how to best design for customization based to the types and degree of customization present in a product.

2.1. Current Approaches to Customization

Customization is achieved through a broad range of methods in product design with the goal being to maximize customer reach and product fit [1, 2, 4, 8, 18-20] similar to Universal Design. However, unlike Universal Design which tries to meet as many consumers' needs as possible with a single product [11], customization tries to meet the needs of the consumers on a group or individual basis [8]. In product engineering, the two main ways customization is achieved are design for flexibility and design for modularity. The primary difference between the two is modularity uses passive adaptability where the product is fixed while in use and flexibility means product is being actively adapted during use to maximize performance [21]. Modularity can be further decomposed into product family design and reconfigurable product design. Product family design tries to reuse modules across the range of products a company provides [4, 9, 10, 22] and reconfigurable design focuses on allowing the user to change the product to their specific needs by changing modules within the product [6, 7, 23, 24]. A subtype of customization is personalization. It focuses on tailoring products to individuals' anthropometrics (the size and shape of a human's body) to maximize the products fit similar to a custom suit [3, 8, 18, 25-27]. Similar to modular design, this work focuses on how individuals are allowed to customize a design to fit their specific tastes.

There are a number of methods to accomplish customization in industry. However, challenges to modular customization include cost associated with design, manufacturing, and storage of modules which decreases profitability [4]. Tonhauser and Rudolph propose using a graph-based design language through the use of flow charts to drive decision making in order for users to customize a product based on the different modules available [2]. Kuo developed a method that utilizes quality function deployment to increase the modularity of software thus facilitating customization [8]. Cormier et al. proposed increasing design flexibility in the early stages of the design process through the reduction of interface and flow dependency between modules in order to reduce redesign cost [28] These approaches to customization focus on the traditional paradigm of manufacturing and consuming. However, in the additive manufacturing context, the end-user has a novel authoritative role in the design process.

Currently, the research into customization for additive manufacturing focuses on the anthropometric needs of individuals by creating custom fit products such as helmets, chairs, medical implants, shoes etc. [10, 20, 26, 29]. Conner and Manogharan developed a ranking system for customizable products on a scale from 0 to 4 where 4 encompasses medical devices and other objects that depend on anthropometrics [30]. However, level 4 prevents most end-user choices and preferences from being implemented in the end artifact which is the primary focus of this work. Ko et al. propose using artifact-user interactions in order to facilitate the customization of a product at user interfaces [26]. Gibson and Srinath proposed allowing doctors to assist in the design of medical implants so that they could install the implant easier [31]. Pandremenos & Chryssolouris propose using Axiomatic Design to personalize a product to an individual based on "user attributes" [10]. However, the customization tools available in the maker community lack formalized approaches for implementing and assessing customization [32]. Further, the considerations of manufacturing are not often included in the development of design constraints. For example, it is easy to configure some designs to the point that they exceeds the physical constraint of the 3D printer that will be used to create them by setting some of the customizable dimensions larger than the print envelop or so that they have sections that are no longer connected to the bulk of the artifact after it is printed. This can be caused be designs that have a non-symmetric body that tries to repeat an aspect in a uniform matter about the body.

2.2. Defining the Value of Customization

Some research exists which tries to understand the effect customization plays on consumers' perceived value. The research shows that what consumers are willing to pay for a product is positively correlated with the products degree of fit [12] and that the degree of fit increases when the consumers have a greater say in how the product looks and functions [13, 15, 16]. However, the amount of effort to reach an acceptable degree of fit on the consumers part will cause the consumers perceived value to diminish [14, 33]. It is important to note that as long as the consumer is able to create an artifact, they will still perceive it as having a greater value when compared to an off-the-shelf product [14]. This requires a way to measure the degree of customization within a design in order to try and minimize the end-users required effort.

One of the main reasons for designers to implement customization is its ability to broaden a products user base by fulfilling more of the users' needs. In an internet based market, customization benefits early adopters at the expense of the competitors causing a *prisoner's dilemma* [34]. Belt et al. developed a method to evaluate how design choices affect the product's market reach which showed a positive correlation between product variety and user demand with a decreasing rate of return as variety continued to increase [35]. The abilities of 3D printers to facilitate customization and the possible resulting market structure have been theorized [19, 20, 36]. By allowing users to customize products, they develop an emotional attachment to the product which increases how much they value it [12, 37]. The difficulty of customizing a product will diminish the perceived value [33]. It is important for designers to be able to effectively create customizable designs in order to enable end-users to easily create an artifact. This requires designers to have access to an understanding for how end-users react to different ways an artifact can be customized.

The other side of customization is the cost to the manufacturer for providing product variety to the consumer which looks at the design and manufacturing costs versus the return on investment and the increase in market reach [34]. Adding customization to products is an easy way to gain an edge in a market since it allows the manufacturer to meet the needs of a larger consumer base when compared to other firms that have not implemented customization [34]. However, customization causes a *prisoner's dilemma* effect in that, if all the competitors in a market implement customization, the price for the products will fall [34]. When it comes to modular customization, products are evaluated on the modules the company wishes to provide to the end user versus the total available modules on the market that can fulfil the same function [1, 9, 10, 28, 38]. This is done with the understanding that, while providing more modules increases a manufacturer's likelihood to meet an individual consumer's needs, they will accrue a higher operating cost [1, 35, 39, 40]. Additive manufacturing allows for a higher degree of customization without the need of more space and an easy entrance into a market which makes it advantageous in the right market.

2.3 Summary

The arguments for this work are based on the current state of the research community and try to address some of the current gaps. Such as, there are currently no formal design rules for implementing customization in additive manufacturing. The rules for customization in traditional manufacturing are geared to the creation of products to meet the needs of a segmented market and not an individual. Developing rules for customization in additive manufacturing requires knowing how customization effects the usability of a design. This requires being able to quantify the degree to which a design can be customized which requires knowing the ways a design can be customized. This work start be defining the types of customization found in additive manufacturing which then transitions into quantifying the degree of adjustability provided by said types of customization.

3. CUSTOMIZATION CLASSIFICATION

Additive manufacturing enables an artifact to be customized by allowing end-users to modify different aspects of the design. In order to develop measurements for the types of customizations found in designs, the customizations must first be defined. To accomplish this goal, a study of artifacts was conducted.

Using a study of 37 different artifact designs, the following three types of customization where defined for additive manufacturing after evaluating how the artifacts allow for different features within them to be adjusted.

- *Surface Customization*: any feature in a design that is continuously changeable in a linear direction and has a defined unit (mm, degree, etc.)
- *Structural Customization*: Any feature that allows the end-user to choose the number of times an aspect or set of aspects is repeated about an artifact or portion of an artifact.
- *Personal Customization*: Any feature that is chosen from a set of predefined options usually related to a standardized object.

