# Design Methodology for Product Designers in the Context of Personal 3D Printing

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By


**Zuk N. Turbovich**

Roll No: 136105010

Supervisors:

**Prof. Amarendra Kumar Das**

**Dr. Pratul Chandra Kalita**

**Indian Institute of Technology Guwahati**

**Department of Design (DoD)**

# Certificate

Date: ________________

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Amarendra Kumar Das, PhD
Professor
Department of Design
Indian Institute of Technology Guwahati
Guwahati 781 039
Assam, India

Pratul Chandra Kalita, PhD
Assistant Professor
Department of Design
Indian Institute of Technology Guwahati
Guwahati 781 039
Assam, India

# Declaration

"I, Tsuk Nechemia Turbovich, declare that the PhD Thesis titled **"Design Methodology for Product Designers in the Context of Personal 3D Printing"** contains no material that has been submitted previously, in whole or in part, for the award of any other academic degree or diploma. Except where otherwise indicated, this thesis is my own work".

Tsuk Nechemia Turbovich, PhD Scholar
Department of Design
Indian Institute of Technology Guwahati (IITG)
Guwahati 781039, India.

(Signature)

Date: ____________ Place: ______________

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# Nomenclature

2D: Two-Dimensional

3D: Three-Dimensional

3DP: 3D Printer

3DPT: 3D Printing Technology

AM: Additive Manufacturing

AMT: Additive Manufacturing Technology

CAD: Computer Aided Design

CNC: Computer Numeric Control

DLMS: Direct Laser Metal Sintering

FDM: Fused Deposition Modeling

FDP: Flexible Democratic Product

FFF: Fused Filament Fabrication

FSDP: Flexible Semi-Democratic Product

Indie: Independent

MC: Mass Customization

OAD: Open Architecture Design

OAP: Open Architecture Product

P3DP: Personal 3D Printer

Polyjet: Photopolymers jetting

RDP: Rigid Democratic Product

RPT: Rapid Prototype Technologies

RSDP: Rigid Semi-Democratic Product

SLA: Stereolithography

SLM: Selective Lase Melting

SLS: Selective Laser Sintering

URS: User Requirements Specifications

VER: Volumes Efficiency Ratio

# Abstract

Many literary and other informative sources refer to 3D printing technologies as one of the generators of the next industrial revolution. Alongside the expansion of the variety of the manufacturing means for industrialists, for the first time in human history, the common people get the chance to own an automatic manufacturing machine that has a potential to dramatically change the way of how they purchase and interact with sustainable products. In recent years, desktop personal 3D printers have become available for sale throughout the Internet, and despite that the common people have not found interest in these revolutionary machines.

The prime motivation for this doctoral research was derived from an attempt to understand the reasons for the clear gap that exists between the market, which offers affordable personal 3D printers (P3DP) to the potential customers that do not show any willingness to buy these machines. The definitive goal of this research was to establish a product design methodology for products that are supposed to be manufactured by P3DPs, so that product designers will truly understand the possibilities and the limitations in this context and will be able to contribute their part in enhancing the personal 3D printing field.

The research included a literature review that reviewed literary sources from 3D printing, product design methodologies, mass-customization, and user involvement fields. The literature review revealed few insights in regard to market faults that derive from lack of standardization and assisted to establish the theoretical basis of the research questionnaire that was conducted as part of this research.

The questionnaire was designed to examine how the common people perceive P3DPs, and the analysis of it has revealed few interesting complicated insights that shed more light on the reasons that cause the mentioned gap. Further to the questionnaire, the research included a comprehensive market review that examined free CAD software and websites that offer products that are supposed to be manufactured by P3DPs, and industrial 3DPs. Conclusions and insights that emerged from the market review, have become to be substantial factors that came to an expression at the establishment of the definitive methodology.

# Preface

***If I am not for myself, who is for me? And if I am only for myself, what am I? And if not now, when?"***

***Pirkei Avot 1, 14 (Ancestors' chapters - Jewish textbook)***

**Abstract.** Human being is a craftsman by nature. This conclusion came out from this personal, selective brief historical review that reflects insights and interest points that formed in the pre-research stage. The wide perspective assisted me to construct the research rationale, and hence the research questions. This initial attempt was made in order to sense the process of the users-products interaction. As an industrial designer, I find great interest in the new desktop personal 3D printers that started to be marketed for home use, and of how they will affect the products' design, and the products market. This personal manufacturing means promises new opportunities and challenges, but raises many questions, regarding the market and the processes that drive it.

The existence of everything we know in the observed world, is possible thanks to complex interactive systems, from the atom level to the level of existence of a thing, as we perceive it. Scientists from all around the world are working these days on the discovery of the fundamental particle of the Standard Model of particle physics - particle calls Higgs boson, named after the British scientist who had anticipated its existence (Peter Higgs). This attempt stems from a general and consistent intention of mankind to understand the essence of existence, inter alia by exploring the material building blocks. The desire and need to find the fundamental particle, which is responsible for building all the endless mechanisms and the creation of the complex systems that surround us, has started from the beginning of the formation of human culture, through the ancient era's philosophers, to present days. This nature of exploration distinguishes us in a certain way, from the rest of the living matter in our world.

Processes that started in Europe, at the Renaissance age, right after a long period of religious dictatorship, placed the human at the center of the essence of existence (instead of the society). These processes matured and formed into a philosophical-cultural expression in the 17th century, in what is called as the birth of the "subject". This thought process was reflected in the statement of the French mathematician and philosopher, Rene Descartes: "cogito ergo sum" (Discourse on the Method, 1637). The great effort that humanity is placing in order to satisfy the individual's needs and desires, involves an integration of many factors and complex system interactions. The opening quotation, from the Jewish wisdom textbook, summarizes in a form of a question the person's place in the social system, and the immediate consequence of his/her actions. This sentence illuminates the hanging bridge between the natural course that requires compliance to social system and ego-centralism. This statement gives a justification for self-improvement process, however, do not forget to specify the address of the general objective i.e. systematic improvement.

Further to that matter, under the subheading "Barter: as old as the hills" (Davies, 2002), the author refers to the fact the interactions, including barter is our natural starting point in any type of society. The early Neolithic society (≈8000 BC) which transformed to be a permanent settlers' society, changed the way of how people experienced life in all aspects. As hunter-gatherers, people had very few tools, which were primary in use for basic survival purposes. Tools were made of trees, bones, leather, stones and ferns, and they could have been found easily, since they were on the surface. The facts that people were constantly migrating, and raw materials for basic tool were on the surface, made tools valueless and not required for preservation. The tribal bonfire was the most significant occasion, where groups of individuals, mostly blood related, were sitting and socializing. The transformative change of becoming permanent settlers, changed the form of all aspects in life, including socialization, and the form of tools. More inventions of new tools were required and needed to be invented in order to fulfill the variety of needs that emerged from the new status. Tools became valuable and needed to endure. Operating agricultural plots required durable tools for digging the irrigation channels, plowing and harvesting. The permanent settlement fact has required durable building tools and molds, transportation means (mostly marine), and storage tools. On one hand, the common people continued to manufacture personal 'basic for survival' tools e.g. hunting tools, dishes, kitchenware, and other improvised tools for different purposes, while on the other hand, people had to professionalize in order to do certain crafts and social functions. The bridge between the need to solve problems / fulfill needs and the solutions, became known as technology.

Development of agricultural villages to city states represents an elaboration of the human culture system. Societies developed governing systems and elaborate commerce systems. The dominant culture in every area was the one who held the most advance technologies, relates to fighting and defending means, food supply and building tools. Access to relevant raw materials, proximity to flora and fauna, water source, transportation means, etc. were also among other things that were basics required for supporting permanent settlers in such a form. The concept of democracy was firstly mentioned in ancient Greece, but the sense of it was there all the time. Every group of people in any form of society wants everything to be accessible and affordable to everyone. Naturally it is not happening, but there is a constant aspiration to that. Technology assists to bring democracy. As irrigation systems and farming technologies democratized food, derivatives of the invention of the wheel increased the level of democratization in enormous fields. The press machine that was invented in the 15$^{th}$ century, increased the level of democratization, regarding to knowledge, while the flying shuttle and the spinning jenny (18$^{th}$ century) increased the level of democratization regarding to clothing. Those kinds of inventions tend to be called transformative change inventions. The impact of this kind of invention radically changes ways of life, and so did the derivatives of the key invention of the motor, which initiated the 19$^{th}$ century industrial revolution.

