PERSONAL FABRICATION: THE DIGITAL CULTURE IMPERATIVE

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1. INTRODUCTION

In recent years, the increasing accessibility of public to the computer platforms together with recent advances in hardware technologies has formed a new paradigm in many socio-technical systems. In this new paradigm, members (agents) of a society follow a set of self-organizing actions, which result in a highly decentralized or distributed system as a whole (Resnick, 1997 and Railsback and Grimm, 2011). This is unlike the traditional *centralized mindset* where the main processes are directed or controlled by a few agents that influence the actions of all other agents (Anderson and Bartholdi, 2000). Personal Fabrication (PF) — as a new emerging mode of production—is an example of such new paradigm. It consists of a network of physical and virtualized nodes of design and manufacturing operations that allows agents to design, customize and fabricate their products on their own (Malone and Lipson 2007, Wu. et al., 2012 and Lipson and Kurman 2013). Self-organizing agents employ small-scale manufacturing machines such as 3D printers, laser cutters, and programmable sewing machines together with a digital design model in order to create a wide variety of objects and products. The objects can be sold, exchanged with other personally fabricated objects, or sent to be assembled into more complicated products. These decentralized interconnections will soon provide a platform for makers, designers, and consumers to supply their custom products, as well as to compete or collaborate with large mass-production companies.

PF, as described by Gershenfeld (2005) is the "integration of logic, sensing, actuation, and display" of almost everything required to make a three-dimensional structure and beyond into a complete functioning system. The modern modes of Personal Fabrication first came into popularity during the 1950s with emergence of Do-It-Yourself (DIY) culture, where people started undertaking personal small-scale projects for the sake of cost efficiency as well as well as recreation (Fox, 2013). This culture was particularly spread by mass-production companies, upon realizing that DIY not only managed to reduce production cost, but also might increase customer valuation and satisfaction (See e.g. Norton et al. 2011). They designed and developed many self-made products that usually arrived with some assembly steps required. However, the main problem with such ready-to-assemble products was that the customers were not typically able to customize their products based on their own personal needs.

Emerging in the late 1980s, Mass Customization was a direct response to the increasing demand of product customization. Kaplan and Haenlein (2006) define Mass Customization as "a strategy that creates value by some form of company-customer interaction at the fabrication and assembly stage of the operations level to create customized products with production cost and monetary price similar to those of mass-produced products". Da Silveira et al. (2001) state that Mass Customization should provide customized products and services through flexible manufacturing processes and at the same time should maintain total production costs at an acceptable level. Pine II (1992) enumerates four levels of mass customization, namely collaborative (co-creation), adaptive, transparent and cosmetic. Although most forms of customization could be placed in one of the aforementioned levels, Turner (2011) mentions that customized products are often limited to a number of features of a pre-designed product. This is different with custom goods where the consumer determines and designs all product features. Regardless of the level of customization, the production systems in Mass Customization are still centralized which controls and confines customer features.

In recent years, the idea of personal fabrication has been fused with novel advances in computer milling technologies and has formed a new mode of production that is referred to as Digital Fabrication (DF). DF consists of a set of processes and technologies, which employ digital information to turn a digital file into a particular form of structure through cutting, joining, and other manipulation of physical materials (Mellis, 2011). Since the path toward DF has been started, its perquisite technologies—3D printers, personal-scale machines, 3D modeling packages, and online sharing platforms— have also been growing and becoming more affordable for ordinary people. This implies that most activities that are done by a single manufacturer, can soon be carried out anywhere by anyone with a basic level of design and computer knowledge. Therefore, we are currently dealing with the personalized aspects of Digital Fabrication— Personal Digital Fabrication (PDF). In this context, people are conscious agents who respond to their needs by making their own tools, using their own digital fabrication machines and by networking with peers with common goals and interests (Tomas Diez, 2012). This, ultimately, moves toward a social shift where a particular personal need will be addressed by a wide range of diverse tools/products designed and fabricated by people with various perspectives.

In this study, we investigate how PDF affects the process of making custom/customized products and how it facilitates the process of generating an idea based on a user's personal needs. Through three simple case studies, this paper explores the process of making a custom/customized product from the idea generating stage to final product, using PDF. The outcome helps people make their customized products less expensive, by lowering production set-up costs. It is also useful when there is a potential need and no specific tool to address it or the solution is not economically feasible to be produced through mass production.

