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Research

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Abstract

Flexible production technologies like 3D printing give users a large solution space to innovate and design. To harness the full potential of these technologies, it is imperative to provide toolkits, with structured and simplified solution space that meets the needs of users with low involvement. This paper explores the manner in which the solution space of 3D printing toolkits is simplified for non-expert users. Toolkit solution space was analysed in 68 toolkits with two perspectives of modularity: 1) Modularity-in-use and 2) Modularity-in-design. First, the solution spaces were categorized in a 2x2 matrix by using the perspective of modularity-in-use, i.e. design questions and design options they offer to users. Second, this categorization and the perspective of modularity-in-design were used to identify mechanisms that simplify toolkit solution spaces. Solution space can be simplified for non-expert users by 1) offering iterative design questions with known design options, 2) using generative algorithms, 3) reusing designs and components from other users and 4) offering 'meta-toolkits' for users to create their own toolkits. The meta-toolkits democratize toolkit creation, and simplify solution space for non-expert users, as they design innovative and customizable products, together with expert users, without losing design flexibility.

Keywords: Solution Space, Toolkits, User Innovation, Modularity, Design Space, 3D Printing.

1 Introduction

Users can innovate and design new products, when the problem information they possess is bridged to solution information of a manufacturing firm. The interaction and information cost arising in this process can be minimized with the use of information systems that enable users to develop new product innovations and designs themselves. These systems are called toolkits for user innovation and design (von Hippel & Katz 2002; Franke & Schreier 2002). Advances in 3D printing (or additive manufacturing as it is formally known) and related technologies, have brought digital design and production into the hands of users. With the help of 3D printing toolkits, users can design unique products virtually and then physically produce them with 3D printing, in almost any shape imaginable and in a variety of materials such as plastics, glass, ceramic, metal etc. (Dimitrov et al. 2006). Thus, a large design and manufacturing freedom is now available to users.

Users can utilize this large design freedom or "solution space" to innovate and design through advanced Computer-aided Design (CAD) software, that are advanced toolkits for user innovation and design (von Hippel & Katz 2002; Franke & Schreier 2002). These toolkits require a lot of user involvement, thus restricting them to expert users. The regular non-expert user who cannot put in as much time and effort to get involved with and learn, needs basic toolkits with smaller solution spaces (Prügl & Schreier 2006) often used for product customization and individualization (Franke & Schreier 2002). A small solution space allows limited elicitation of only relevant user preferences, thereby striking a balance between flexibility and ease-of-use (Zipkin 1997; Franke & Schreier 2002). In the context of 3D printing, basic toolkits are often easy to use web applications that allow users to customise existing products by changing a few parameters (e.g., a customisable finger ring with different sizes and patterns). These toolkits require much lesser user involvement than CAD software but are restricted to their underlying product design.

The importance of developing toolkit solution space, opening its development (Helminen et al. 2015) and democratizing it for non-expert users has been under researched in literature (Goduscheit & Jørgensen 2013; Salvador et al. 2009). This research problem is accentuated when the non-expert user's needs are too heterogeneous to be captured using only restrictive basic toolkits, as can be seen in 3D printing. Hence, this study examines toolkits in 3D printing and answers the research question of how solution space of 3D printing toolkits is simplified for non-expert users. Using a multiple case study approach, a database of 68 cases of toolkits in 3D printing was created. Theory on modular systems (Baldwin & Clark 2004) was used as the foundation for developing the cases and categorizing them based on design questions and design options they offer to users. To identify mechanisms for simplifying solution space, the cases were analysed using this categorization and modularity-in-design, for instances where they reduced design questions or design options for the non-expert user.

Out of the four mechanisms identified, opening of toolkit creation to users is highlighted, as this extends the 'openness' of toolkits in bringing ideas from outside the firm (Chesbrough 2003), by opening their development itself to users. It was found that 3D printing firms often include external toolkit makers into toolkit design; thus sharing the 3D printing solution space between external toolkit makers and users. In some of these cases, the external toolkit makers are also users rather than professional designers. Using a system that acts as a 'meta-toolkit', these users freely create toolkits for other users. Expert users use the meta-toolkit to design innovative products and then convert them into customizable basic toolkits for non-expert users.

The rest of the paper is structured as follows: It begins with literature background on toolkits, followed by the detailed research design and framework used to create and analyse the case studies. It then briefly describes the analysis of sample toolkits, presents the findings and discussions on the main findings. Finally, the paper concludes by providing implication for practice and research.

2 Background

2.1 Toolkits for User Innovation and Design

Hippel and Katz propose that toolkits for user innovation enable users to reach the following objectives (von Hippel & Katz 2002). Toolkits allow users to learn through performing cycles of trial-and-error. Secondly, they offer users a 'solution space' of design freedom not exceeding the manufacturer's production capabilities. Thirdly, well-designed toolkits are user friendly enough to enable their competitive use without additional training. Fourthly, they will contain libraries of standard modules that can be used as a starting point for their design changes. Fifthly, properly designed toolkits will ensure that user designed products or services can be produced by the manufacturer without requiring any further revisions. Toolkits can be classified into high-end or expert toolkits and low-end or basic toolkits based on the solution space they offer (Franke & Schreier 2002; Prügl & Schreier 2006). Expert toolkits are a source of radical innovations as they offer virtually all the solution space within the manufacturer's production capabilities to users. Thus they tend to be more challenging to use and demand greater user skill. Expert toolkits can be used to significantly alter a product or even develop a new product to meet unmet needs. Basic toolkits on the other hand offer a limited solution space to users and focus on customization and individualization (Franke & Piller 2003). They have lesser interaction costs in designing products as non-expert users are willing to only invest in design if the benefits of an individualized product exceed the costs associated in creating it (von Hippel 1994; Franke & von Hippel 2003). Basic toolkits have also been described as configurators, choice boards, design systems, or co-design platforms (Franke & Piller 2003). Table 1 provides a summary of key literature on toolkits for user innovation and design.