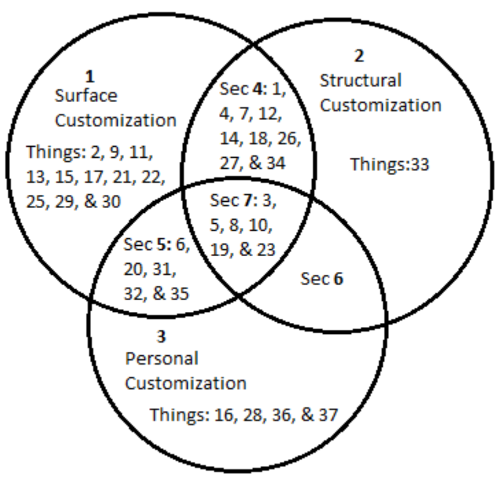

Figure 1. Chart of customizable artifacts' used to define the types of customization.

Figure 1 shows breakdown of the artifact designs relative to their types of customizations. Sector 1 contains designs for a specific physical function such as electronic housings or vacuum nozzles. Sector 2 houses designs focusing on objects with variable number of sides such as a gaming top. Sector 3 consists of personalized designs such as name plates and terrain tiles for board games. Sector 4 has designs where feature sizes can be adjusted as well as features are repeated such as a cable management strip and a cookie cutter. Section 5 consists of hybrid designs between sections 1 and 3 such as name tags and dice with adjustable sizes and personal areas. No designs were initially found that had only personal customization and structural customization, thus leaving section 6 empty. However, a design for a customizable light switch cover was later found that allows for a selection of the number of outlets to cover and the output types for the cover. In section 7, designs that utilize all three types of customization are found. The designs consist of namable boxes, and toys such as fidget spinners.

To provide a more relatable example of the different types of customization, a table is used as an artifact. The surface customization dimensions would be the table’s height, width, and length. This could be extended to the how thick the legs of the table are as well as the radius of the table corners which allows for round and oval tops. Its structure customization would be the number of legs the table has and the number of feet per leg. The number of legs and feet will affect the stability of the table. The personal customization would be the router bits available to use on the edge of the table. The degree of personal customization is defined by what is available to the end-user.

4. DEFINING METRICS

4.1 Surface Customization

Equation 1 is proposed as a way to evaluate a product's degree of surface customization:

$$A_{sur} = \sum_{i}^{m} d_i / t_i \qquad (1)$$

Where d_i is the distance range of a single dimension on an artifact constrained to the build volume of a given printer and that meets the physical requirement of the artifact, and m is the total number of artifact features that meet the definition for surface customization. The t_i is step distance of the ith feature. This allows for the total degree of surface customization within a design to be measured.

Similar to the research into valid CAD modeling which looks at parameter ranges for which an CAD model can still be generated correctly [41] and resilient modeling which looks at how to make CAD models as flexible as possible [42], the metric evaluates the geometric flexibility of a customizable design within the range of a given printer's build envelop. This metric can be coupled with the number of customizable surfaces to again an estimate of the designs geomantic complexity. Designs benefit when d_i lower and upper bounds are defined by the designer rather than the printer that is going to be used since it will insure that the customized design will be functional.

4.2 Structural Customization

Equation 2 is proposed as a metric for the structural customization of a design. That is, for a surface composed of a pattern, equation 2 quantifies the adjustability of the pattern. A pattern contains one or more reoccurring features about the surface. The feature can have a size that allows the pattern to have one or more repetitions. Each feature in the pattern can be defined by the number of sides. These parameters of the feature define the resulting structural customization in the following equation.

$$A_{Str} = \sum R_i * S_{sequence,i} \quad (2)$$

Where R_i is the number of repetitions of the feature. $S_{sequence,i}$ is the amount of adjustment that comes from the potential number of sides of the feature. $S_{sequence}$ is defined in equation 3. Min_S is the minimum number of sides feature can have. For fixed shapes, $S_{sequence}$ is equal to 1.

$$S_{sequence} = \frac{3}{Min_S} + \frac{3}{Min_S+1} + \cdots + \frac{3}{Max_S} \quad (3)$$

The $S_{sequence}$ is created by summing the fraction of sides from the minimum to the maximum allowed for each feature. Three is the minimum number of sides that a feature may have to form a geometric shape. Practically, as a feature increases in the number of sides, it tends towards the shape of a circle. $S_{sequence}$ is defined this way because the more sides that a feature can have increases the customization. However, a feature with a greater number of sides has fewer unique orientations. For example, a feature that can have between 3 to 5 sides (Min_S *to* Max_S) would have an $S_{sequence}$ value of:

$$S_{sequence} = \frac{3}{3} + \frac{3}{4} + \frac{3}{5} = 2.35 \quad (4)$$

This defines only a few possibilities for the sides of the features. However, increasing to more sides provides a diminishing benefit due to rotational limitations. For example, a range of sizes 4 to 10 results in an $S_{sequence}$ = 3.29 using the same approach.

This metric is akin to pattern compression research in 3D modeling. Pattern compression tries to minimize the bites required to encode objects with repeating patterns or features such as a chandelier or a room full of chairs [43]. The metric measures the degree of repetition customization within a design by summing the range of repetitions for each repeatable feature. It is believed that a design with two features that can be repeated three times each will have an equivalent amount of repeatable customization as a design with three features that can each be repeated twice. This would require a human experiment to show which is outside the scope of this work.

4.3 Personal Customization

Equation 5 is proposed as a way to quantify the personal customization of a design. Where, each area for personalization can contain a limited selection of options predefined by the designer.

$$A_{per} = \sum V_i \tag{5}$$

Where V_i is the set number of options afforded to the end-user. For example, a customizable monogram has a section for three different characters. Each character is independent from the other two. As such, the end-user will have to select a character from three different sets of predefined options.

This metric is an adaptation of the one used in modular design and measures the total predefined choice selection afforded to end-users within a customizable design. The general metric used in modular design measures the total number of modules a firm provides divided by all the modules available on the market [40]. The metric develop for personal customization omits the denominator since the number of possible options that could be provided in a customizable design are theoretically infinite.

Equations 1, 2, and 5 are ways to measure the three different types of customization. They cover the surface, structural, and personalization aspect of a design. These metrics assume that the uses of FEA and continuity analyses are used to eliminate non-feasible variations for designs.

5. APPLICATION OF METRICS

In order to see how these metrics of customization and quality apply to real objects, we look at the following examples; a coffee cup sleeve, vacuum nozzle, and door key. All models came from the thingiverse.com customizable database [44-46]. The printer used to evaluate the artifacts is a fused deposition 3D printer, namely, the Ultimaker 2+ extended.