2. DECENTRALIZED MODE OF MANUFACTURING

The main catalyst for boosting the technology and market of Digital Fabrication is crowd sourcing, where people take part in different stages of product development. While millions of people throughout the world consume mass-manufactured products, a fast growing number of them are now designing, producing, and marketing their own products. This is a continual transition state from centralized system to a "maker culture" of decentralized manufacturing innovation (Igoe and Mota, 2011).

Figure 1 depicts a conceptual representation of the centralized and decentralized manufacturing systems. In centralized systems, a few particular agents are responsible for developing, producing, and supplying the products and the remaining agents are only consumers who do not play major roles in manufacturing processes. By employing the standard parts and procedures, the manufacturing agents attempt to minimize deviation from the standard designs. The products are typically designed to match with the needs of the majority of consumers. Even those products that seem personalized or customized keep sharing some essential components of mass manufactured products (George, 2010).

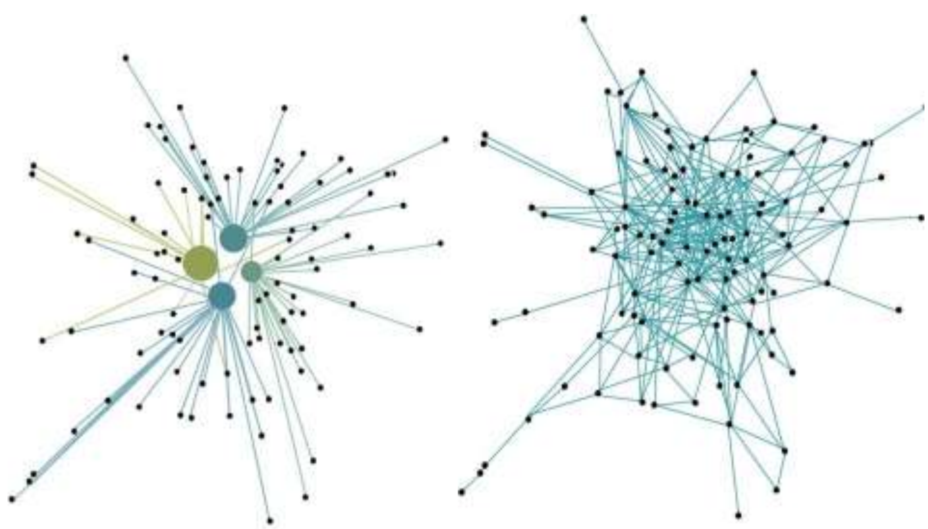

Figure 1. Hypothetical centralized system (mass production) and decentralized system (Personal Digital Fabrication)

In a decentralized system, agents are autonomously able to contribute in all stages of the production process— research, design, pre-production, manufacturing and supply. In this system, products and their production processes are often more simplistic than those manufactured by centralized mass production systems. However, they together form a complex network of supply and demand which provides more flexible and diverse products. The agents in a decentralized manufacturing system are self-organizing, intelligent, and purposeful. They collaborate with other agents to identify their needs, design to respond to those needs and share their solutions via online platforms.

PDF is a multi-agent decentralized system, where various players influence and are influenced by the manufacturing network as a whole. Figure 2 presents the agents that play major roles to form a democratized structure for manufacturing systems. They affect the marketplace, increase the variety of goods and address small-scale design problems. The following types of agents can be significant in a decentralized manufacturing system:

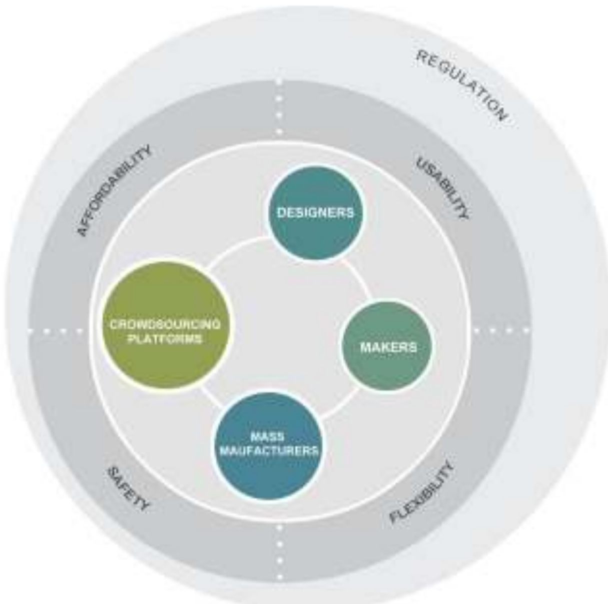

Figure 2. The players of a PDF agent-based system

- **Makers**: Makers are of the essence to the personal digital fabrication. They are people with basic computer skills, yet creative enough to use digital tools and desktop fabrication machines and make *almost everything*. Makers are *digital DIYers*, who share their ideas and solutions through their objects and prototypes (Anderson, 2012). They are “Expert Amateur” agents, who revitalize their old products, digitally recreate the missing parts, and replace them with the outdated ones (Mota, 2011). In a decentralized market, makers are buyers and sellers at the same time. They buy the digitally fabricated parts, assembled with the self-fabricated components and supply them in the market.
- **Designers**: Designers are professional agents that enable makers to design and fabricate complicated products. In the decentralized mode of manufacturing, designers are thinkers who identify hidden needs, create novel ideas to address these needs and sell them to the makers through digital files and online platforms. Designers are the expert makers who fabricate more complex and elaborated products with higher levels of functionality and aesthetics. Valamanesh and Shin (2012) state that in complex projects, digital fabrication allows professional designers to develop their design ideas in a timely manner. This is mainly because the fast prototyping process facilitates the processes of tangible modeling and model refinement.
- **Crowdsourcing platform**: If makers and designers are the nodes of a PDF decentralized network, online Crowdsourcing platforms are lines that dynamically connect nodes together and allow them to exchange their needs, ideas, 3D files, and physical objects. According to *Crowdsourcing.org*, in 2012 more than 2000 different crowdsourcing platforms were active and raised about $2.7 billion. They provided a wide range of services including, idea generation, design, 3D printing, crowdfunding, 3D file sharing and so on. The interconnection between online Crowdsourcers and other agents move the PDF practices towards the democratization of manufacturing where many people gain access to all required software and hardware to make their personal products.
- **Mass Manufacturers:** Mass manufactures are also agents in PDF agent-based systems. They interact with other agents, in particular makers and designers—who are now able to fabricate parts in their homes. They

solicit contributions from makers to fabricate those parts of their products that are not feasible or economically justifiable with their current manufacturing technologies.

In addition, Figure 2 presents two external layers that can facilitate the PDF practices within a decentralized system. The first layer is related to the PDF technology. Both digital fabrication hardware and software *technology* have been rapidly growing and their prices have significantly been lowering. Lipson and Kurman (2010) refer to the personal manufacturing technologies as *Fabbers*—the small sized, low-cost version of mass manufacturing machines. The new generations of Fabbers are *affordable* for a wide range of makers and designers. The personal-scaled 3D printers and laser cutters are now about $1000 and their prices have significantly dropped in the last few years. They often use built-in sensors and mistake-proofing techniques to avoid user mistakes and decrease *safety* problems (Lipson and Kurman (2010)). Fabbers are now more *flexible* and a wider range of materials can simultaneously be combined into a single product. The flexibility in choosing raw materials allows makers and designers to have more *usability*. They look into any hidden needs and address them with many digitally fabricated solutions. They are able to evolve their inventions over time by testing them in practice. Moreover, the agent-based decentralized model consists of an outer layer of regulation (See Figure 2). Design files can be copied and scattered throughout the Internet just easily as a digital music track can be copied today (Morris, 2007). 3D files, blueprints, and 3D digitally fabricated objects need to have comprehensive regulatory compliances to ensure that people are aware of relevant copyright laws and regulations.

3. CASE STUDIES

In this section, through three small-scale case studies, we discuss how users can employ a 3D printer, and simple digital models to create various objects. The main objective of this study is to investigate several possibilities that PDF provides for users— not necessarily designers— to address their personal needs. In fact, the possibilities are endless. However, in this study, we focus on three specific cases that highlight the decentralized mode of manufacturing. We choose simple examples to stress that the makers with a basic level of design and computer knowledge are able to fabricate small-scale personal products. We employed MakerBot Replicator 2X Experimental 3D Printer, which used Fused Filament Fabrication technology, as well as ABS Plastic as raw material. To define good case studies, we looked into a number of our personal needs hidden in our daily activities and tried to turn them into simple useful objects through PDF. We focused on simple needs of makers that were ignored by mass manufacturers for different reasons. The case studies were selected in such a way that illustrated different modes of PDF practices.