	Toolkit Objectives (Reference)/ Empirical Field
Expert Toolkits	Motivate and capture innovations from consumer community (Jeppesen & Molin 2003) / Computer Games
	Facilitate problem solving and aid information diffusion with community (Jeppesen 2005) / Computer Games
	Training inexperienced users to leading innovative users (Prügl & Schreier 2006)/ Computer Games
	Convert user community to a firm asset (Jeppesen & Frederiksen 2006)/ Music Instruments
	Co-creation experience around the toolkit (Kohler et al. 2009; Thomas Kohler et al. 2011; Kohler et al. 2011) / Virtual Worlds
	Identifying innovative users and innovation communication (Hung et al. 2011)/ Social networking
	Develop new services (Kankanhalli et al. 2015)/ Mobile Apps
Basic Toolkits	User satisfaction through customization (Franke & von Hippel 2003)/ Server Software
	Higher willingness to pay (WTP) for self-designed products (Franke & Piller 2004)/ Watches
	Peer assistance in toolkits improved problem solving behaviour (Franke et al. 2008)/ Carving Skis
	Customers have higher WTP when they know what they want (Franke et al. 2009) / Newspapers, fountain pens, kitchens, skis, and breakfast cereals
	"I designed it myself" effect creates economic value (Franke et al. 2010) / Scarves, T-shirts, cell phone covers, skis, and watches

Table 1 Toolkits for user innovation and design in literature

2.2 Solution Space Development

Solution space was in the past restricted by limits of flexibility in the production process, but this has been improving as new production processes and manufacturing systems have enabled firms to produce individual goods at near mass-product efficiency (Tseng & Jiao 1996; Dimitrov et al. 2006). Some of the first methods on developing solution space include (a) analysing existing consumer products and determining the dimensions required to design them, (b) making existing in-house design tools if any user-friendly or (c) using feedback from lead users. The solution space can then be fine-tuned by recording and observing usage patterns in the toolkits (von Hippel & Katz 2002).

Solution space in basic toolkits is often restricted, to keep a balance between design flexibility and perceived ease-of-use for the user (Dellaert & Stremersch 2005; Salvador et al. 2009). There is a trade-off in the design effort required to use the toolkit (Zipkin 1997), between retrieving exact customer preferences and keeping the toolkit user friendly (Randall et al. 2005; Prügl & Schreier 2006). At the same time, solution space with a minimal design effort gives users the "I designed it myself" feeling while designing their products (Franke et al. 2010).

In basic toolkits that work as configurators, solution space is in the form of configurable options in the toolkit. There can be a discrete set of options from which the user selects one, or a potentially infinite range where users can enter their exact preference (e.g., a text field or a picture upload option) (Huffman & Kahn 1998; von Hippel & Katz 2002). Randall et al. (2007) emphasize on offering a design parameter toolkit with exact product parameters to expert users, while offering a need-based toolkit (based on user needs) to non-expert users. In the case of a need based toolkit, providing a high 'preference fit' of users to their needs is preferred (Huffman & Kahn 1998). These user needs or preferences are characterized along three dimensions: fit, functionality and aesthetic design (Piller 2005).

Hermans has proposed a very extensive model for evaluating solution space of basic toolkits based on experiential creation (Dahl & Moreau 2007).The model interprets customization as a creative task and has two dimensions: Firstly, the level at which target outcome is dictated. This can be in terms of type of customizable product attributes, mechanisms for customization and amount of choice. Secondly, the amount of guidance provided to the user in creating an outcome. This is in the form of different starting points in the customization process, guiding method, instructions to the user and feedback of the process (Hermans 2012; Hermans 2014).

As can be seen in the above literature, solution space of basic toolkits (customization) has been researched. However, in the context of 3D printing, solution space is large and can be used in a wide range from customizing products to designing innovative products. This wide range of solution space needs to be researched as a whole in this context. Simplifying the solution space offered by 3D printing is significant in this context and presents a challenge for both expert toolkits (innovation) and basic toolkits (customization). For an expert toolkit, solution space has to be broken down into appropriate, simplified design decisions that encourage non-expert users as well. For basic toolkits, solution space needs to cater to heterogeneous demand from users that may otherwise fall out of their scope. For example, the 'Sake Set Creator' app (Shapeways 2015) can be used to design sake themed crockery and then manufacture them using a 3D printer. This toolkit allows users to visualize the product in three dimensions, and the solution space is restricted to creating cylindrically symmetrical shapes. However, users who need to create something other than a sake set will not have their needs met. These needs are outside the solution space of the toolkit even when they are well within the production capabilities of the firm. Thus, the basic toolkit that is aimed towards non-expert users is not sufficient for heterogeneous user demand and it offers only a part of the capabilities of a 3D printer to its users.