The ability to motorize machines opened new opportunities. Factories, companies and other central powered sources owned manufacturing means along with marketing and distribution systems. The mass production system, which constantly lowered the costs of parts, increased the affordability aspect, and the marketing and distribution systems provided the accessibility aspect. Changes in the 20$^{th}$ century were a direct result of processes that formed and matured in the previous century. Factories and other central powered sources increased their influential power, and the counter strengthening of the proletariat class along with the middle class, gave a rise to social movements as a counterweight to the central powered sources socio-economic capitalist management system. The most radical practical formation of the socialist ideology came to an expression in the Bolsheviks revolution in Russia and in the countries that afterwards assembled the Soviet Union, along with China and other countries. Regardless of the governing ideology, scientific research and discoveries fed industrialists which invented new manufacturing means in order to manufacture tools and products from new and better raw materials with suitable properties for implementation of the function. The mass production system evolved once Henry Ford introduced the T-Model assembly line (1908). New marketing, sales and distribution approaches and systems had to be developed in order to maximize the manufacturing potential and the profits. Advertisements from the pre-industrial age, which were mostly textual-informative, as can be seen in "The Boston News Letter" from 1704 (Figure I.) and in the "Franklin Philadelphia Gazette" from 1735 (Figure II.) evolved during the industrial age and changed their approach towards the use of images and thus visually attract the potential consumer's attention.


The Boston News-Letter.

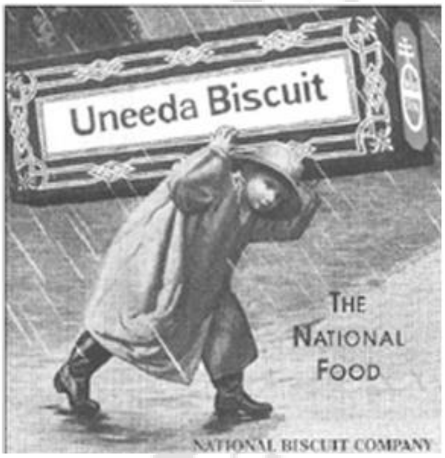



**Figure I** **Figure II** **Figure III**

Printed advertisements like "N.W. Ayer & Sons" - Uneeda Biscuit from 1899 (Figure III.), and from the advertisement page in the Scientific American Journal from 1894 (Figure IV.), reflect the new approach of integration of images with, or without informative text. Increased business competition had led to branding – an act which meant to positively differentiate companies and products over competitors by emphasizing and individualizing the brand.




**Figure IV** **Figure V** **Figure VI**

Early examples for industrial age branding can be seen in "Wrigley's" advertisement from the beginning of the century (Figure V.), and in "Kellogg's" advertisement from 1906 (Figure VI.).

Recession years in Europe, that followed World War I, had weakened the consumption power and increased the need to find cheap solutions for different purposes. Radio shows and newspapers offered tips for how to make things by yourself. Contents that related to clothing and cooking addressed women, and contents that related to furniture making and home maintenance addressed men. 'The New Poor – Making the Best of it', an article that was published in "The Times news" in 1920 (Atkinson, 2006), put self-making outcomes as solutions for the poor. Most of times, people were making a lot of things by themselves, and within a century, self-made products considered as low value comparing to mass produced products. The phenomena of self-making named in radio shows and books by W.P. Matthew (1930) as 'Do It Yourself' (DIY), and since then, this term describes section of products that in order to bring them to final form, user's involvement is required.

The lack of skilled workers during World War II days, made DIY skills become more required and appreciated. Discoveries and developments which were made during the war, found their way to the commercial market in form of suitable for common people use applications. An example to mention is the silicon polymeric compound that was discovered during the war, in a failed experiment to synthesize synthetic rubber, and turned in post-war times (1949) to a popular toy – the 'Silly Putty' (Figure VII.).


**Figure VII**

This elastic piece, which basically was a piece of raw material, got immediate commercial success. The user involvement during usage was required, and the user was experiencing new raw material that reacted in a new way and kept the user constantly active. The user could redesign or keep the creation, and thus the relation to the product became more personal and emotional. In the same year, the American company 'P. Duff & Sons' started to market another new development – Duff's Ginger Bread Mix (Figures VIII., IX.). At times when the nation tried to rehabilitate the economy, it seemed that the new dry powders mixture technology would spare time of the American housewife, but the product did not gain much commercial success.

Post marketing questioning of potential consumers discovered an interesting insight. Beside the natural suspiciousness toward the new technology, baking successful cakes and bakeries perceived as one of the appreciated skills of the American housewife. A complicated process concentrated into adding water, mix and bake process. It seems like the good intention took away something else – the importance of the house wife. Accordingly, the company decided to remove the dried eggs powder from the mixture and started to market the product with the slogan: 'Just add 2 fresh eggs'. This act apparently increased the trust in the new technology, and moreover, put more value in the user involvement and allowed the user to feel more related to the product. Even though the Silly Putty and Duff's Ginger Bread Mix are different products, an understanding that in a mass production world, user involvement in standard products is adding important desired values to the product.

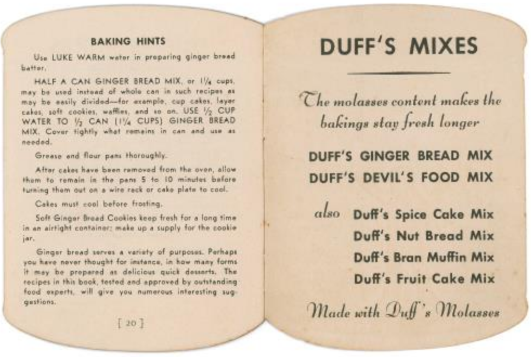




**Figure VIII** **Figure IX**

TV started to charm people, bloomed and grown rapidly in the 50th. Atkinson mentions Barry Bucknell show that presented DIY TV content and gained popularity. The trend of user involvement and DIY in products continued, and configurations of products that were launched in the 50th e.g. Mr. Potato Head (1952) and the Barbie Doll (1959), can still be found nowadays in toys stores. Companies that relied on mass production systems, started to develop techniques for a creation of competitive advantages. Under the limitations of the mass production system they tried, wherever it was possible, through the design, to enable customization and user involvement in products. One of the many challenges was to flex the manufacturing process according to each customer's needs. Therefore, in order to enable customization, they designed relevant products with adjustment mechanisms, or provided modular design, or / and offered variety of the same solution in different scale and / or color. The user involvement aspect got intention in two levels:

1. Involving potential users in the R&D process by using Quality Function Deployment (QFD), beta testing, etc. techniques, in order to develop products with better chances to succeed among potential users.

2. Giving the user the option to assemble the product, and / or to determine the final design according to certain possible modules.

Since these phenomena were observed, scholars from different fields, examined the intervention of psychological values in products.

In the 50th and the 60th, with the Cold War in the background, the consumption culture had flourished. Chain stores, supermarkets, malls, TV, etc., hosted the acting of the brands and the celebrities. The Pop-Art movement expressed through art, the voluntary surrender of persons to the mounting advertising and marketing forces, and also the puzzling blurriness between art and products.

The Punk movement which started to act in the U.S. in the mid-70th, turned down the aggressive consumption culture, and contents that were dictated by advertisers. In front of the unshakable bond between governmental and commercial center powered sources, the Punks developed anti-consumption, almost anarchist ideology. Their main expression was through music with short and simple messages, and by emphasizing their individuality through fashion. The masses did not follow the movement, but its voice was heard, and questions, among the common people, started to arise regarding to the over power of the central powered sources. The principles of DIY and individualism became a cultural value and changed status from a solution for the poor to a social-message carrier.

In the year 1984, two inventions were presented to the public. The first was the first desktop personal computer (PC), that was presented by Steve Jobs, and the second was the first 3D printer (3DP), based on Stereolithography technology, that was presented by Charles (Chuck) Hull. While the PC was a result of an evolution of previous large-scale machines, the 3DP was a brand-new technology. The computer and the PC as a derivative, can be considered as a transformative change invention. Along with the intensification of the Internet it has transformed all way of life and opened a new significant interaction space - the cyber space. Today we can all buy all kind of goods and products, communicate with people, share and consume knowledge, share and consume all kind of contents, get services, and much more, in this part of live cyber space. The expansion of the computers and the Internet to smartphones, tablets, lap-tops, smartwatches, and other applications, made them to be an integral part of life for almost every person in the world. The fact that the computer and the Internet are accessible and affordable, and they increased the level of accessibility and affordability, i.e. the level of democratization in so many fields, made them to be widely adopted by the common people. Things that we used to pay for, e.g. music content, news, knowledge, communication are now free in the cyber-space. Things that we used to spend a lot of time in order to do them in the physical space, e.g. paying bills, find reading content, buying all kind of goods, products and services, are now can be done from almost everywhere. As mentioned above, in the same year when the first PC was introduced, a new computer numeric control (CNC) machine, the 3DP, was introduced as well. The initial purpose of the 3DP was to produce prototypes for the sake of product designers, mechanical engineers and architects, during the development process. Since that invention was introduced, other techniques that imitate the concept were developed, and it is almost 7 years (since 2009) that desktop size personal 3DP can be found in the market along with free CAD software and free to download suitable files for 3DP, that can be found in the cyber space. For the past 5 years, many articles, books and the media covered and reviewed the new technology. The general tendency is to crown it as the swallow that heralds the next industrial revolution. Even though 3D printing technologies had undergone a series of serious developments, and it is also functioning nowadays, as an additive manufacturing mean, and 3D printed parts and products can be found today in the commercial market, the common people, did not, and still do not widely adopt the technology.