3.1. CASE STUDY I: MACBOOK'S AC PLUG HOLDER

Our first case study is to fabricate a holder for MacBook's AC plug. The MacBook's power adapter includes a small AC plug, which is used to connect PC to the AC power supply. In addition, the AC power cord can be attached to the adaptor by removing the AC plug. The problem is that since the AC plug is a tiny component, it is quite common to leave it when moving the MacBook. Therefore, there is always a possibility to lose the AC plugs, while the original component is not currently supplied by the mass manufacturer. This is an example of a hidden need that was ignored by the manufacturer. The idea is to design an AC plug holder that can be attached to the power adapter and that users can always keep somewhere close to the adapter.

Figure 3. The Macbook’s AC plug holder and its 3D model

Figure 3 presents the 3D model together with the digitally fabricated object of the first case study. The proposed design is a simple idea that is similar to the space that was already designed for the AC plug by the manufacturer on top of the adaptor. The holder is attached to the adaptor using a 2-side tape and its final cost is less than a dollar. In this case study, we remove the sketching step and directly provide the digital 3D model by measuring the actual dimension. This is because it is assumed that all processes of PDF were done by an agent who had basic knowledge of computers and 3D modeling platforms.

3.2. CASE STUDY II: CAR IPHONE HOLDER

The second case study is a customized iPhone holder, which was designed for 2003 Mazda 6i. Nowadays, car manufacturers provide a wide range of choices that allow users to customize the exterior and interior features of their cars. However, there are still many cases where the users need to add new personal features or customize the current arrangements. Many various vacuum flasks or water bottles are used by people with extremely different physical shapes. There is no single cup holder that can fit with all types of cups and bottles. Smart phone holders do not necessarily match with all cell phone models. Users can generate various ideas to address their personal needs and bring their ideas into reality by using Fabbers with lower price.

In the second case study, we designed and digitally fabricated a customized IPhone holder for a specific car. The design needed to compromise with the physical geometrical characteristics of the car. We intended to design the object as simply as possible so that the ordinary Makers can easily design and fabricate it. In addition, it needed to be close enough to the driver without distracting his/her concentration while driving. We designed a very simple IPhone holder that allows users to mount their IPhone onto their car’s CD player.

Figure 4. The Car iPhone holder and its 3D model

Figure 4 illustrates the 3D model and the printed holder in different views. It consists of two blades that expand inside the CD player and keep the holder locked in place. It should be strong enough in bumpy roadways and can be designed to be able to connect to the player’s auxiliary input using a cable. The result is a very simple object that fits with the specific shapes of the car’s interiors. This is an example of a custom product that is fabricated for personal uses under specific physical and geometrical conditions.

3.3. CASE STUDY III: HAIR DRYER CONCENTRATOR NOZZLE

The third case study is a concentrator nozzle, a component of personal hair dryers, which is used to concentrate and direct the air, give better control and prevent hair from being burned or damaged. However, due to the heat, sometimes the concentrator is melted on the inside and is unable to remain on the nozzle. This causes the concentrator to be dropped and cracked easily. There are many examples where the main product functions properly, however, a subcomponent needs to be replaced and repaired. Even, for many reasons the failed component may not be available on the market. In this case, users can employ PDF technology to produce replaceable components.

Figure 5. The hair dryer concentrator nozzle and its 3D model

Figure 5 illustrates different views of a 3D model related to a specific concentrator nozzle. The model was made using Autodesk 3DS MAX. This case study is a good example where a replacement part is needed for an outdated or failed device, however, it is not possible for users to purchase it or order it remotely. In addition, it is beneficial for mass manufacturers that can upload the 3D models of main parts. Agents can download files and fabricate them using their own machines.

4. ANALYSIS

The above case studies are examples of simple PDF practices done independently by agents— makers or designers. The collection of such simple PDF examples forms a complex decentralized market, where agents interact with each other and exchange their self-made products. In fact, the above case studies present different levels of customization and respond to various categories of needs. Three categories are identified from the above-mentioned examples and discussed in this section.