3 Framework of Modularity to Analyse Toolkit Solution Space

Toolkits, as described earlier, are built using modular libraries. Therefore, the theory on modular systems provides a valid perspective to study toolkit solution space. Modularization also serves the purpose of managing complexity (Baldwin & Clark 2004; Baldwin & Clark 2001) making it suitable for the research problem of how complex solution space is simplified. Two principles of modularity are relevant to the study: 1) modularity-in-use and 2) Modularity-in-design. Modularity-in-use is relevant to solution space as users mix and match elements at each level of the solution space to build their final product that suits their tastes and needs. On the other hand, modularity-in-design is relevant to solution space as the process of design is split up by the toolkit into separate modules that are operated by separate entities (users, manufacturers etc.), which are coordinated by design rules. These principles are further described below.

As users mix and match elements at different levels to build their suitable products with toolkits, they are following the principle of modularity-in-use. They design products by selecting different design options for each level of design questions offered by the toolkit. This can be better understood using the terminology of 'Questions' and 'Options' borrowed from design space analysis (MacLean et al. 1991). Design space analysis provides the rationale behind the design of an artefact, explaining not only the design of the artefact but also the reasons behind why it was exactly designed in that manner. It uses a simple notation called QOC that represents the basic concepts of decision space analysis: 1) Questions, which are the key design issues for the product; 2) Options, which are the possible answers to each design question; and 3) Criteria, which are the bases for evaluating and choosing among the options. Using this analysis, a finished product design can be explained as a series of 'QOC steps'. Table 2 explains the QOC notation using an example of designing simple 3D printed cufflinks using the "Round Cufflinks" Customizer from Mixeelabs.

Each design function or parameterized attribute in the toolkit is a design question. The user effectively 'selects' an option by choosing an attribute or applying the design function in a specific manner. The design questions and design options are limited by taking into account constraints of production and required user involvement. Although design criteria followed by users may be influenced in a toolkit by highlighting certain options over others (Randall et al. 2005), it is a characteristic of users rather than toolkit solution space. Hence, solution space is analysed in this framework by omitting criteria and using only the dimensions of design questions and design options from the QOC notation.

Design Questions *What different elements of the cufflink are customised?*	**Design Options** *What options does each design question have?*	**Design Criteria** *What are the criteria for choosing from the options?*
What material do the cufflinks have?	Steel, Silver, SLS Nylon Plastic	Has to be inexpensive
What is the colour/finishing?	Steel, Gold Plated, Bronze Plated	Needs to fit to formal occasions
What is etched?	Text or graphic	Personalized with users name
What text is added?	Any text can be entered	Personalized with users name
How is the text positioned?	Along the surface of the cufflinks	Aesthetically placed
What size is the text?	XS, S, M, L, XL	The final design should be aesthetic

Table 2 QOC steps for designing with the "Round Cufflinks" toolkit

As the user designs a product with a toolkit, the process of product design has contributions from both the user as well as the toolkit maker, following the principle of modularity-in-design. Highly networked additive manufacturing industry also behave like modular organizations (Schilling 2000; Schilling & Steensma 2001; Sanchez & Mahoney 1996) where the process of product design is split up and distributed across separate modules. Furthermore, these modules of contribution are coordinated by design rules enforced by the toolkit rather than direct coordination between users and manufacturers (Baldwin & Clark 2004). Toolkit makers contribute to their module of product design and set the design rules for coordinating with users' modules of product design. These design rules are often enforced by limiting toolkit solution space to only the allowed design rules of the toolkit maker (von Hippel & Katz 2002). Modularity-in-design can be used to answer where design contributions come from when using each toolkit, and identify mechanisms through which non-expert users benefit, with lesser design questions and options.

4 Research Method and Data

To fulfil the objective on how to simplify solution space for non-expert users, solution space of toolkits for both user innovation and design in 3D printing is analysed as a whole and examined as a complex system that can be simplified. Since this is a rather new phenomenon, an exploratory qualitative method is used to discover and generate theory in the form of propositions derived from data (Eisenhardt 1989). The paper aims to investigate systematically and in depth the contemporary state of the art of toolkits in 3D printing. It also addresses a "how" question where the investigators have little control over events, with many variables of interest and can take advantage of multiple sources of data, hence making case study research suitable for this study. A multiple case study design is chosen here with a single unit of analysis for all the cases (Yin 2013). A case here refers to a toolkit in 3D printing and the solution space of the toolkit is the unit of analysis. Solution space of each of the cases is iteratively analysed and compared across cases to bring out attributes and to identify mechanisms for simplifying solution space.

4.1 Research Design

The research process followed is described with the following five steps. The first step was to conduct desk research and direct keyword search to identify 3D design software. Second, data regarding the 3D design software was gathered and developed into case vignettes. Third, the 3D design software cases were screened to a sample of 3D printing toolkits. Fourth, data from these toolkits was analysed along relevant concepts in theory of modularity and design space analysis to derive the attributes of solution space and modular approaches used to simplify solution space. Fifth, the sample cases were enriched and synthesized based on the respective toolkit attributes and modularity approaches. Each of these five steps is further elaborated below.

As the study focusses on toolkits for end users, it was limited to toolkits publicly available to retail end users and available online in the form of web based applications, downloadable software for PC or downloadable mobile apps. The first step was to identify relevant software that allowed users to design in 3D. This was done by means of desk research and keyword search. Direct keyword search for the search terms '3D printing', '3D design' and '3D tools' using Google itself resulted in 89.3 million, 454 million and 254 million results respectively. Hence, the search results for these terms were limited to the first 100 results from each keyword and the search was repeated with Bing and Yahoo online searches for new results. In all, these research approaches led us to identify 118 instances of 3D design software. For each design software, the name, its organization, URL and contact email were recorded.