Stanley M. Davis described the term Mass-Customization (MC) in his book "Perfect Future" (1987) as a situation in which "the same large number of customers can be reached to as in mass markets of the industrial economy, and simultaneously treated individually as in the customized markets of pre-industrial economies". Since the most challenging thing to do for the mass production system is to flex the manufacturing process in order to fulfill Davis's ideal, it seems like the 3DP, in all its forms, is the missing piece in the puzzle. The gap that exists between Davis's ideal to the situation in which theoretically, all the options are on the table, but the ideal is not being realized, was the drive to start to explore this issue, from a perspective of an industrial designer.

# CHAPTER 1

# INTRODUCTION

# Design Methodology for Product Designers in the Context of Personal 3D Printing

**Abstract.** Rapid advancements of 3D printing technologies have created new opportunities and challenges. The Fused Filament Fabrication (FFF) and the Stereolithography (SLA) 3D printers which were recently launched in a desktop size, herald new time in which common people will be able to own a manufacturing mean in their homes. The prime motivation of this study was driven from the gap that exists between the market that offers desktop 3D printers, along with access to 3D printed products and the users which still had not widely adopted this new technology.

## 1.1. Research Rationale

The natural course of industries shows that there are two main phases: the initial centered-power phase and the secondary democratic phase. The transformation from the initial to the secondary phase takes usually more than a lifetime, and it is a long continuous process that relies mostly on technological developments and the time that it takes the society to adopt those changes. "Transformative change happens when industries democratize, when they're ripped from the sole domain of companies, governments, and other institutions and handed over regular folks" (Anderson, 2012). This aspiration for equality can be observed along the human culture history, as mentioned in the preface. The democratization aspect does not represent an ownership of something by everyone, but rather the level of the affordability and accessibility of something to everyone. The present ongoing Digital Revolution, or the Information Technologies Revolution, which we are now experiencing, was evolving thanks to the inventions of the personal computer (1984) and the internet (1991). The influence of this revolution cannot be summarized yet, however evidence shows that it has increased the level of democracy in many industries. Additive instruments and tools like the personal digital printer increased the level of democracy as it relates to printing, and expanded the market, contrary to the concerns of the industrialists of the printing market, which have been proven wrong. Anderson refers to the music industry, as an industry that has undergone a most significant change. Today, a musician can produce a musical composition, or a song, all by himself with a computer and with/without other complementary instruments. Once the musician decides to share the creation, it can be done immediately through designated distributive platforms e.g. YouTube, Vimeo, SoundCloud, etc. In the initial stage, the virtual audience can choose to listen, or not, to the musical composition, without any human intermediaries. The artist can gain his/her popularity purely from the common people, without any assistance from a marketing department of a records label. The relationship between the artist and the audience became more direct. Instead of reality, when the artist had to beg the records labels to take responsibility and sponsorship over him, records labels are now "begging" successful artists to sign with their label. This transformative change along with the fact that listeners can consume the artist's product selectively and freely, can demonstrate a completion of a positive democratic change. A mentioned in the preface, in the same year (1984), when the first personal computer was presented by Steve Jobs, the first Stereolithography (SLA) 3D Printing Technology (3DPT) was presented by Charles (Chuck) Hull. It took approximately 30 years until this concept became accessible and affordable for home use. Many writers and scholars refer to the invention of the 3D printer (3DP) as the means that heralds the next industrial revolution, out of the democratic move that it embodies. The rational of the research derives from the fact that the secondary democratic phase has begun. The desktop personal Fused Filament Fabrication (FFF) and SLA 3DPs, which recently started to be marketed for home use, represent the transformative change that needs to be examined, when users will be able to manufacture their products in their homes.

## 1.2. Research Motivation

Working as chief designer in an innovation group of a world leading company, and as 3D printing laboratory academic supervisor, I'm constantly dealing with 3D printing. Despite the fact that the quality of the 3D printed part and models are not equal to models that were produced with conventional technologies, I always sensed that it's a matter of time until problems will be solved, and new age in design will come. The entrance of the desktop size personal 3DPs to the market, opened for me new world of ideas and wonderings. If a person owns a personal 3DP, then the only thing that divides the person from me, as industrial designer, is the cyber space. Many questions started to arise regarding the way of how the interaction will look like, how people will consume their products, and of how the principle of operation of the 3DPTs will influence design. Naturally, every new manufacturing technology gets practical interpretation in design, the same as the bending steel pipes technology got interpretation by Marcel Breuer who designed a chair (Figure 1.1), with a form that challenged the well-known, proven classic design of chairs. New abilities, like the ability to manufacture assembled product with moving parts in a single print, or the possibility to manufacture almost every form, have potential to radically change designs.

**Figure 1.1. – "Wassily" armchair. Marcel Breuer, 1925-26.**

Review of designs and art works oriented to 3D printing, discovered that there are two archetypes of designs. The first type is non-oriented to 3DP designs, and the second is 3DP oriented. Most of the parts that people 3D scanned, and other parts that people designed in CAD software and uploaded to designated sharing 3D printing files websites, are among the designs that belong to the first archetype. Art works, like the "Monocoque 2" by Neri Oxman (Figure 1.2.), and demo models like the single print Objet's "Braingear" (Figure 1.3.), belong to the second archetype.

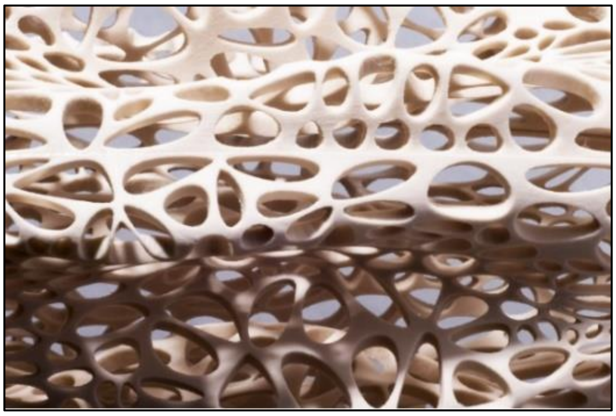


**Figure 1.2. – "Monocoque 2". Neri Oxman, 2007**.

**Figure 1.3. – Objet's Braingear.**

Initial observation on 3D printing oriented designs, shows that there are two types of design approaches. Art-works and other experimental designs, that tend to mimic structures from nature, and design organic shapes, and engineering designs, which purely demonstrate engineering principles and emphasize the advantages of the technology.

The theoretical option to communicate directly with users, and present designs without physical intermediaries became real, thanks to kind of websites that act as cyber stores and allow craftsmen, designers, jewelers, and practically everyone to offer things for share, or for sale. Informal pre-research examination of how the direct connection with users looks like, in oriented to 3D printed products platforms, was conducted. I designed a one part Q-tips holder (Figure 1.4.), suitable for small size 3DP, and uploaded the .stl file to designated website of sharing part and products for 3DP (Thingiverse.com).