In the first category, agent employs PDF to respond to a personal *implicit need* by making a completely *custom* product. In this category, the agent often identifies the need based on his /her personal experience; however, there is no similar product available –or at least accessible to respond to his/her personal need. This is because it is not a common need for many other agents. In addition, mass manufacturers are not currently interested in addressing this need or cannot present a good solution because of technological barriers or lack of adequate resource or expertise. The first case study, MacBook’s AC plug holder belongs to this category, where an implicit need is addressed using a simple PDF solution. In a decentralized network of PDF, agents transform a wide range of implicit needs into simple personalized objects and share it via Crowdsourcers.

In the second category, the need is *explicit* and has been widely addressed by mass manufacturers. However, since the flexibility of mass manufacturing for customization is limited, it is not able to cover all the customers’ requirements. In this situation, agents can effectively *customize* their available products, or create new products that are completely customized with their needs. The customized iPhone holder discussed in the last section is an example of the second category. There has been a wide range of car iPhone holders and mounts in the mass production market. However, none of them may fit with a particular make and model of a car. PDF provides this opportunity for agents to design and fabricate their own iPhone holders based on the dimensions and physical characteristics of their cars.

Finally, PDF can be used for repair and replacement of mass manufacturing products. In this category, the product is *not customized* in a practical sense; but one or more components are customized to be replaced with the malfunctioning original parts or recreated for revitalizing a failed product. Agents can share their components with other people with the same problem through crowdsourcing platforms. They are able to download other ideas by other designers and make them with their own Fabbers. Mass manufacturers are also able to upload the 3D files of some of their products' components together with their instructions, so that agents can digitally fabricate them. This lowers the repair and replacement cost for users and increases the level of service for manufacturers. The concentrator nozzle case study belongs to this category. The hair dryer and its components are not customized

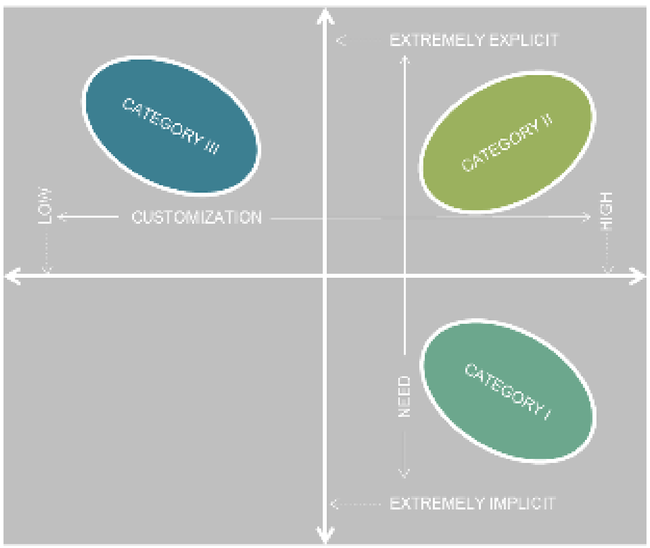

Figure 6. Three categories of PDF products regarding their levels of customization

Figure 6 compares the aforementioned categories in two aspects: The horizontal line illustrates the level of customization, which ranges from standard mass manufactured products to the completely custom products. The vertical line is "the state of need" that varies from highly explicit needs to the completely hidden needs. The categories are situated in different zones of the plot. Category I is related to those PDF products that are highly customized and responds to the implicit personal need, whereas, Category II is less customized but more explicit. Category III often includes the PDF products that are not necessarily customized and the need is completely explicit.

5. SUMMARY AND CONCLUSIONS

This paper studied the effect of digital fabrication on the process of making custom/customized products to address personal needs. PDF provides a decentralized system of manufacturing where agents can generate ideas, design their personal objects, and turn them into real products through their own small-scale manufacturing machines. We identified four types of agent—Maker, Designer, Crowdsourcing Platforms, and Mass Manufacturer that interact with each other and create a complex decentralized market. Moreover, using a number of simple case studies, we classified the personal fabrication practices into three categories and analyzed the characteristics of each category. Categories help people to realize how they can discover their personal needs and make tools and products to address them using PDF methods. Further categories, which show other aspects of PDF practices, can be an area for potential future research. In addition, another potential area is to study more use cases and create further categories to cover a wide range of PDF applications. In doing so, one can extract more common characteristics for each category.

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