The websites of the 3D design software were then examined in the second step and all relevant data such as documentation, video tutorials, FAQs, support information, forum posts and other community discussion were recorded in a central repository and subsequently used to create the case vignettes. Each case vignette followed a structure that included meta-data of the 3D design software, such as the organization providing it, its availability, and the type of output they generated. The data collected for the vignettes was used for screening the cases in the following step.

For the third step, the design software was functionally trialled whenever the full or demo version was freely available and the rest were excluded for lack of access. Some of the 3D printing toolkits were filtered out because they were only web forms to get users' preferences and they did not provide users a direct visualization of the 3D design which is needed for trial-and-error cycles (von Hippel & Katz 2002). The 3D design software cases were also screened to see if their outputs could be used for 3D printing. Hence, selected toolkits either generated .STL files (an established format for 3D printing) or were connected to 3D printing services. This filtered out cases of 3D design software that did not create closed 3D shapes (3D animation software etc.). Design software that were CAD systems purely for professionals, were filtered out as well to yield a sample of 68 cases.

In the fourth step, the cases were again enriched with data collected by following usage documentation, tutorials, community discussions and online content to reflect the context of their real-life use. The cases were then analysed, using modularity theory and design spaces described earlier. After multiple iterations of analysis, the attributes of solution space were identified and recorded. The identification of the attributes was done inductively, within the theoretical framework. Mechanisms of modularity used to simplify the complexity of designing in 3D were also identified and documented into the cases.

In the final step, the identified attributes and modularity mechanisms derived in the previous step were used to code and enrich the cases. The cases were repeatedly updated using data from the repository that related to solution space attributes and mechanisms of simplifying solution space. The case analysis and findings were compiled and then presented in this paper.

4.2 Data Sample

The 68 identified toolkits were offered to users by both 3D printing services as well as external toolkit makers. The toolkits offered two ways of 3D printing. Thirty-eight toolkits used APIs (Application Program Interfaces) offered by 3D printing services such as Shapeways, i.materialise, Sculpteo etc. and they directly connected to these services. The others allowed users to download or save their 3D designs in the form of standard 3D printing file formats such as .STL. A bulk of the sample (45 toolkits) in the sample were linked to 3D printing related organizations such as the services mentioned above and Thingiverse the online 3D printing community from Makerbot. Out of the 68 3D printing toolkits, 54 toolkits were web based and 14 were desktop software that could be downloaded and installed. Out of the web-based toolkits, 11 allowed users to design online and download the design files while 43 web-based toolkits restricted user designs to their servers and directly connected with 3D printing services. The desktop-based toolkits all allowed users to save their designs and print it themselves. Table 2 lists the sample toolkits used in the study.

3D Tin	Cus. iPhone Case	Meshmixer	Shapeways Minetoys
3D Trophy Factory	Cus. Lithopane	Mixee Knotty Ring	Shapeways Mineways
Adobe Photoshop	Cus. Torus Knot	Mixee Me Figurines	Shapeways Sake Set
Ambretine Koeketine	DAMN Cufflinks	Mixee Round Cufflinks	Shapeways Shapewright
Anne Zeilien Gold	Draw your own earrings	Mixee Square Cuff Links	Sketchup Make
Anne Zeilien Silver	Dreamforge Cookie Caster	Mr. Maria Night Lamps	Sketchup Pro
Archipelis	Electrobloom ring	ODO	Skimlab
Archipelis Custom Ring	Figure Totem	OpenSCAD	Super Flowers
Archipelis Poker Chip	Flower	Parametric Cookie Cutter	Text Totem
Autodesk 123D Catch	Fontbox	Parametric Music Box	The Vibe iPhone case
Autodesk 123D Design	Jweel embossed ring	Parametric Parts	Tinkercad
Autodesk 123D Sculpt +	Jweel Freestyle Pendant	Printcraft	Toyze
Cafe Costume	Jweel Text Pendant	Quark Jewelry	Uformit
Cell Cycle	Jweel Text Ring	Ring Shapewright	Universal Phone Car Mount
CubeTeam	Kees Customizer	Sculptris	Wall Mount Key Holder
Cus. Battery Tray	Materialise Fluid Forms	Sealring	Wave Bracelet
Cus. Easy Gyro	Materialise Fluid Vase	Sertae Knotwork Necklace	Zbrush

Table 3 List of the 68 sample toolkits

The cases on these sample toolkits were developed using the theoretical lens of modularity described earlier and analysed to find significant results. The principles of modularity and design spaces serve as a framework for empirical analysis of toolkit solution spaces. It also is a basis to compare each toolkit against the overall design process needed to design a product for 3D printing. By applying this framework, mechanisms used in existing toolkits to simplify 3D printing solution space are identified for the non-expert user. This is explained in further detail in the following sections.

5 Analysis of Cases

The solution spaces of the 68 toolkits were analysed using the two modularity frameworks described previously and the analysis is presented. First, as users follow the modularity-in-use principle to design their products, toolkits solutions space can be categorized based on the number of design questions and their respective number of design options (see Figure 1). Section 5.1, describes the four categories, with the help of exemplar toolkits. Section 5.2 describes the analysis of toolkit solution space based on their resulting modularity-in-design.