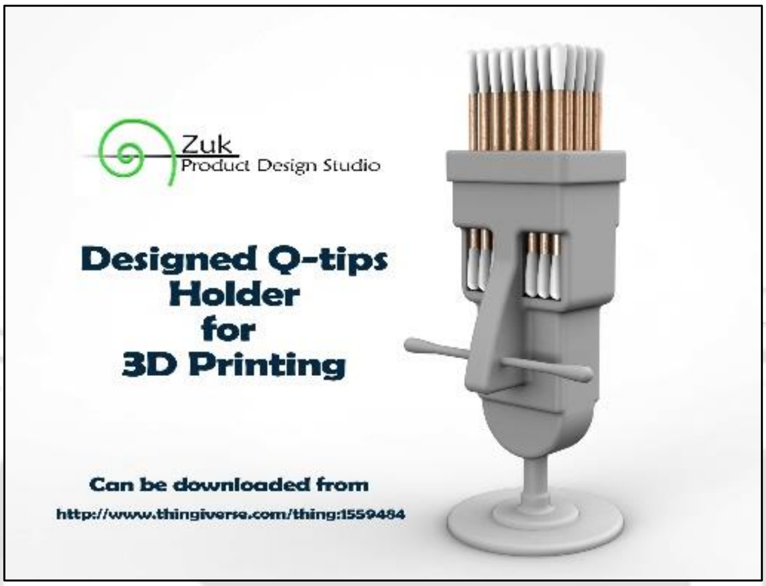



**Figure 1.4. – Designed Q-tips holder – Zuk Turbovich, 2016.**

I was asked to categorize the product, provide searching keywords, upload illustrations of the final outcome, and provide tips of how to get good results. I could not choose whether to sell or share the product, like in other websites, and the only option was to share. As of 04/07/2016, and after approximately two months on the air, the Q-tips holder got 110 likes, 107 users collected the file, 4 users positively commented, and 0 users reported if they actually printed it. I did another examination, and uploaded the file to sharing and selling 3D printed products website (Shapeways.com). I have uploaded the file, and the website's team priced it in 57.44 USD. I got no indication if someone liked, downloaded, or ordered the product. I assume that only uniquely enthusiastic people will agree to pay this price for a maximum 5 USD product.

Out of the brief review of the market and the pre-research examination, I found that the 3D printing market is in a forming process. Therefore, the prime motivation of the research was driven from the need to deeply understand the current situation, in favor of finding insights and development tools that will assist to maximize the potential of this market. The immediate derivatives from the prime motivation were secondary motivations that relate to the factors that assemble the desktop personal 3DPs market. The desktop personal 3DP, the product designer, the home user, and the suitable for 3DP products are accordingly the factors, and the actions that were set for examination of these factors, were to:

1. Explore about the abilities and the limitations of the personal 3DP, in order to know inside-out the potential of it as a personal manufacturing mean.
2. Analyze the current 3D printed products market, for widely and deeply understanding of the current situation, and to identify types of users and products in this market.
3. Study about practical product design methodologies and examine their relevancy to the personal 3DPs market.
4. Review Mass Customization (MC) methods and paradigms as reference for advance approaches for strategies in the products market.
5. Review user involvement methods and paradigms as reference for advance approaches in products design and use.

## 1.3. Research Question

One of the main starting point wonderings, was about the gap that exists between the market which already offers desktop personal 3DPs and the potential users who avoid / reluctant to adopt the technology. The wide major pre-research question focused on why does that gap exist? Further studies and explorations, naturally revealed that different disciplines are involved in this market, and each one of them should examine that question according to its expertise. Materials, software, mechanical, mechatronics engineers, marketers, sellers, industrialists and designers are all among the involvers that try to develop, promote, and use the technology.

Out of initial spatial understanding of the current situation in the 3D printing products market, and out of the product designer perspective, two main questions and two sub-questions arose:

**$Q_1$** – What are the stages, and what needs to be included in a design process of a product intended to be manufactured by a personal 3D printers?

**$Q_{1.1}$** – Which types of products might be designed and be suitable for personal 3D printers?

**$Q_2$** – What type of personal 3D printer people will want to have, if any?

**$Q_{2.1}$** – Will a person with personal 3D printer prefer to 3D print standard, or customized products, or it depends on the type of the product?

## 1.4. Research Objectives

Since the 3D printing market embodies many research directions, the research objectives were extracted from the pre-research studies and the research questions, and were determined as follow:

1. To set a methodology for product designers which relates to design of products for desktop personal 3DP, for understanding of the differences between this methodology, and methodologies for mass-produced standard, or one-of, tailor-made, products.
2. To identify the factors that assemble the value chain that links designers, 3D printable products, and home users, for knowing all the factors that participate in this interaction.
3. To define types of products in a desktop personal 3DPs market, in order to assist to establish strategic plans.
4. To define types of users in a desktop personal 3DPs market, in order to punctuate the understanding, in a direct interaction scenario.
5. To examine how potential home users perceive 3DP, in order to better understand the market gap that was mentioned previously, from the perspective of the potential user.

## 1.5. Research Hypotheses

**$H_1$** – Once desktop personal 3D printers and its raw materials will be affordable and accessible for the common people, they will prefer to have one.

**$H_2$** – Users that will own desktop personal 3D printers will prefer to customize their products according to their needs.

**$H_3$** – A methodology for product designers, which will communicate how to design products for the personal 3D printers, will help them to deeply understand the challenges and the opportunities in this market.

## 1.6. Research Method

Out of an analysis that was made according to the data that was collected, the initial conclusions and the research questions and objectives, the main intention of the research was to form a methodology for product designers that will instruct them how to design products for personal 3DP. Accordingly, the subject of the research can be described as 'Design Method Research'. The method of the research (Figure 1.5.), was constructed from 5 stages (right margin) which represent 4 major research actions (left margin). Stage 'Zero' represents the pre-research stage, and it includes all the taken actions, which were mentioned previously. The outcomes of this data mining, and initial conclusions secondary stage (the research's rationale, question, and objectives), were constantly updated during the general research, but they were placed under 'Zero' stage, where they have been formed for the first time.

The first stage included focused data mining, under the literature review title. The main subjects that were reviewed, were according to the requirement to examine fields that derived from the 'Zero' stage. Product design methods, user involvement methods, mass-customization methods, and 3D printing were the main fields, but other peripheral subjects e.g. trends in product design, open architecture products, advance technological thinking (Ray Kurtzweil), philosophy (Jean Baudrillard), and bicycle design, were reviewed. Along with the conclusive second stage, the first stage constructs the descriptive research phase, in the general research.

In order to fulfill the research objectives, and answer the research question, the third stage included an integrative comparative-quantitative research. Unanswered questions were asked through a questionnaire that examined among non-professional cyclists how they perceive 3DP, what type of 3DP they think they will own, if any, and the desired level of customization. The fourth and the fifth stages construct the last conclusive research. This final stage, includes cross-sectional conclusions from all the previous stages, and the formulation of the methodology for product designers that presents the required actions that need to be taken in design for personal 3DP.