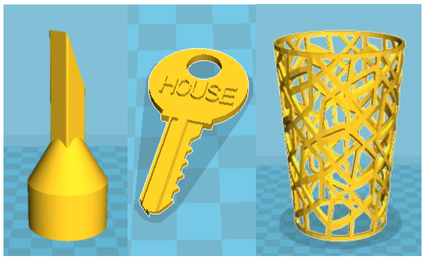

Figure 2. Vacuum nozzle [44], door key [45], and coffee cup sleeve [46] artifacts used in the case study.

5.1 Surface Customization Metric

Our surface customization metric is an assessment of the amount of adjustability of the overall surface boundaries and physical functionality. The surface customization of the coffee sleeve is limited only by the printer boundaries. The minimum wall thickness w_t is 2mm as dictated by the design parameters. There are three dimensions that control the coffee sleeve: base diameter, height, and top diameter. Since the design itself has no fixed limits the available printers form the boundary of what the dimensions can be. In our case we are using only one printer which provides the following ranges.

The range for the base diameter (*Db*) is:

$$2 * w_t \leq Db \leq 223 \text{ mm} \tag{7}$$

Where 223 is the maximum build length in the X-Y directions in millimeters of the printer used and 2*w_t is the wall thickness of the artifact without overlapping itself.

The range for the height *H* is:

$$w_t \leq H \leq 315 \text{ mm} \tag{8}$$

Where 315 is the maximum build height of the printer in millimeters of the printer used and t is the minimum thickness for the design.

The range for the tops diameter *Dt* is:

$$Db \leq Dt \leq 223 \text{ mm} \tag{9}$$

Where the lower limit of *Dt* is equal to Db to prevent reoccurring geometries (identical artifacts at mirrored orientations). The maximum diameter for *Dt* is the printer's X-Y boundary. Because *Dt* is dependent on *Db,* the sum of their ranges will equal the range of *Db*. Therefore, since the range of Db is 219mm, *H* is 313 mm*,* and the step distance *t* is 2 mm, the resulting surface customization for the coffee sleeve is:

$$A_{sur} = \frac{219}{2} + \frac{313}{2} = 265 \tag{10}$$

The surface customization for the vacuum nozzle consists of seven dimensions. These are: vacuum hose collar diameter, vacuum hose collar-nozzle interface length, total nozzle length, opening length side A, opening length side B, opening radius, and angle of opening. The minimum change for all length dimensions is 2 mm. Therefore, the resulting total surface customization is:

$$A_{sur} = \left(\frac{60}{2} + \frac{90}{2} + \frac{265}{2} + \frac{116}{2} + \frac{116}{2} + \frac{60}{2}\right)\left(\frac{\text{mm}}{\text{mm}}\right) + \frac{87°}{3°} = 382.5 \tag{11}$$

Where the numerators are equal to the ranges of vacuum hose collar diameter, vacuum hose collar-nozzle interface length, total nozzle length, opening length side A, opening length side B, opening radius, and angle of opening respectively, and the denominators are the minimum artifact thickness and angle respectively.

The surface customization of the door key has five dimensions. They are the five key teeth which give the key its physical functionality. Each tooth has a range of 0-9, with the smallest increment (*t*) equal to 1. Therefore, the resulting surface customization score is:

$$A_{sur} = 5 * \left(\frac{10}{1}\right) = 50 \quad (12)$$

5.2 Structural Customization Metric

Our structural customization metric is an assessment of the overall amount of total surface pattern adjustment an artifact can undergo. The structural customization of the coffee sleeve consists of only one figure per pattern. The pattern can repeat between 4 to 36 times around the coffee sleeve. The figure can have between 3 to 20 sides. This results in a structural customization score of:

$$A_{Str} = 32 * 6.293 = 201.4 \quad (13)$$

Since only one figure is possible in the pattern, *F*=1. The range of potential repetitions of the pattern is *R*=32. We compute the $S_{Sequence}$ over the range of shape sides permitted of 3 to 20 under the geometric limit of a 3 sided shape. This gives a value of:

$$S_{series} = \frac{3}{3} + \frac{3}{4} + \cdots \frac{3}{20} = 6.293 \quad (14)$$

For the door key, the only source of pattern is in the head of the key. This pattern can consist of one figure that has only 1 repetition, resulting in the shape of the key head. The range of the permitted sides for that figure is (4-12,16,20,24,28,32). In this way the $S_{sequence}$ is the only contribution to the structural customization. The structural customization score for the door key is:

$$A_{Str} = \frac{3}{4} + \frac{3}{5} + \cdots \frac{3}{32} = 4.47 \quad (15)$$

The vacuum nozzle has no permitted figures in the pattern of the surface, resulting in a solid surface. This means that the structural customization of the vacuum nozzle is zero.

5.3 Personal Customization Metric

Our personal customization metric assesses the overall amount of predefined or standardized selections within the artifact. Only the door key example allows for personal customization. The end-user has two personal selections. They are the key's number of teeth and an option for a personal text. The number of teeth has two options one for a 4 cylinder lock and the other being for a 5 cylinder lock giving a value of 2 for that dimension. The Text dimension gives a value of 1 since the font and text size are fixed. Thus, the total personal customization of the door key is:

$$A_{per} = 2 + 1 = 3 \quad (16)$$

6. DATA

All data for this work was collected from thingiverse.com manually with the help of a matlab code. A third of the data was collected over a month time period from the newly published designs and given a year and a half to be used before being evaluated for their remix rate. Another third of the data was collected from the most popular designs of all time. The last third of the data collected was based on what the researcher found interesting or unique.

Figure 3 represents all the collected data graphically based on four dimensions. The axis represent the degree of adjustability measures of the three types of customization metrics with the X-axis representing surface customization, the Y-axis representing structural customization, and the Z-axis representing personal customization. The remix rate is defined by the heat map on the graph and ranges for 30 to 0.