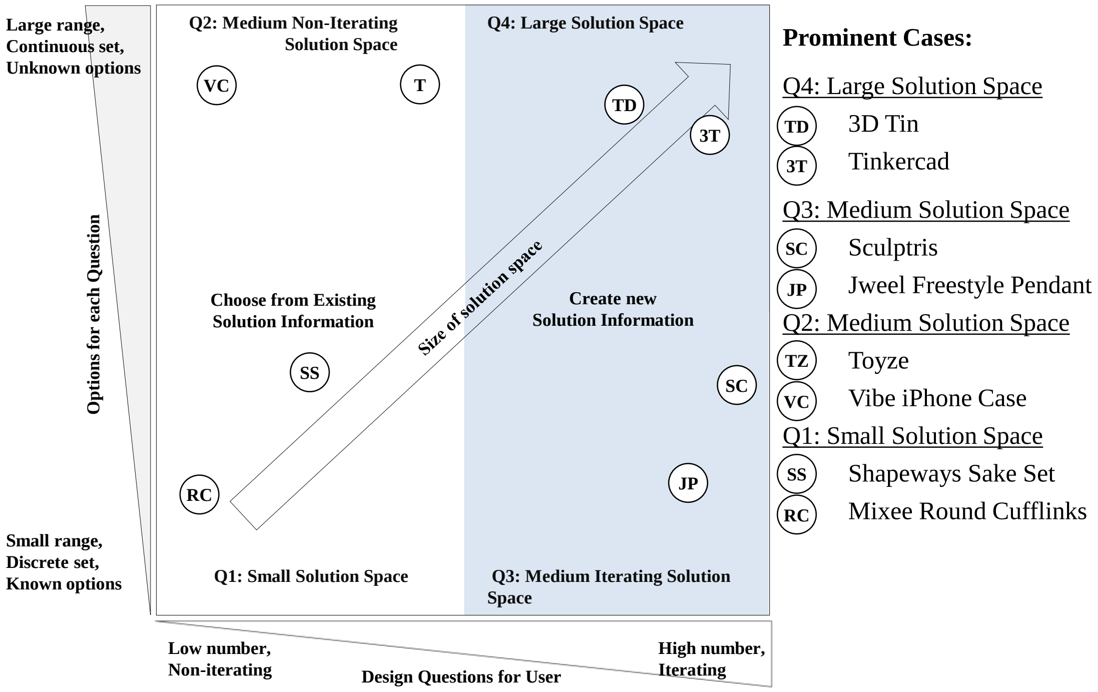

Figure 1. Categorization of solution spaces in 3D printing toolkits.

5.1 Solution Space Categorization based on Modularity-in-use

The toolkits were categorized by the nature of most of the design questions and options in their solution space. Design questions in a toolkit with a small solution space are a fixed set and low in number. This is in contrast to toolkits with large solution spaces where there are many design questions and they are answered iteratively by the user to design shapes that are more complex with each iteration. The dimension of design options for these questions in toolkit solution space can vary from being a discrete set of known options that are small in number to a continuous set of unknown options that first need to be explored by the user with trial-and-error cycles.

Quadrant Q4 in Figure 1 represents a large solution space that requires a lot of user involvement. The 3D printing toolkits Tinkercad (TD) and 3D Tin (3T) fall in this quadrant. They are web based 3D design tools dedicated to 3D printing, which give users a lot of flexibility but are much less complex than professionally used CAD software. They give users many basic 3D shapes such as cubes, spheres, cylinders, etc. to use as building blocks, whose dimensions can be highly configured and then placed so that they add to or subtract from existing shapes. Hence the user can ask design questions such as "What shape do I use?", "How is the shape configured?", "Where is the shape placed?", "Does the shape add or subtract to other shapes" etc. repeatedly in many iterations to design complex 3D designs.

Quadrant Q3 represents a medium solution space. Here the solution space has users answering many iterative rounds of design questions. However, each of these questions has only a limited set of simple, easy to visualize design options. The toolkit Sculptris (SC) is a 3D design tool where users can design in 3D as if they were sculpting with clay. It offers sculpting tools such as smooth, sharp, flatten, grab etc. that can be applied at various strengths and to various areas of the 3D design, just like a sculptor would operate with real clay. Hence, the questions are "which sculpting tool do I use?" "How strongly should the tool be applied?", "Where should the tool be applied" etc. The design options for these questions are limited, but on repeated application of the sculpting tools can be used to design complex shapes. Jweel Freestyle Pendant (JP) uses a similar solution space for users to design their own jewellery.

The other quadrant of medium solution space is Q2, where there are a fixed and relatively low number of design questions, but users have a wide range of unlimited design options that often need to be explored by users. The Vibe iPhone Case Creator (VC) for example, etches the waveform of an audio clip onto an iPhone case. Here there is only one major design question, "What sound clip should I use?" However, a user may first need to try out many possible options of audio clips. Toyze (TZ) is a 3D printing toolkit where users can create, customise and order figurines of popular mobile game characters in various poses, outfits and accessories. Here again the design questions are limited and fixed. However, each design question has a large number of design options, which are often new. The user needs to be familiarized with these options through many trial-and-error cycles before finalizing the product.