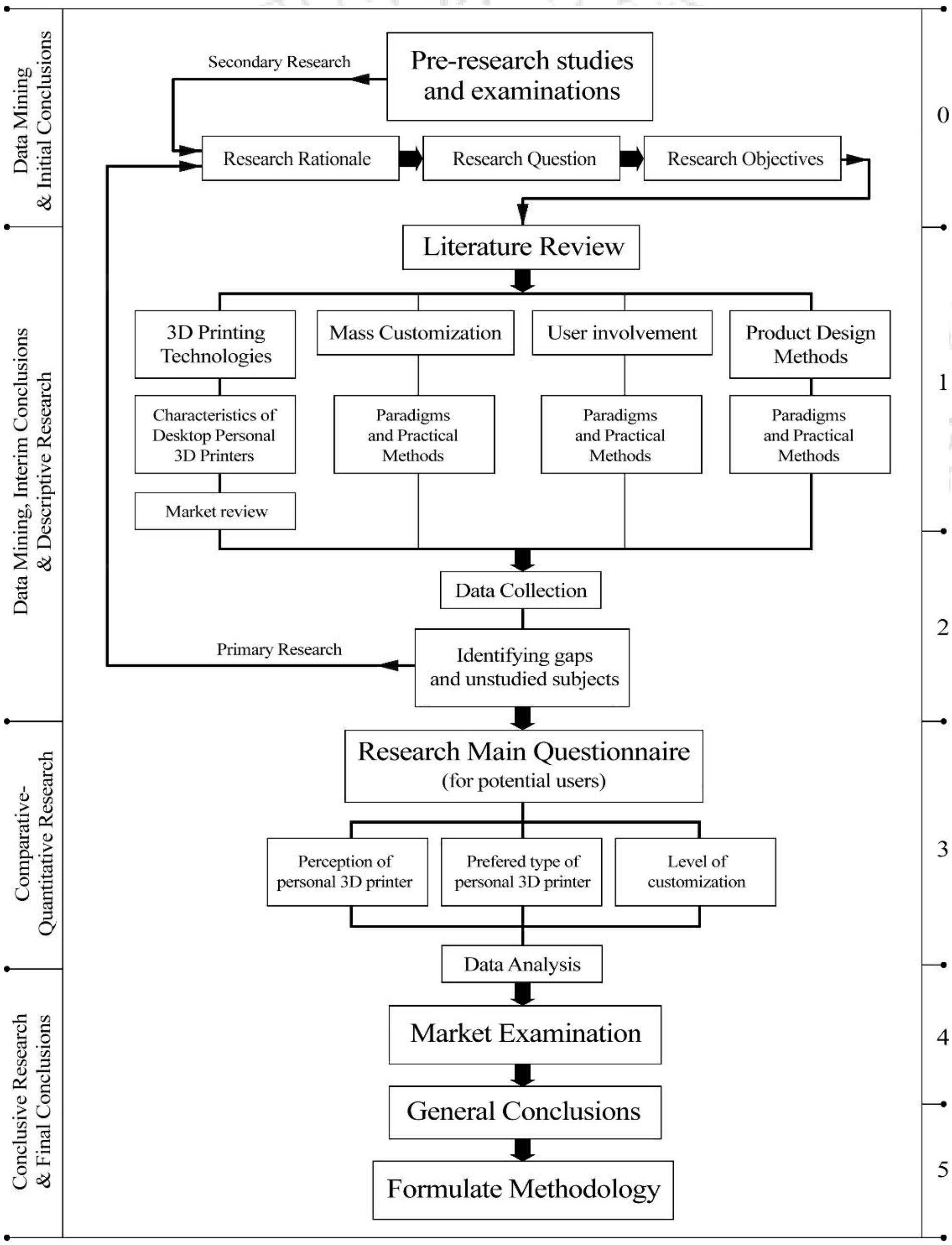



**Figure 1.5. – The flow of the research stages.**

# CHAPTER 2

# LITERATURE REVIEW

## 2.1. 3D Printing

Since the 3D printing invention was introduced, its primarily purpose was to produce prototypes along design processes, in service of product designers, mechanical engineers, architects, jewelers and artists. Therefore, in early publications and references, the various technologies were described as rapid prototyping technologies (RPT). Since the technologies have started to enable production of parts and products to the commercial market, the references expanded the definition to 3D printing, or to additive manufacturing technology (AMT). The term 3DP refers mostly to printers which produce prototypes, and desktop personal 3DP, while the term AMT refers mostly to 3DPs in service of the mass production system as one more manufacturing mean. The following review will present examination of all the 3DPTs, studied and unstudied applications, and references that examined the impacts on the market / users / design.

### *2.1.1. 3D Printing Technologies – Technical Review*

The principle of operation of all the 3DPs is based on an initial step of a computer aided design (CAD) model that needs to be converted to a polygons geometry, suitable for 3DP file (mostly stl, or x.t files). The suitable file needs to be imported into a designated software that determine the properties of the printing, and generates G-code that directs the 3DP how to operate. The principle of operation itself, is building the required model layer by layer, bottom to top, like if the physical model was sliced into many fine slices and re-glued as described. The method of how every layer is being created, the thickness of every layer, and the optional raw materials which can be in use by the 3DP, are the main factors that distinct between 3DPTs.

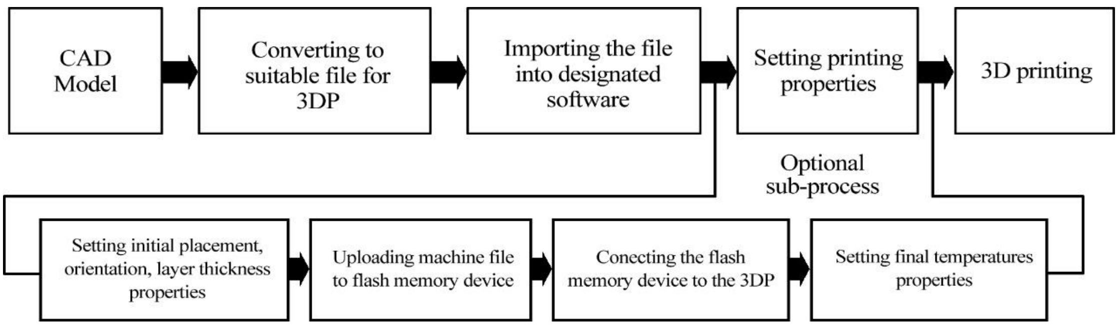



**Figure 2.1A – A simplification of the pre-3D printing process.**

Most of 3DPTs require final activation through the 3DP inner computer. In few technologies, a sub-process is required, as described in Figure 2.1A. According to the principle of operation of the 3D printers, there are 5 different techniques of how to produce the layer-by-layer model:

- Materials extrusion.
- Photopolymers solidification.
- Powders solidification.
- Photopolymers jetting.
- Sheets lamination.

**Materials Extrusion**

This conventional extrusion manufacturing process, was configured to operate according to the operation principle of 3DPTs, and nowadays, it is considered as the most affordable, and common 3DPT. This type of 3DPs has range of applications, depends on the raw material feeding. The most practical use is for manufacturing models for the product design, mechanical engineering and architecture industries, but recently, it started to be in use for final products manufacturing in home / office environment. The most common raw material that are in use for these purposes are thermoplastic polymers e.g. Acrylonitrile Butadiene Styrene (ABS), Ploylactic acid (PLA), and other composite materials. There are other exotic applications, e.g. concrete, ceramic and food 3D printing, which can be found in the Dutch unique restaurant 'Food Ink', in 3D printing artists' studios, and in experimental projects. "…thermoplastic extrusion was invented by market-leading company called Stratasys that labelled it 'fused deposition modeling' (FDM). The term FDM is therefore widely used (and misused) to refer to thermoplastic extrusion, and even to material extrusion technologies more generally. Stratasys is, however, the only 3D printer manufacturer that can use the labels 'fused deposition modeling' and 'FDM' as it has them trademarked. Because of this, other companies refer to thermoplastic extrusion as 'plastic jet printing' (PJP), 'fused filament modeling' (FFM), 'fused filament fabrication' (FFF), or other 'fused deposition method'." (Barnatt, 2013).

**Principle of operation:** Generally, there are two principles of operation, depending on the raw material, and the way of how the building tray and the printing head functions. In certain 3DPs the tray is static, and the printing head in moving along all axes, thus the printing head creates the cross-sectional shape of each layer and determines the thickness of the layers, while on other 3DPs, the printing head is moving along the X, Y axes and creates the cross-sectional shape of each layer, and the tray is moving along the Z axis and determines the thickness of the layers. In thermoplastic polymers, composite materials and food 3DPs, the tray needs to be heated, and the raw material needs to be pushed through heated nozzles that bring the raw material to viscous condition, and deposit it according to each layer's cross-sectional shape. Some 3DPs come with fan cooling systems and some rely on cooling by the room's temperature (it is also a matter of the raw material that is being in use). Figure 2.1B shows s schematic illustration of the general principle of operation of FFF 3DP, and all other 3DPs that follow the described process.

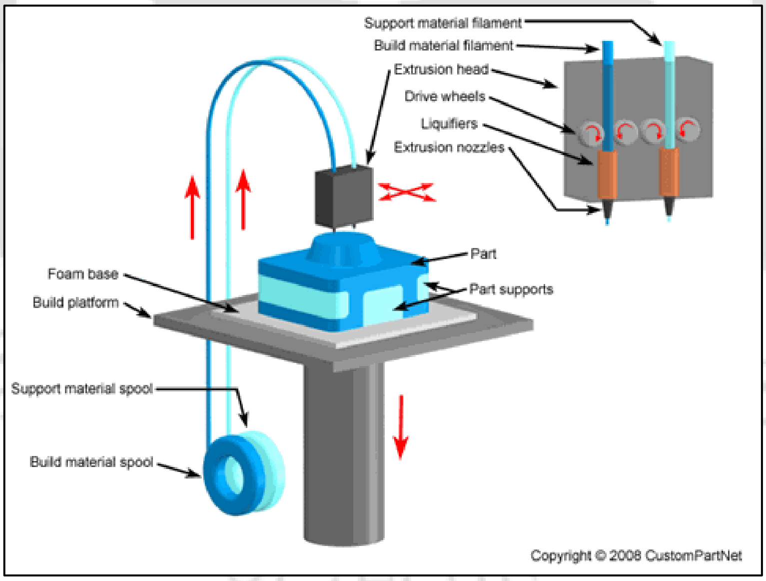



**Figure 2.1B – FFF – Principle of operation schematic illustration.**

The most basic types of FFF 3DPs have 2 nozzles, one for building material and the other for the support material. In case of geometries with hanging-on-air elements, the 3DP builds trusses to support those elements, simultaneously to the building process. Those trusses can be removed after printing by simply breaking them, or by soaking the model in acid, which dissolves the trusses only (depends on the support raw material). Relatively new FFF 3DPs have 3-4 nozzles, which allows to print multi-color / materials models. Ceramic and concrete 3DPs operate almost the same, even though the nozzle and / or the tray stays relatively cold, and the final model becomes hard after it is exposed to air / soaked in hardening resin / burned.