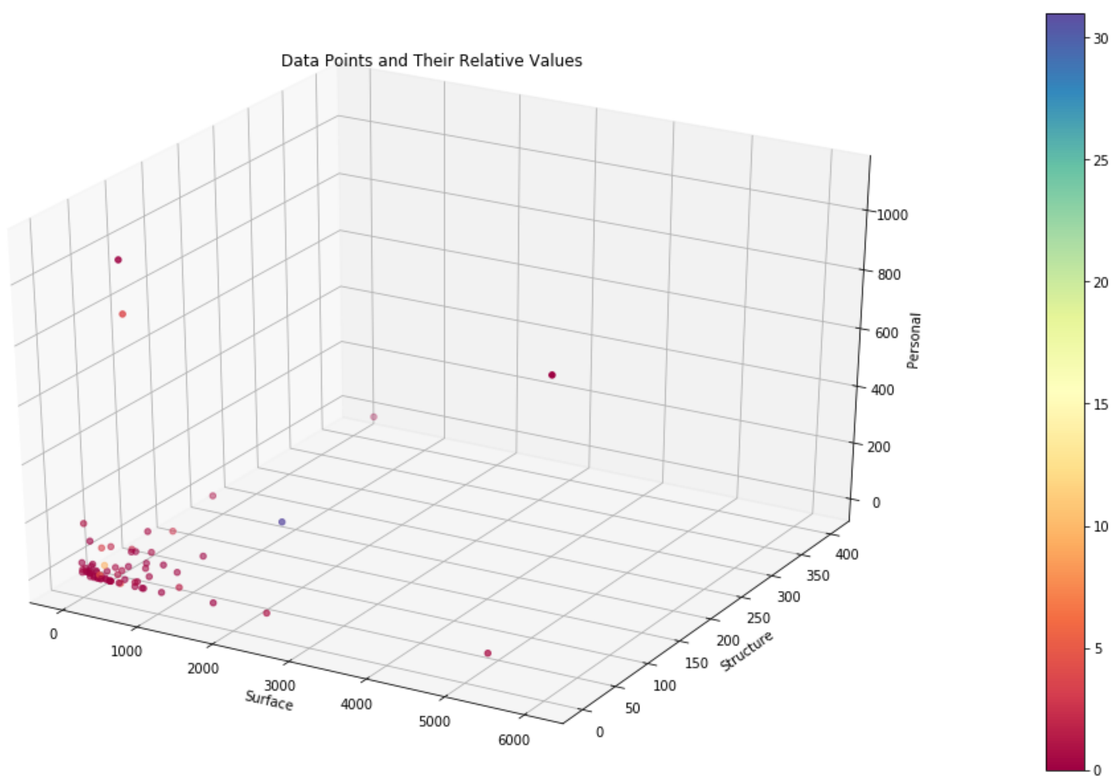

Figure 3. Scatter plot of all data collected from Thingiverse.com with a heat map of the data points normalized remixes per day

Aside from human error, the data at the time it was collected is accurate. However, the publishers of designs can change the design at any time without affecting the published data. This means that the associated values for surface, structure, and personal customization can change over time and the remix rate will also be subject to the changes since the design might go through several different versions while on the website. Human error is most likely to come into play when dealing with poorly defined customization areas such as unbounded surface dimensions. In an attempt to mitigate this error, geometric evaluation is done to find the maximal and minimal possible settings for a given boundary area, in this case it was the build envelop of an UltiMaker 2+, and the special surface customization equation used to minimize measuring bias.

7. RESULTS

The hypothesis of this work is that the value of customization, the remix rate, is related to the three metrics presented and that the three metrics are independent. In this section, the interdependency of the metrics are calculated. Two models for how the metrics relate to the remix rate are proposed and evaluated.

7.1 Pre-Evaluation

For the evaluation of the interdependency of the three metrics, the data for the customization types was normalized within each respective data set to itself. The results were plotted against each other, and the Pearson correlation coefficients between the three metrics were calculated. The plot for the normalized surface customization compared to the normalized personal customization is show since their relation has the highest correlation coefficient. The plot for the other two relations can be found in appendix B.

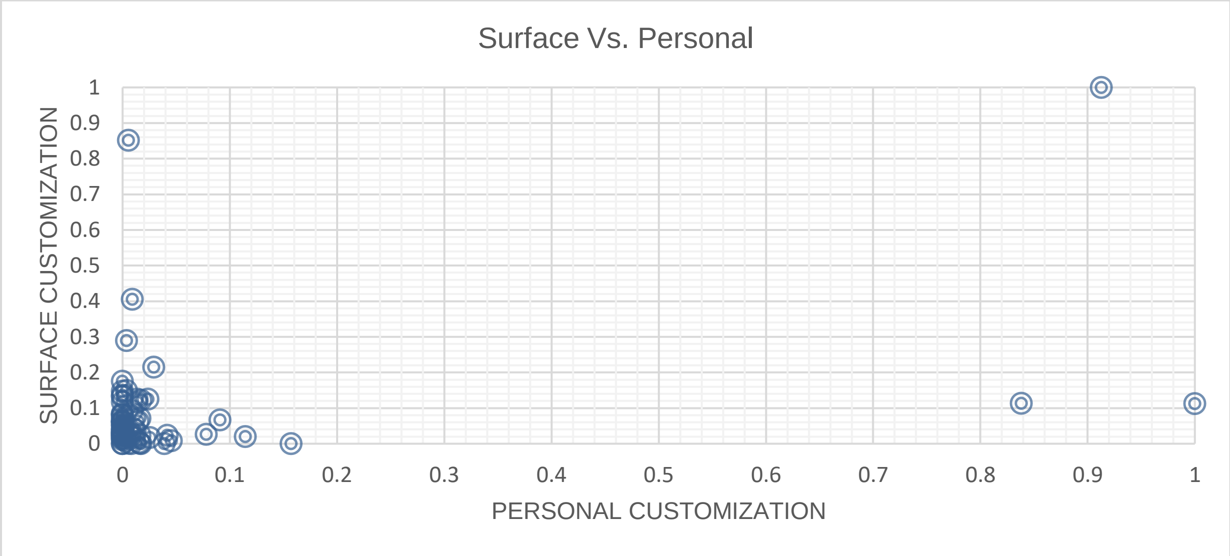

Figure 4. The graph of the normalize surface customization relative the value of the normalize personal customization

Table 1. Pearson correlation coefficients for the independent variables

	Surface	Structure	Personal
Surface	1.0000	-0.0849	0.4267
Structure	-0.0849	1.0000	-0.0926
Personal	0.4267	-0.0926	1.0000

7.2 Nomenclature

Names: the index of the names of the artifact designs used in this study

Sur: the sum of the measures for the amount of adjustability allotted from surface customization within each artifact design

$$Sur = A_{Sur,j}\ for\ j\ in\ Names \tag{17}$$

Str: the sum of the measures for the structural customization of each artifact design

$$Str = A_{str,j}\ for\ j\ in\ Names \tag{18}$$

Per: the sum of the measures allotted by the number of preset and personalize texts inputs for personal customization in each artifact design

$$Per = A_{per,j}\ for\ j\ in\ Names \tag{19}$$

Remixday: the number of remixes of an artifact design has received normalized by time since its upload date

$$Remixday = \frac{Remixs_j}{Day_j}\ for\ j\ in\ Names \tag{20}$$

β_i: the constant of the ith term of the model

7.3 Models

The following two models were used to try and model the remix rate versus the independent variables. The results can be found in table 2.The first model is for a simple linear relationship since there is little to no relation between the independent variables.