The quadrant Q1 represents a small solution space and has the simplest toolkits. They tend to have a discrete small set of fixed questions with a small set of fixed design options for each question. The Mixee Round Cufflinks (RC) allows users to select different materials and enter initials on them. Hence, the design questions are "What material do I use?" and "What initials do I use?" each of which has a limited number of design options. The questions and options are relatively known; hence, they require much lesser user involvement. The Sake Set Creator (K) described earlier is similar as it allows users to change the shape of a sake pot along certain dimensions and configure the pattern. This typically leads to a small number of possible solutions. They may not be perfect solutions, but for the non-expert user with a high cost of user involvement and lower aspirational levels, these solutions are sufficient. Design questions in this quadrant were often also in a fixed order to further simplify the solution space.

5.2 Solution Space and Modularity-in-design

Modularity-in-design involved in the designing with these toolkits were analysed and is presented. While product design when using a toolkit is expected to come from the user and manufacturer, there is additional design modularity seen in 48 toolkits. Product design in these cases may have additional contributors, such as toolkit makers, users who design (both novices and experts), users with their own 3D printers, or organizations providing a 3D printing service. The modularity in design is further explained by looking at the architecture of the toolkits that reveal design rules between the modules.

Thirty-two of the toolkits in our sample were created with libraries based on JavaScript such as WebGL. Some examples of toolkits created by this method are Cell Cycle, Dreamforge Cookie Caster and Kees Customizer. The libraries were augmented by APIs provided by 3D printing services for functions such as printing cost, printing feasibility, ordering prints etc. This architecture gives a lot of flexibility to toolkit creators, as they are free to design any 3D shapes, as long as the output is a printable 3D design (manifold or watertight meshes). The toolkit maker then identifies aspects of the 3D design that can be parameterized and given to users to customize. This results in fixed and small number of design questions with associated options to form niche but innovative basic toolkits. However, the toolkit maker who does the bulk of the design contribution needs an advanced knowledge of a browser based programming languages and libraries used for 3D rendering. The toolkit maker does not follow specific design rules and hence there is some interaction between the toolkit maker and the 3D printing service before a toolkit is verified and accepted.

The second group of 16 basic toolkits were developed by users themselves, using intermediate systems provided to them. These systems acted as meta-toolkit that enabled users to create basic toolkits. The first meta-toolkit identified is the 'Customizer' app by Thingiverse that enables users to create basic toolkits. Users create scripts written in OpenSCAD that describe a 3D design of an object. This design can be parameterized and users can specify limits for each parameter and an appropriate form element such as drop down boxes, sliders, checkboxes, radio buttons etc. These scripts are uploaded into the Customizer App, which converts the script into a basic toolkit called a 'Thingiverse Customizable'. An example of such a basic toolkit was the Mobile iPhone Case Creator mentioned earlier. The Mixee Creator is also a meta-toolkit that imports scripts by users written in 'Three.js', a powerful java script library for 3D design that is based on WebGL. Similar to the OpenSCAD method used by the Customizer App, the mixee creator also provides a library of shapes and geometries, which users can use to create a 3D object with parameters. Tinkercad also uses this approach by letting users develop their own parametrized shapes using JavaScript based libraries and uploading them into their servers. These parametric shapes can be used by other starting points as building blocks for their designs. Digital Formation takes this principle further through Odo, their "Software as a Service" offering to designers. It enables designers to build customization toolkits rapidly that are already integrated to 3D printing services and e-commerce websites.

The meta-toolkits above are in the form of a library of user input elements such as dropdowns, radio buttons, sliders etc., 3D shapes such as cube, sphere, torus, cylinder etc. and operations such as move, scale and merge these shapes. They offer a set of known design questions for the user. Firstly, what are the underlying shapes of the users design? Secondly where are these shapes located and thirdly, which parameters of these shapes are customizable? These questions can be asked iteratively to give sufficient design freedom while managing complexity. They result in the creation of customizable designs based on embedded 3D printing related design rules, with simplified solution space that is decided by users.

6 Findings: Simplifying Solution Space for Users

To identify how solution space of 3D printing toolkits can be simplified, four mechanisms were identified in the 68 compiled cases of toolkits that gave users flexibility in design while reducing their involvement or encouraging their involvement in the design process. Figure 2 illustrates the four mechanisms by marking how solution space is simplified by reducing design questions, options or both. The findings describe the four mechanisms below along with propositions.

Design questions with a large number of options that are unknown to users require many cycles of trial-and-error before users become familiar and can actually start using a toolkit. Breaking these design questions down into design questions whose outcomes are known to the user encourage their involvement. Sculptris and Jweel Freestyle Pendant, the two cases explained earlier can be used to design a wide variety of 3D shapes without prior knowledge using simple sculpting functions. It reduces design options in the solution space (Q4 to Q3 in Figure 2) at the cost of going through more but known design questions. This leads us to:

> **Proposition 1:** Offering known, iterative design questions and options instead of unknown design questions and options can simplify solution space for users.