**Types of 3D printers:** Appendix 2.1.1A

**Photopolymers solidification**

This technique of 3D printing is actually the one which started this world of 3D printing, and all the other technologies that were invented afterward, followed the same concept in different ways. As mentioned previously, the first to be invented photopolymers solidification technology calls Stereolithography (SLA / STL / SL), and it was patented in 1984 by the American engineer Chuck Hull. In 1988, the company '3D Systems' bought the invention and started produce the first SLA 3DPs. In interviews that Hull gave along the years, he mentioned that prior to the invention, he was working in a company that was dealing with UV curable materials, and the inspiration to the invention came out from the process that this company was dealing with. Hulls needed to produce plastic parts for prototypes, and because of the cost of plastic parts production with conventional technologies, he got inspired from the UV curing technique, and thought about building plastic parts for prototypes by curing layers of cross-sectional controllable shape on top of each other. Since the SLA 3DPs started to operate, two more technologies that use that principle of SLA were invented. The 'Digital Light Processing' (DLP) projection, which uses white light beam instead of laser, and the 'Two Photon Polymerization' (2PP), which uses laser same as SLA, but with much better accuracy. Moreover, the range of materials that can be in use for these types of 3DPs was expanded, and today many photopolymers with different properties, and photo-elastomers are available. In recent years, SLA and DLP 3DPs started to be marketed in desktop size, for personal use, but since the technology started to operate, and still, the most common use is for producing plastic parts for prototypes, and models for the products development and manufacturing industries.

**Principle of operation:** Generally, the SLA 3DP has two main sub-assemblies. The projection system, and the building chamber system (Figure 2.1C). In the initial stage, the build platform which locates inside a liquid photopolymer bath, is placed one-layer thickness height below the liquid upper surface level. The projection system projects selectively a laser beam on the photopolymers, according to the layer's cross-sectional shape, and after curing the first layer, the build platform moves one-layer thickness height down, a sweeper spreads evenly the photopolymer on top of the first layer, and the projection system cures the next layer. This process continues layer after layer until completion, and the same as in FFF 3DPs, hanging-on-air elements get supportive trusses.

**Types of 3D printers:** Appendix 2.1.1B

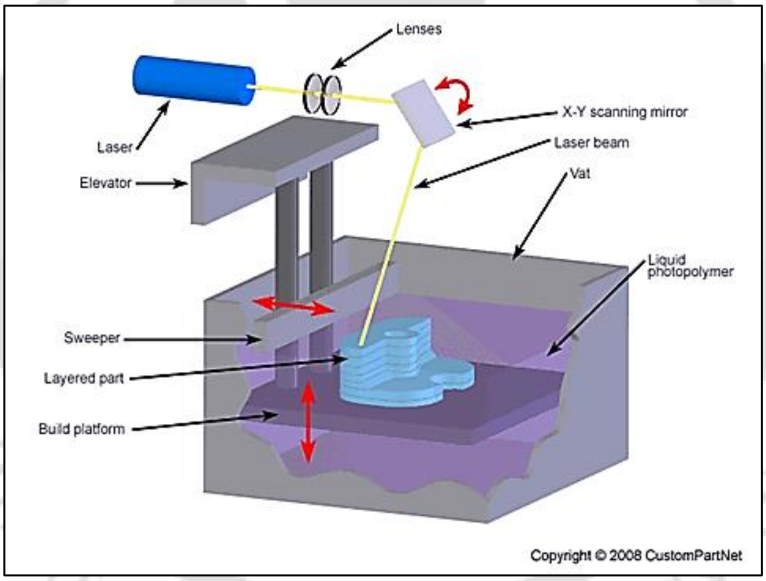



**Figure 2.1C – Stereolithography – Principle of operation schematic illustration.**

**Powders solidification**

This 3D printing technique has the widest variety of raw materials that can be in use, and it is the most common technique of 3D printing that has become integrated as AMT, in existing manufacturing systems. Almost every raw material that can be brought to fine powder condition, is possible for 3D printing, e.g. types of polymers, types of metal alloys, ceramics, glass and sand. The powders solidification technologies, have two main techniques of how to produce parts and models. The first technique uses binder jetting, i.e. the printing head sprays binder selectively according to the cross-sectional shape of each layer, and by that glues the powder's granules. Depending on the raw material, (metallic, ceramic, or glass), an after-printing processes are required, such as curing and strengthening in designated ovens, or kilns. There is a unique ability in ceramics binder jetting to paint the model simultaneously to the building process, by additional inkjet printing head that colors each layer, according to the 3D colors mapping. The second technique uses laser beam, which similarly to SLA projects selectively on the powder according to the cross-sectional shape of each layer. Differently from SLA, the intensity of the laser beam is higher, and it melts the powder to viscous condition, hence solidifies the semi-melted granules into one constant solid body. The most common definitions for this method are 'Selective Laser Sintering' (SLS), 'Selective Laser Melting' (SLM), and 'Direct Laser Metal Sintering' (DLMS). In cases when the powder is a mixture of ceramic, or metals, with binding material, the laser beam melts only the binder, and by that solidifies the granules. In cases when the powder is a pure ceramics mixture, or metallic alloy, the laser beam, which has even higher intensity, melts all the granules (required much higher temperature). SLS refers to the first mentioned cases, and the SLM and DMLS definitions, refer to the second.

**Principle of operation:** All powders solidification technologies operate according to a same method, with one different change. Binder jetting 3DPs use printing head, which sprays the binder that solidifies the powder granules, according to the cross-sectional shape of each layer, and laser projection technologies (Figure 2.1D), use projection mechanism. Both in binder jetting and laser projection, the printing head, or the laser beam, move only along the X, Y axles, and the build platform moves along the Z axis, hence defines the thickness of each layer. In the initial pre-start printing stage, the build platform locates one-layer thickness below the upper surface of the powder, which is contained inside a chamber that practically defines the building volume of the 3DP. Once the 3D printing operation starts, the laser beam / binder printing head solidifying the first layer, and immediately afterward the build platform moves one-layer thickness down, a leveling roller, or wiper spreads one more level of powder above the previous solidified layer, and similarly the next layer is being created. As mentioned above, after production actions like curing and hardening are required in the case of ceramics and metallic solidification by binder jetting.

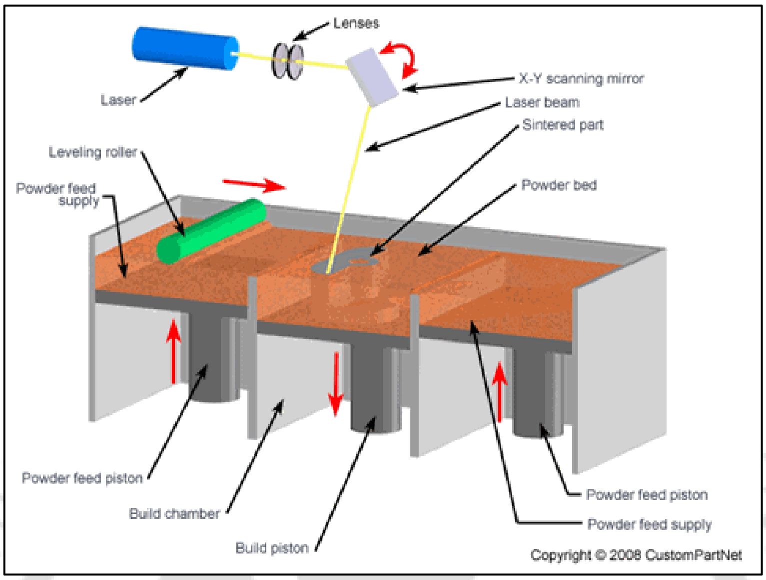



**Figure 2.1D – SLS – Principle of operation schematic illustration.**

Powders solidification technologies have significant advantage comparing to all other technologies, which is the absence of the need to build support to hanging-on-air elements. The remaining unsolidified powder granules support those elements, hence eliminate the support matter, which prevent waste of raw material.

**Types of 3D printers:** Appendix 2.1.1C

**Photopolymers jetting (Polyjet)**

Polyjet 3DPT fusing Inkjet 2D digital printing with 3D printing methods. Instead of ink, the printing head injects liquid photopolymers / photoelastomers, which become hardened by immediate curing process. Despite the effort to minimize the size of those printers in order to be suitable for home / office environment, even the smallest printers are relatively big, compared to desktop personal FFF 3DPs. The properties of the hardened photopolymers/elastomers, suits mostly for use for prototypes making, and less for 3D printed products. The cured raw material is very sensitive to environmental effects relatively to polymers that are in use by the mass production system, and which the photopolymers trying to imitate their properties.