$$Remixday = \beta_0 + \beta_1 Sur + \beta_2 Str + \beta_3 Per \tag{21}$$

The second model examines the remix rate versus the squared value of the independent variables with the exemption of personal customization due to squaring it causing ill conditioning.

$$Remixday = \beta_0 + \beta_1 (Sur)^2 + \beta_2 (Str)^2 + \beta_3 Per \tag{22}$$

Table 2. OLS regression results for the models

Model 1	Coef	Std. Err.	p
B_0	0.6941	0.582	0.237
B_1	0.0007	0.001	0.208
B_2	-0.0016	0.009	0.852
B_3	0.0020	0.003	0.433
BIC	397.0	=====	=====
Adj. R^2	0.013	=====	=====
Model 2	Coef	Std. Err.	p
B_0	-0.0275	0.787	0.972
B_1	0.0567	0.035	0.111
B_2	-4.819e-06	2.42e-05	0.843
B_3	0.0019	0.002	0.439
BIC	396.0	=====	=====
Adj. R^2	0.027	=====	=====

8. DISCUSSION

From the graph and tables, a preliminary understanding of the customization metrics relationships can be gleamed. The evaluation of the models is limited to linear correlation due to the small sample size of the data set and its condition. However, this does not mean that the types of customizations relate linearly to the remix rate or each other. The hypothesis is not proven in this work non it is necessarily disproven.

The hypothesis was that the metrics are linearly independent and that they can be used to estimate the reuse rate of a design. The metrics are independent based on the results from table 1 with the potential for there being a slight relating between surface customization and personal customization. The relation between the remix rate and the metrics based on the 2 models presented cannot be calculated. However, the relationship of the remix rate to surface customization in model 2 has some degree of significance. For a more affirmative statement to be made about the relation between the metrics and the remix rate, a larger and more varied set of data point is needed.

There are some designs that will inherently have some error in their remix rate due to the end-users being allowed to choose whether or not to publish their remix of the design. Only published remixes are actually listed under the design they were derived from and thus can be accounted for. There are a number of reasons to do this. The most prominent reasons being personal privacy and safety. A few examples within the data used are customizable house keys, business card, and name plates. Publishing a house key opens up an individual to robbery since anyone with a 3D printer or slight knowledge of keys would be able to create or acquire a copy of that individual’s house key. The business card and name plate design might include the end-users name, email, and phone number which they might not want to be public. These designs compared to others that do not have personal information associated with them such as the vacuum tool or fidget spinner will be more likely for end-user to publish their remixes.

Another issue with designs is the mimicry of off-the-shelf products that are superior due the material they are made out of in conjunction with their functionality. Two examples from the data set are a meat tenderizer and a whiteboard marker holder. A store-bought tenderizer will work better for its intended function as well as be more durable in the long run. As for the marker holder, most whiteboards have a tray built into them or can be magnetized to facilitate the storage of markers. This may be due to a function based driver for the use rate of designs based on an examination of designs on the high and low ends of the remix rate. For these reasons, many designs go unused.

9. CONCLUSION

This work provides a basis for measuring and classifying customization in additive manufacturing by defining the current ways designs are customized and deriving a set of metrics to measure the degree of adjustability provided by the different types of customization. A preliminary evaluation of the relationships between the metrics and how their values relate to the use rate of customizable designs is done, as well as an examination of potential issues that can cause a design to seem underused or to go unused all together.

The metrics expand the knowledge of engineering by providing a way to measure the degree of customization in additive manufacturing. Surface customization provides a way to quantify the geometric flexibility of a design in a way that provides a degree of engineering assurance that the end artifact will be usable. The structural customization matric enables us to calculate the degree of repeatable features in a design in order for designs to be compared to each other. The metric of personal customization was modified from the standard metric for measuring degree of customization for modularity such that the degree of customization for predefined options afforded to end-users can be measured.

This work as a whole enables the research community to develop a way to quantify the degree of customization in additive manufacturing product design and to evaluate how customization effects the use rate of designs. The current types of customization found in additive manufacturing have been defined, however this could expand in the future. This work provides a novel way to measure these new types of customizations. A preliminary analysis of the effect these types of customization have on the use rate of designs has been presented and show that there is some potential for a model to be developed.

There is a growing interest in understanding the paradigm of user's who also act as producers of artifacts. This requires a broad view of engineering design in terms of the range of information content in the designs. The metrics in this paper highlight how those ranges can be quantified to evaluate the adaptability of a design. By defining these types of customization found in additive manufacturing, this work is able provide a means to quantify the degree of customization through the associated metrics. The metrics allow trends between the types of customization within additive manufacturing designs to be examined. While this work does not provide an exact way to measure the use rate of a design relative to the measured amount of customization, it provides insight into how the different types of customization interact and how the interactions effect the use rate. These insights will allow for the development of rules for creating customizable designs for additive manufacturing such as surface and personal customization should be coupled if possible.

This work's simple examination of the relationships between the metrics and the remix rate, while not conclusive, allows for some advances into how designs for customization in additive manufacturing should be created. The main primary general rule that can be derived is that surface and personal customization should be used together in a design if possible. It can also be said that personal customization has a positive effect on the remix rate of a design. Unfortunately, the current set of artifacts cause too much instability in the graphs for anything conclusive to be said about the linear relationships of the other two metrics, other than that structure customization has a slight trade-off with the both surface and personal customization.

10. FUTURE WORK

This work has a number of areas to expand into with future research. The research presented only focused on defining customization and quantifying the degree of customization provided by each type of customization with a design. A preliminary evaluation of how the metrics relate to the remix rate is presented. If a larger set of design data was collected, the development of a model that quantifies the remix rate to the degree of customization provided by the three metrics. The work could be expanded further at that point to include the number of dimensions that comprise the sum of adjustability for each metric. An examination of artifact sets could be used to break down customization requirements into classes based on the type of artifact or the function the artifact will perform.

The most logical extension of this work would be to develop a general model for the effects the types of customization have on the remix rate of a design. This would require the collection of more data with a relatively high remix rate since the current data set is mostly clustered between 0 and 1 remixes a day. With the expanded data set, a more visible trend in the graphs of the remix rate to each respective metric would hopefully appear, thus giving us the ability to create a model for the remix rate. The graphs would also allow for a more definite idea of the reactions between the metrics themselves. After this study was completed, the research could branch in two ways.