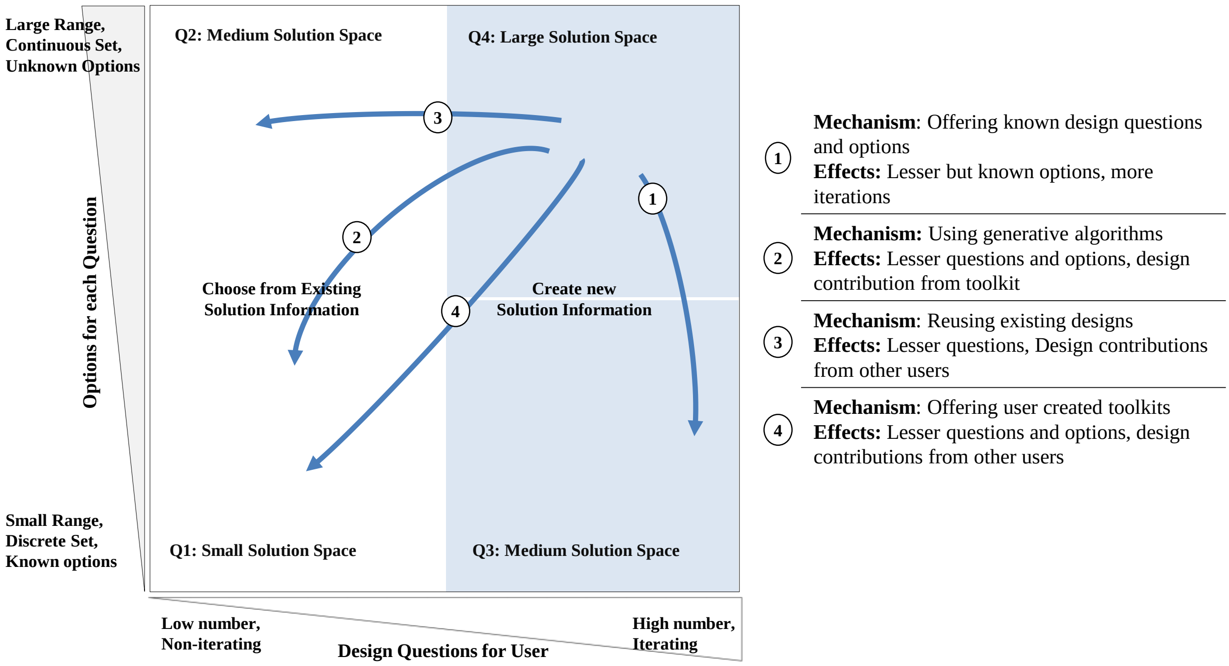

Figure 2. Mechanisms for simplifying solution space for users in 3D printing.

Toolkits like Cell Cycle and Super Flowers customizable generate their 3D designs by algorithms. The generated designs are inspired by nature such as microscopic cells and flower petals with parameters that can be customised by users. The users do not have to design complicated shapes as this is done by the algorithms, thus reducing design questions. This also ensures that the solution space has variety in design output while being within the aesthetic limits set by the toolkit makers. Hence also potentially eliminating certain design options from the solution space (Q4 to Q1 in Figure 2). This leads us to:

> **Proposition 2:** Using algorithms to generate 3D design can simplify toolkit solution space for users

The Autodesk 123D Catch generates 3D designs from user-uploaded photos. The Fluid Form toolkits connect to external services like Google Maps and Google Earth and generate 3D designs from maps or 3D images of these locations. Tinkercad, Sketchup, 3D Tin etc. are connected to a design database where users can access designs from other users and improve them. These features reduce a lot of the design effort of users and hence simplify toolkit solution space by reducing their contribution in design. This mechanism considerably reduces design questions the user would otherwise have required to answer (Q4 to Q2 in Figure 2). This leads us to:

> **Proposition 3:** Offering the ability to extend existing designs can simplify solution space for users.

Meta-toolkits like the Customizer from Thingiverse, converter from Mixeelabs, parametrized shapes from Tinkercad highlight a new approach in toolkit design where firms enable users to create innovative basic toolkits rather than just products, thus spreading user involvement in design between various users. These meta-toolkits democratize toolkit creation by allowing some users to design toolkits themselves and reduce the contribution needed from others. Hence, users only customise certain parameters rather than designing from scratch, reducing both design questions and options (Q4 to Q1 in Figure 2). This leads us to:

> **Proposition 4:** Offering users the ability to create their own toolkits can simplify solution space for some users.

7 Discussion Based on the Findings

Out of the four mechanisms identified, the first encourages non-expert users to use a toolkit by making each design decision easy. However, expert users may find it frustrating, as they will have to perform many iterations of these design decisions. The other three mechanisms reduce design questions and options for the user. Similar mechanisms can be seen in other settings. Using algorithms to filter design questions and options can be seen in recommender systems for decision making (De Bruyn et al. 2008). Design tools that learn and acquire problem specific knowledge and then support decision making have been developed and presented (Gero 1996). Likewise, sharing existing designs is a common mechanism that has been reported in toolkits for mobile (Piller et al. 2004) and computer (Prügl & Schreier 2006; Jeppesen 2005) games. However, the conversion mechanism by which existing non-3D design content such as photos, external services etc. can be converted to 3D designs can be considered novel to this field. Furthermore, 3D printing toolkits take two approaches in terms of openness in knowledge access. One approach is through a cloud-based service, they restrict all creation to the toolkit servers, hence restricting design sharing while encouraging selling of designs to other users. The other approach is to offer a toolkit that allows users to save their designs and share them or to connect to open design databases. By doing so, users can freely reveal their knowledge and benefit each other (Von Hippel & Von Krogh 2006).