**Principle of operation:** Polyjet 3DPs have three main collaborative systems (Figure 2.E). The printing head, along with attached UV lamp that follows the path of the head and curing the photopolymers, the build platform, and the raw materials cartridges storage chamber. The printing head is fed from two types of thermoset photopolymers/elastomers cartridges. In one set of cartridges, there is a type of raw material, which becomes hard after curing (for modeling), and in the second set, a support raw material is present which becomes like rubber which can be crumbled, and washed away by using water-jet. The purpose of the support material is to keep the stability of the geometry of the model, during the printing process, especially where there are hanging-on-air elements, which need to be supported, same as in other 3DPT (except powders solidification technologies).

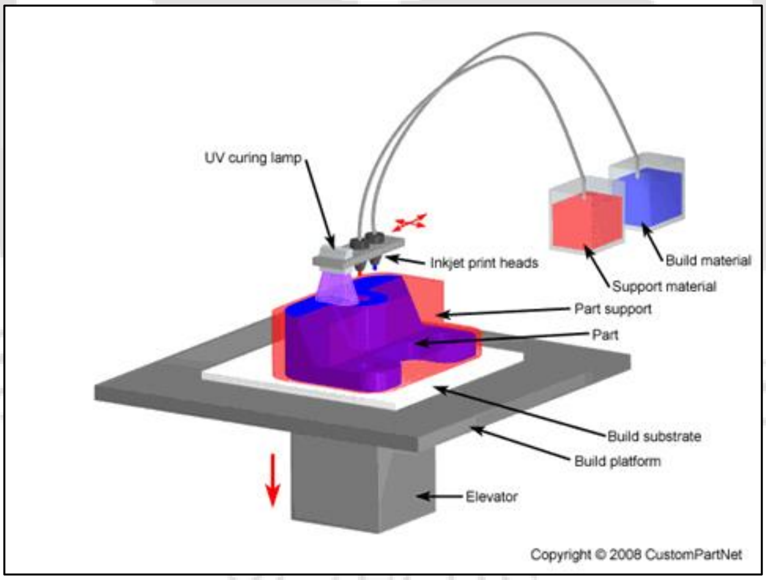



**Figure 2.1E – Material jetting – Principle of operation schematic illustration.**

The printing head moves along the X, Y axles, hence creating the cross-sectional shape of each layer, and the build platform moves downward the Z axis, hence determines the thickness of each layer. In the initial stage, the build platform is in its most upper position. The printing head prints and cure the first layer, which is made from the support raw material, the build platform moves one-layer thickness down, and the printing head prints the next layer on top of the previous one, until model building completion. The first few layers are always made from the support material, because after process, the model need to be manually scratched from the build platform. Remaining support material is manually removed by using water high pressure water jet, and the model is ready for use, immediately after cleaning.

**Types of 3D printers:** Appendix 2.1.1D

**Sheets lamination**

This 3D printing exceptional method, stacks and glues cross-sectional shapes of plastic / paper sheets, or metal foils, on top of each other. The most common name for this type of technology is 'Laminated Object Manufacture' (LOM) and is considered as relatively cheap compared to all other 3DPT. The outcome model is not trying to imitate any raw material that in use by mass productions system, and it mostly in use for producing cheap extruded parts, or for commercial exotic purposes, such as building figurines of 3D scanned real people. Depending on the raw material, LOM technologies have two techniques of how to produce a model. In case of binder coated plastic sheets, papers and metal foils, each layer is cut by a laser beam, and glued by a press of heated roller, while in case of plain A4 paper, each layer is cut by a blade and glued by designated glue.

**Principle of operation:** Laminated sheets technologies have four, or sometimes five main collaborative systems: The cutting head / laser projection system, heated roller / gluing head, build platform, sheets feeder, and in plain A4 paper 3DPs, an additional Inkjet printing head. In case of binder coated sheets (Figure 2.1F), in the initial stage, rolled material sheet is stretched on the build platform, and attached to a second rolling mechanism, which supposed to roll wasted material during the 3D printing process. The build platform placed in its most upper position, heated roller presses the relevant section of the sheet, and the laser beam cuts the cross-sectional shape of the first layer together with the outline of the building box. After cutting, the build platform moves one-layer thickness downward, the waste take-up roller rolls the sheet until full uncut section is placed on top of the previous layer, the heated roller presses the new layer and gluing it to the layer below, the laser beam cuts the cross-sectional shape of the upper layer, and so on until completion. Remaining inside the box outline material functions as support for hanging-on-air elements, and it must be removed manually after production.

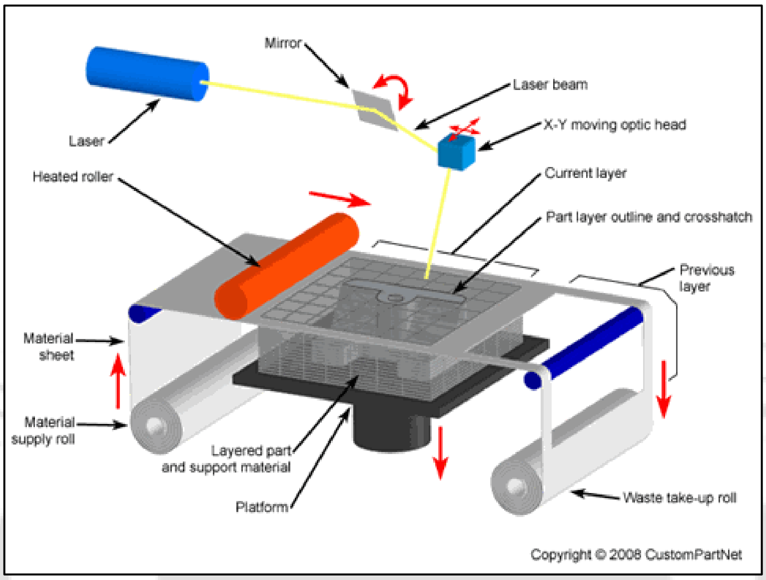



**Figure 2.1F – LOM – Principle of operation schematic illustration.**

In case of plain A4 papers 3DP, there is a feeder that places papers on top of each other, when each paper is cut, colored and glued to the paper below. This kind of technique enables production of colored models, which is a quality that can be found only in certain binder jetting technologies, and in the newest Polyjet 3DPs.

**Types of 3D printers:** Appendix 2.1.1E

### *2.1.2. 3DPTs Technical Review - Interim Summary*

Presently, all the reviewed 3DPT, are in use in the market for different purposes. As can be seen in the technical comparison table (Table 2.1.), there is a clear advantage to the powders solidification method, regarding the variety of raw materials, model's properties, and the lack of necessity to waste support material. Therefore, but not only, those technologies, are mostly in use as AMT, or for production of models / 3D printed products with real functional requirements.

**Table 2.1. – Technical comparison between the reviewed 3D printing technologies.**

| Method | Technologies | Principle of Operation | Materials | Model Support | Post-Production Processes |
|---|---|---|---|---|---|
| Materials Extrusion | Fused Filament Fabrication (FFF) | Extrusion and deposition of heated wired raw material. | - Thermoplastic Polymers<br>- Composite Materials | ✓ | - Support removal<br>- Optional: Surface finish treatment |
| | Other Material Extrusion Technologies | Extrusion and deposition of raw material. | - Ceramics<br>- Concrete<br>- Edible Materials | | - Support removal<br>- Hardening (Ceramics) |
| Photopolymers Solidification | Stereolithography (SL/SLA/STL) | Solidification of liquid photopolymers by laser beam projection | Photopolymers | ✓ | - Support removal<br>- Final Cure |
| | Digital Light Processing (DLP) | Solidification of liquid photopolymers by white-light beam projection | | | |
| | Two Photon Polymerization (2PP) | Solidification of liquid photopolymers by a white-light beam | | | |
| Powders Solidification | Binder Jetting | Solidification of powder granules by binder | - Polymers<br>- Metals<br>- Ceramics<br>- Sand<br>- Glass | - | - Curing<br>- Hardening<br>(Depends on the raw material) |
| | Selective Laser Sintering (SLS) | Solidification of powder granules, mixed with binder, by a laser beam | | | |
| | Direct Metal Laser Sintering (DMLS) | Solidification of powder granules by a laser beam | | | - Optional: Hardening |
| Photopolymers Jetting | Photopolymers Jetting (Polyjet) | Solidification of liquid photopolymers by immidiate curing | Photopolymers / Photoelastomers | ✓ | - Support removal |
| Sheets Lamination | Laminated Object Manufacture (LOM) | Stack and glue binder coated plastic / paper sheets, or metal foils | - Binder coated plastic<br>- Binder coated paper<br>- Binder coated metal foil | - | - Extra material removal |
| | A4 sheets Lamination | Stack and glue A4 plain papers | Plain A4 Paper | | |

The main reasons of why powders solidification technologies are in use as AMT, and are mostly owned by factories, professional modelers, and academic institutes, are because of the size of the machines, which is not suitable for home / office environment, and their high cost.