The first branch will be to incorporate the number of dimensions under each type of customization to see if there is a limit to how many dimensions a design should have. Knowing if there is an upper limit dimensions for each type of customization would allow for designs to be optimized in order to maximize the use rate. The current data set could be adapted with a little work to include the dimensional values for each metric in order to facilitate such research. The addition of such a variable would be done by coupling it with its associated metric as a weight factor. Another any to evaluate the effect of dimensions on designs would be to use them to find the average value for each metric to see if there is a range in which designs become more usable to end-users.

The second branch for continuing this work will be to break artifacts down into classes based on their intended functions and evaluate if the models are constituent in specific cases or if the model diverges which would mean that the metrics added value to the remix rate are functionally dependent. A quick comparison between some of the better preforming artifacts in the current data set to some of the worse preforming ones lends some validity to this idea. For example, two of the artifacts with a remix rate of zero are a meat tenderizer and whiteboard marker holder. The general function of a meat tenderizer is to flatten meat which is aided by most tenderizers being made of metal. As for the whiteboard marker holder, most whiteboards have a marker holder built in and if not, it is not uncommon to find a pack of markers that come with a free magnetic marker holder. On the other end of the remix rate is a customizable keychain tag and a 3D printed picture generator. The primary function of both of these artifacts is to convey some type of information visually to an individual's surroundings.

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12. APPENDIX A: ARTIFACT DATA

Table 3. Data of artifacts used in analysis

Thing	Category	remix/ day	Surface	Structure	Personal	Notes	Number	Link
Coffee Sleeve	life hack	0.192110656	265	402.8	0	adjustable height top dia and bottom dia, can change # sides of shapes and rotate them	1	
Vacuum Nozzle	Life hack	1.457954545	382.5	0	0	can change coupling dia, height, opening, cut angle, radii of corners	2	
Door Key	simple/life hack	0.33656644	50	4.47	3	5 notched key, can change head shape, add 5 letter word	3	
Cable Management strip	life hack	0	438	44	0	No constraints, Uses a repeating arc (segment), no physical constraints in model, only visual	4	https://www.thingiverse.com/thing:2364708
Einfache box rond	box/personal	0.003236246	286	2.105	1	simple box, constrained height and diameter, selectable 'roundness', in German	5	https://www.thingiverse.com/apps/customizer/run?thing_id=2364124
Name Tag	fashion	1.081168831	210	0	1	adjustable length, can add name to it. (numbers seem not to work in file)	6	https://www.thingiverse.com/apps/customizer/run?thing_id=2089058
flower/cusper circle cookie cutter	cooking	0.007692308	314	31.5867	0	can change radius of circle, adjust number of pedals and their trace length	7	https://www.thingiverse.com/apps/customizer/run?thing_id=2316775
the ultimate box maker	box/electronics	3.815109344	686	1.7889	922	prim. dimen. are unrestrained, uses google fonts, has option for vent holes (struc)	8	https://www.thingiverse.com/thing:1264391
the unlimbited Arm v2.1	human/DIY/medium	4.373025516	513	0	0	put in arm dimensions, program do the rest (gives reference to current research)	9	https://www.thingiverse.com/thing:1672381
Customizable Yin-Yang fidget spinner	toy	0.212765957	6	4	18	can change # of Yin-yangs, select weight used from list, adjustable radius, rotation 120-170 Degrees uses sliders	10	https://www.thingiverse.com/thing:2101254

Table 3 cont. Data of artifacts used in analysis

Thing	Category	remix /day	Surface	Structure	Personal	Notes	Number	Link
Customizable Holder For peg board	life hack	0.100697906	374	0	0	larger than actual, object is simple cubic shell for peg boards	11	https://www.thingiverse.com/thing:1268879
parametric fidget spinner	DIY/toy	0.046367852	182	15.3	0	can repeat arms 10x, weights and bearings Dimen. Are user set(not slides)	12	https://www.thingiverse.com/thing:2369135
puzzle sphere stand	DIY/Storage	0	242	0	0	input puzzle radius, set depth of cut for sphere, set offset from ground	13	https://www.thingiverse.com/thing:2362682
customizable universal fidget spinner	DIY/toy	0.04	132	3	0	fixed number of arms, sphere or round weights, set weights/bearing sizes	14	https://www.thingiverse.com/thing:2360208
customizable (parametric) simple pipe adapter	life hack	0.040322581	705	0	0	2 diameters and a slope from on to the other, height made up of 3 sections	15	https://www.thingiverse.com/thing:2368875
Pelican nameplate customizer	life hack	0.046277666	146	0	46	2 texts, can extrude or cut, font sizes are different	16	https://www.thingiverse.com/thing:2365679
Customizable Cap	DIY/life hack	0.006072874	1060	0	0	has 2 walls, and 2 diameters, auto seeds holes in the top with adjustable diameter	17	https://www.thingiverse.com/thing:2372632
Customizable Lamp Shade	Fashion/art	0.038461538	902	3804.5	0	4 base shapes, adjustable # of sides up to 255, have petal repeat of flower, basic surface dimensions plus offset cut	18	https://www.thingiverse.com/thing:2373638
Customizable paw fidget spinner	simple/toy	0.024340771	10	4	6	Can choose how many weights, can add claws to paws, adjust size of paws and rotate them 90, adjust cut depth.	19	https://www.thingiverse.com/thing:2375945
Business card holder	simple/life hack	0.020283976	680	0	1100	google texts, 21 characters displace them -+10, 3 adjustable size ranges	20	https://www.thingiverse.com/thing:2374918
customizable Dome Hair Shield	simple/life hack	0	155	0	0	Simple dome, has base come off it, adjust hole diameters, can adjust separation between holes	21	https://www.thingiverse.com/thing:2378603