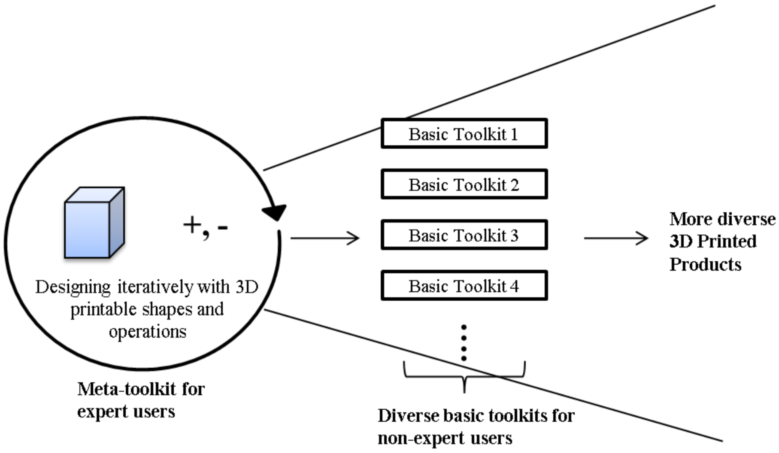

Figure 3. ‘Meta-toolkit’ for user designed toolkits lets users design many basic toolkits that altogether span a large solution space

The meta-toolkit is highlighted Figure 3 as it improves upon the traditional approach of creating solution space of basic toolkits in 3D printing. Unlike the traditional approach, where toolkits are created in-house or by professional designers, offering a meta-toolkit opens solution space development to users. It enables users to create their own solution space for toolkits (Helminen et al. 2015) and can be considered closer to the overall aim of democratising innovation (von Hippel 2005) that was found wanting (Goduscheit & Jørgensen 2013). It is a dedicated system to create basic toolkits in 3D printing, hence uses 3D printable shapes as building blocks and appropriate operations. It enables users to innovate by repeatedly answering a smaller set of known design questions, in contrast with using all-purpose 3D design software libraries. From this meta-toolkit, expert users can create basic toolkits with small solution spaces aimed at non-expert users. Hence, this *toolkit for user created toolkits* is a new approach and ideal for simplifying solution space of 3D printing.

8 Implications and Conclusion

This study has research implications as it provides a framework to analyse toolkit solution space and suggests how it can be simplified for the non-expert user. In doing so, it identifies and describes mechanisms in the field of 3D printing that simplify solution space which may be extended to other problem domains such as do-it-yourself electronics (Baafi & Millner 2011; Cvijikj & Michahelles 2011; Mikhak et al. 2003), app development etc. The resulting modularity based framework can be used as a theory to analyse solution space and the developed propositions can be used as a theory to predict solution space design and construct toolkit artefacts based on the identified mechanisms (Gregor 2006). User created toolkits corroborates with the study on toolkits used in the game 'The Sims' where expert users, discontent with the official toolkits provided by the manufacturer, created and used their own toolkits that also had a high demand among other users. The approach of offering meta-toolkits extends the 'sticky information' approach of von Hippel (von Hippel & Katz 2002; von Hippel 1994). Instead of just transferring sticky solution knowledge from firms to users, the purpose of toolkits is extended. Users can also select appropriate sticky solution knowledge relevant to them, and the toolkit transfers it to other users. This multi-level approach has implications on how users, user communities and firms can truly leverage each other's capabilities to develop more innovative and differentiated products. The role of the manufacturer in design inputs is quite limited to the meta-toolkit offered to its users. The next level of design inputs comes from expert users who use this meta-toolkit and create innovative designs and define what attributes of the designs can be customised. Other users provide final design inputs by creating their customised and innovative products.

This study has managerial implications for 3D printing firms developing toolkits for user innovation and design. It identifies mechanisms with which non-expert users can be further included in the user design process. Furthermore, as basic toolkits or customizable products do not always meet the diverse needs of heterogeneous users (in the context of 3D printing's large solution space), it identifies and highlights a new approach of offering meta-toolkits to users. These lead to development of toolkit ecosystem in the rapidly growing field of 3D printing where users can always find configurable products closest to their requirements. For example, users have created more than 800 basic toolkits using the Thingiverse Customizer. It also emphasizes on a strong user community as a valuable source of competitive advantage to the firm even when addressing non-expert users. Thus enabling users to design their own toolkits is the way forward to unleashing the potential of 3D printing technologies.

The cases were limited to publicly available browser based basic toolkits. The study was also limited to the perspective of toolkit designs and their solution space without considering other interesting perspectives such as user motivation, value creation, firm strategy etc. A limitation of the meta-toolkit is that non-expert users have to depend on expert users to innovate for them. Future studies may follow a design science approach (Hevner et al. 2004) and design various toolkits based on the identified mechanisms. Toolkits that assist non-expert users to innovate by generating solutions may address the 'wicked problem' (Rittel & Webber 1984) of giving non-expert users solution space that is both flexible and simple. Validating the four mechanisms, identified using quantitative studies will also form a challenging future study.

To conclude, this study explains how the potentially large solution space of 3D printing is structured and simplified for the non-expert user. It improves on existing categorization of toolkits between expert (high-end) and basic (low-end) toolkits by providing measurable attributes of 3D design solution space based on design questions and options. Among the many mechanisms found in empirical data of 3D printing toolkits to simplify solution space for non-expert users, it emphasizes on the mechanism of offering users meta-toolkits to create their own toolkits. Through meta-toolkits, users can themselves create many basic toolkits that could potentially span the entire solution space and diverse user needs. This multi layered user involvement in innovation and design bridges concepts of user innovation and customization and effectively handles the problem of structuring toolkit solution space.

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