Table 3 cont. Data of artifacts used in analysis

Thing	Category	remix/day	Surface	Structure	Personal	Notes	Number	Link
Cube in a cube	Art/medium	0.004056795	361	0	0	2 adjustable ranges one for inside cube other for outside cube	22	https://www.thingiverse.com/thing:2374398
XXL Fidget Spinner	Simple/toy	0	26	10	17	adjustable #arms and weights per arm, list of weights, can round edges and arm length	23	https://www.thingiverse.com/thing:2386571
Customizable Paper tag Frame	DIY/life hack	0.002053388	820	0	0	width, length, wall height, board width are adjustable parameters	24	https://www.thingiverse.com/thing:2386086
Customizable Box Catch	Simple/life hack	0.002053388	377	0	0	can adjust size of latch (width, length, height, and corner radius) w/ sliders	25	https://www.thingiverse.com/thing:2385537
Whiteboard Marker Storage	Simple/storage/life hack	0	90	10	0	adjustable height, depth, diameter, and thickness, can choose number of makers	26	https://www.thingiverse.com/thing:2388056
food thirdener with handle	medium/life hack	0	493	8	0	adjustable height, diameter. Can change the number of portions	27	https://www.thingiverse.com/thing:2386699
Infiniground generator	simple/toy/module	0.008196721	6040	0	1004	add grey scale map, can add name to the bottom (note this is for suggested text size)	28	https://www.thingiverse.com/thing:2383855
Harke (rake)	medium/ object	0	491	0	0	handle, head, and tooth size adjustable	29	https://www.thingiverse.com/thing:2382673
CTC replicator spool holder	simple/life hack	0	199	0	0	only dimension is diameter	30	https://www.thingiverse.com/thing:2381676
custom die (dice)	simple/toy	0.015267176	257	0	11	adjustable width, edge smoothing, 5 fonts for text	31	https://www.thingiverse.com/thing:2305969
Worst cup ever	simple/toy	0	103	0	11	mug height, diameter, thickness, can choose location of "joke"	32	https://www.thingiverse.com/thing:2282587
spinning top	simple/toy	0.001782531	0	12.1	0	number of sides is adjustable	33	https://www.thingiverse.com/thing:2221546

Table 3 cont. Data of artifacts used in analysis

Thing	Category	remix/day	Surface	Structure	Personal	Notes	Number	Link
fidget ball cube	simple/toy	0.007042254	67	12.1	0	hole size, sphere diameter, adjustable # sides	34	https://www.thingiverse.com/thing:2204181
customizable fidget cube (story block)	simple/toy	0.026362039	123.7	0	126	6 text options, change cube size, adjust hinges and spacing	35	https://www.thingiverse.com/thing:2203150
Any coin Wall Mounted Bottle Opener	life hack/simple	0.00533049	0	0	9	2 personalization areas, tongue and what coin is used (toad head)	36	https://www.thingiverse.com/thing:1433314
desktop name coin	fashion/simple	0.015363128	0	0	43	personal name, 2 fonts, 4 preset titles, 5 logos	37	https://www.thingiverse.com/thing:1842381
Customizable Monogram Pendant with multiple loops	Fashion	0.60247678	405	51	100	3 preset letter options, multiple text options , diameter thickness and rotation, number of holes and number of sides	38	https://www.thingiverse.com/thing:330855
NUT JOB | Nut, Bolt, Washer and Threaded Rod Factory	life hack	5.090347924	234	0	13	select from standard head types, all other options are dimensional input	39	https://www.thingiverse.com/thing:193647
Parametric pulley - lots of tooth profiles	life hack	2.230549898	148	54	18	need to read cad file to understand	40	https://www.thingiverse.com/thing:16627
Customizable U-Hook	life hack	0.868665977	2450	0	10	see image on page, plus options to have screws and two have curves	41	https://www.thingiverse.com/thing:1367661
Parametric Hinge	life hack	0.539766702	384	57	16	dimensions are open-ended, selectable number of screw holes and hinges, choices are the usual yes/no square/curve questions	42	https://www.thingiverse.com/thing:2187167
Customizable Sanding Stick	life hack	0.465553236	562	30	10	select end types, choose number of teeth screws have, adjust size with sliders screws have open inputs	43	https://www.thingiverse.com/thing:2404850

Table 3 cont. Data of artifacts used in analysis

Thing	Category	remix/day	Surface	Structure	Personal	Notes	Number	Link
Gear Bearing	life hack	2.623848764	168	110	0	diameter, width, pressure angle, teeth overlap, drive size, teeth and number of planetaries	44	https://www.thingiverse.com/thing:53451
Customizable drawer box with hex pattern sides	storage	0.242661448	755	15	15	uses drawers to set size, repeat of # of drawers, can add text and select drawer types	45	https://www.thingiverse.com/thing:421886
Auto Coin Sorter for All Currencies	toy	0.24471711	740	0	19	can customize number of coin slots, have good selection of presets	46	https://www.thingiverse.com/thing:499177
Pegstr - Pegboard Wizard	life hack	0.349548297	890	40	0	change x/y diameters of holes, wall thicknesses etc., set # holes in x/y directions	47	https://www.thingiverse.com/thing:537516
Customizable Cable Holder	life hack	0.170436612	105	0	0	parameter adjustments, has built in spacing	48	https://www.thingiverse.com/thing:130495
Customizable Fan Grill Cover	life hack	0.053497942	757	35	26	select from set of standard size frames, adjust size of lines, adjust number of lines	49	https://www.thingiverse.com/thing:2802474
Parametric Music Box	toy	0.750364964	107	175	28	complicated, lots of tuning for teeth sound, gear adjustments teeth number	50	https://www.thingiverse.com/thing:53235
Battery box for AA cells	life hack	0.165126309	0	10	0	select number of battery slots	51	https://www.thingiverse.com/thing:331394
Cap that Hole	life hack	0.693877551	5145	17	6	make caps, select shape and fin types, select # of fins, Set sizes with sliders	52	https://www.thingiverse.com/thing:1943463
Print-In-Place Fidget Cube	toy	0.233160622	320	0	2	choose style, select height and tolerance of part	53	https://www.thingiverse.com/thing:230139
Preassembled Secret Heart Box	storage	0.739503817	708	0	15	personal texts font size and font, abjustable sizes (doesn't render)	54	https://www.thingiverse.com/thing:44579

Table 3 cont. Data of artifacts used in analysis

Thing	Category	remix/ day	Surface	Structure	Personal	Notes	Number	Link
Vasemania: Low poly vases	life hack/art	0.057803468	140	54	8	choose object, # steps, # side, radius spike size, twist factor	55	https://www.thingiverse.com/thing:2638924
Three Cube Gears	toy	0.636002271	5	0	19	texts, fonts and font size, tolerance, teeth sets	56	https://www.thingiverse.com/thing:213946
Stretchy Bracelet	fashion	0.080346593	140	60	0	diameter, difference in diameters, height, # gaps, # twists	57	https://www.thingiverse.com/thing:13505
Parametric universal spool holder	life hack	0.218266254	250	0	0	3 parts, diameters X4, heights X2	58	https://www.thingiverse.com/thing:767317
Customizable Lithopane	Art	9.50768468	185	12	26	adjustable hole, layer thickness, text placement, 13 places for personalization, # of layers to form picture	59	https://www.thingiverse.com/thing:74322
Customizable Easy Gyro	toy	0.764150943	317	22.1640625	0	select diameter, height, ring thinness and spacing, # rings, resolution	60	https://www.thingiverse.com/thing:802145
Customizable Fidget Spinner Ring	toy, fashon	1.198439242	429	5	18	select diameter, height, ring thickness, font spacing, font height, 4 types of rings, number of loops, select font types, font size, etc.	61	https://www.thingiverse.com/thing:188275
ANET A8 | Customizable E3D v6 Carriage / Bowden Mount	life hack	0.211631664	1747	0	4	mount types, sensor yes/no, adjust mount aspects	62	https://www.thingiverse.com/thing:2099577
Hollow Calibration Cube	simple	0.1	800	0	0	xyz and thickness adjustments	63	https://www.thingiverse.com/thing:271736
Customizable USB stick and SD card holder	life hack	1.897607656	52	35	50	select setup, # number of cards, spacing between cards, sign height	64	https://www.thingiverse.com/thing:46335

Table 3 cont. Data of artifacts used in analysis

Thing	Category	remix/day	Surface	Structure	Personal	Notes	Number	Link
The Snowflake Machine	art	3.434086629	157	12	86	choose seed, loop?, adjust randomizer, change thickness, radii and diameters, choose # step to take	65	https://www.thingiverse.com/thing:1159436
Customizable Multiline Tag or Keychain	art, fashion	30.97020626	2680	0	338	250 fonts, adjustable spacing, multiple heads, boarder option etc.	66	https://www.thingiverse.com/thing:739573
ANET A8 Spiral vase linear bushing	life hack	0.59057072	202	25	0	like bracelet but with adjustable angles	67	https://www.thingiverse.com/thing:2537701
WALLY - Wall Plate Customizer	life hack	1.043645084	0	5	173	# of plates in design, select from per defined ports	68	https://www.thingiverse.com/thing:47956
Customizable Universal Charging Dock	life hack	1.58432304	1300	0	32	input phone dimensions, add names and other selection yes/no options	69	https://www.thingiverse.com/thing:1655546

12. APPENDIX B: EXTRA GRAPHS

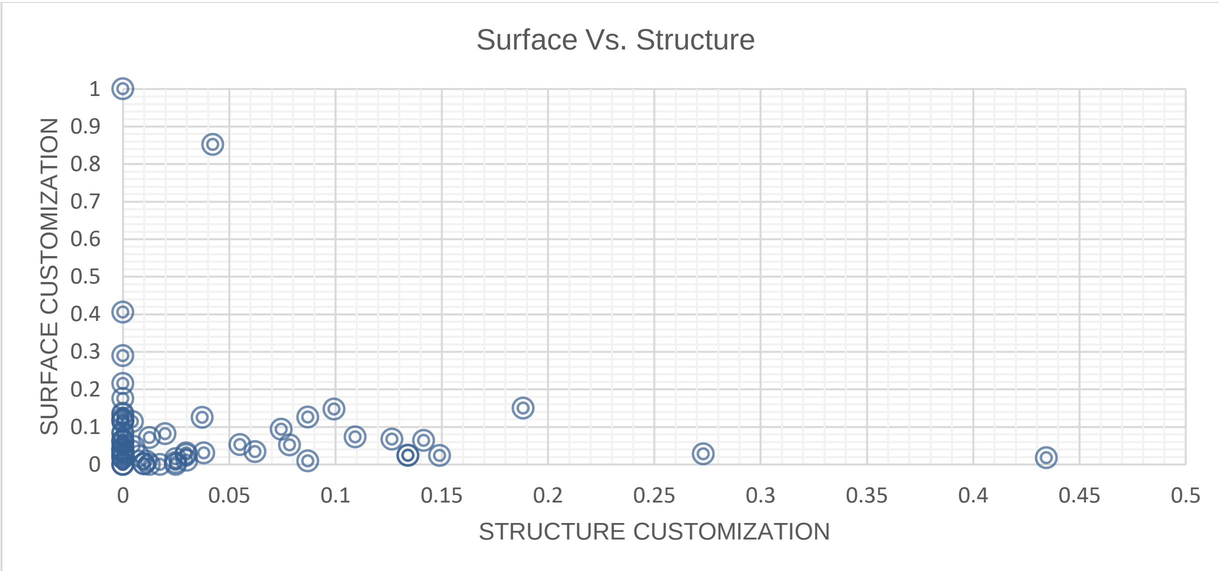

Figure 5. The normalized surface customization relative to the normalized structural customization

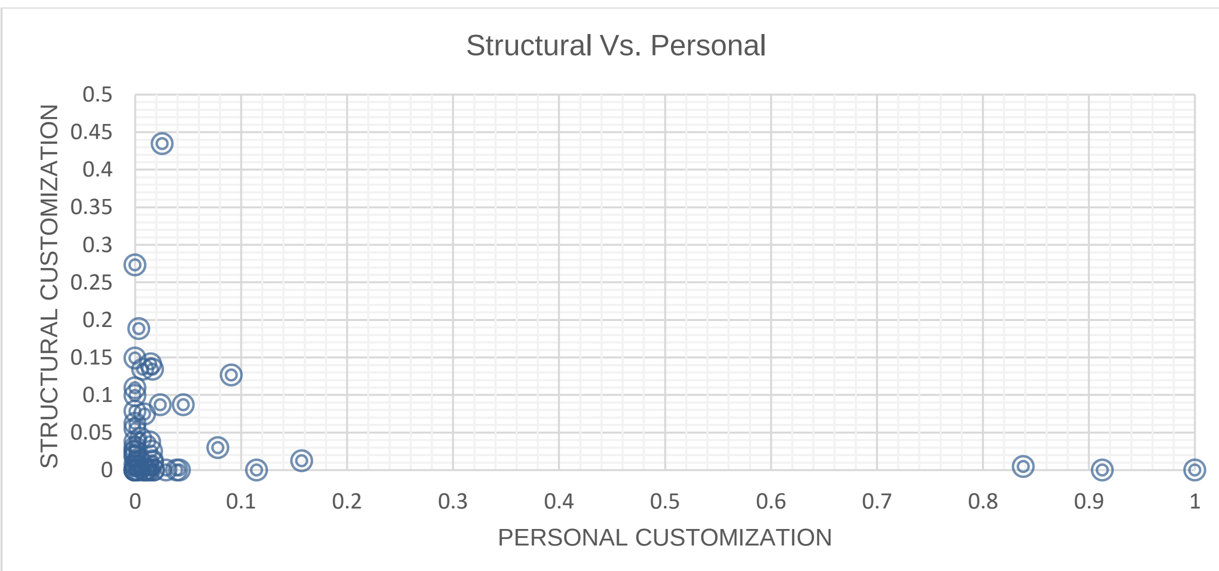

Figure 6. The normalized structural customization relative to the normalized personal customization