There is a constant effort to minimize almost all the technologies, and it seems like that the developers are trying to find the breakthrough to the personal market. According to the estimation of 'Wohlers' (Figure 2.1G), more than 278,000 desktop 3DPs that were priced under $5,000, were sold in 2015, and it seem like there is a trend of consistent growth since 2007. In 2007, the first desktop size 3DPs started to be offered to the market, and since then, the prices reduced significantly. Relatively to desktop 2D digital printer, which can be considered as a precedential case, the sum of $5,000 is not an affordable price for the common people.

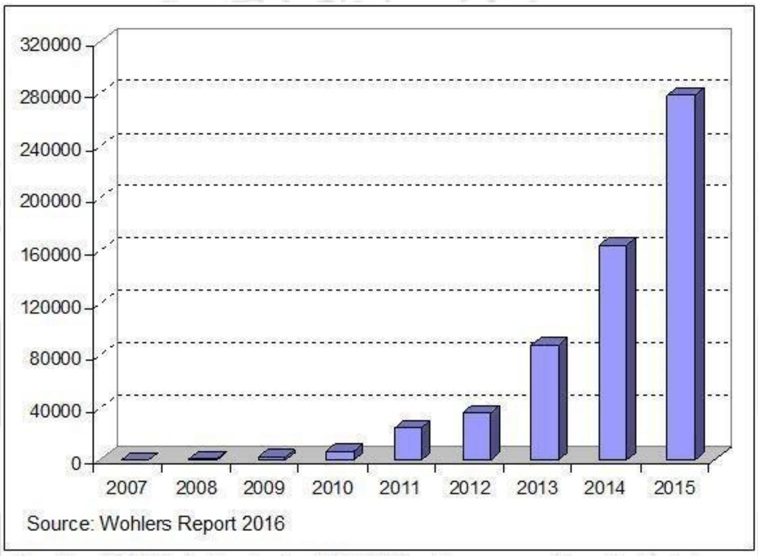



**Figure 2.1G – Wohlers Associates Report – Estimation of desktop 3DP selling.**

In an interview that I conducted with Eng. Zvi Greenberg (2014), who owned a leading marketing company of 3DPs in Israel (Caliber – 3D Printing Solutions), he mentioned that the main reason of the growth in the desktop 3DPs selling is the reduction in size and costs, but the vast majority of the buyers are schools, academic institutes, Fab-labs, designers/ engineers/ architects/ jewelers/ artists offices and studios, and significantly less, ordinary people.

The effort to minimize the external size of 3DPs and to reduce costs, had led to successful developments of desktop material extrusion, SLA and DLP machines. As can be seen in the general comparison table (Table 2.2.), powders solidification and photopolymers jetting methods were marked with crossed-check-mark, because despite the reduction of the size of several machines, they still relatively much bigger, comparing to others desktop 3DPs. Companies which sell powders solidification 3DPs, emphasize new machines with smaller external dimensions and lower price, but no one mentions the word 'desktop'.

**Table 2.2. – General comparison between the reviewed 3D printing technologies.**

| Method | Technologies | Applications | Advantages | Disadvantages | Desktop Personal 3DP |
|---|---|---|---|---|---|
| Materials Extrusion | Fused Filament Fabrication (FFF) | - Prototypes<br>- Functional testing<br>- Fit / Form testing<br>- Presentation models<br>- 3D printed products | - Durable models<br>- Relatively cheap<br>- Relatively fast | - Course surface finish<br>- Relatively low accuracy<br>- Post-production process | ✓ |
| | Other Material Extrusion Technologies | - 3D printed products<br>- Buliding houses<br>- Food | - Unique outcome | | ✓ |
| Photopolymers Solidification | Stereolithography (SL/SLA/STL) | - Prototypes<br>- Functional testing<br>- Fit / Form testing<br>- Presentation models<br>- 3D printed products | - Fine details<br>- Fine surface finish<br>- High accuracy | -Sensitive to environmental effects<br>- Post-production process<br>- Limited diversity of raw materials | ✓ |
| | Digital Light Processing (DLP) | | | | ✓ |
| | Two Photon Polymerization (2PP) | | | | - |
| Powders Solidification | Binder Jetting | - Prototypes<br>- Functional testing<br>- Fit / Form testing<br>- Strength testing<br>- Presentation models<br>- 3D printed products<br>- AMT | - Fine details<br>- Fine surface finish<br>- High accuracy<br>- Diversity of raw materials<br>- Highly durable models (depends on raw material). | -Relatively expensive<br>- Post-production processes (depends on the technology)<br>- Relatively slow (depends on the technology) | ✗ |
| | Selective Laser Sintering (SLS) | | | | ✗ |
| | Direct Laser Metal Sintering (DLMS) | | | | - |
| Photopolymers Jetting | Photopolymers Jetting (Polyjet) | - Prototypes<br>- Functional testing<br>- Fit / Form testing<br>- Presentation models<br>- 3D printed products | * Same like 'Photopolymers Solidification' | | ✗ |
| Sheets Lamination | Laminated Object Manufacture (LOM) | - Prototypes<br>- Presentation models | - Relatively cheap<br>- Relatively fast | - Course surface finish<br>-Sensitive to environmental effects<br>- Post-production process<br>- Limited diversity of raw materials | - |
| | A4 sheets Lamination | - Prototypes<br>- Presentation models<br>- Decorative 3D printed products | - Unique outcome | | |

Stratasys markets 'Objet 24' and 'Objet 30' as desktop Polyjet 3DPs, but relatively to non-crossed-check-mark technologies, those 3DPs are much bigger. Stratasys is not misleading by using the word 'desktop', because those 3DPs fit for home / office environment, and there is no real standard regarding for what can be considered as 'desktop' 3DP.

There is an open question regarding to the minimal build volume of 3DPs. Similarly, to A4 paper in 2D desktop digital printers, a standard for build volume is required. An examination of what should be the standard minimal build volume, which will define the maximum size of the 3D printed parts, needs to be done. A comparison between 23 desktop 3DPs (Tables 2.3., 2.4.), clearly shows that there is no constancy in the specification of the build volume between the reviewed 3DPs.

**Table 2.3. – Build size (mm) and build volume (mm$^3$) comparison between 23 desktop 3DP.**

| | Brand | 3DP | B.Length | B.Width | B.Height | Build Vol. |
|---|---|---|---|---|---|---|
| | | **Material Extrusion** | | | | |
| 1 | Stratasys | Mojo | 127 | 127 | 127 | 2048383 |
| 2 | MakerBot | Replicator Mini | 100 | 100 | 125 | 1250000 |
| 3 | MakerBot | Replicator | 252 | 199 | 150 | 7522200 |
| 4 | MakerBot | Replicator 2X | 246 | 152 | 155 | 5795760 |
| 5 | MarkForged | Mark Two | 320 | 132 | 154 | 6504960 |
| 6 | FlashForge | Dreamer | 230 | 150 | 140 | 4830000 |
| 7 | FlashForge | Creator Pro | 225 | 145 | 150 | 4893750 |
| 8 | MakerGear | MakerGear M2 | 254 | 203 | 203 | 10467086 |
| 9 | Ultimaker | Ultimaker 2 | 230 | 225 | 205 | 10608750 |
| 10 | Ultimaker | Ultimaker 2 Extended | 230 | 225 | 305 | 15783750 |
| 11 | BQ | Witbox 2 | 297 | 210 | 200 | 12474000 |
| 12 | Zartax | Zartax M200 | 200 | 200 | 185 | 7400000 |
| 13 | CEL | Robox | 210 | 150 | 100 | 3150000 |
| 14 | Beeverycreative | BEETHEFIRST | 190 | 135 | 125 | 3206250 |
| 15 | LulzBot | LulzBot Mini | 152 | 152 | 158 | 3650432 |
| | | ***Average*** | ***217.533*** | ***167.000*** | ***165.467*** | ***6639021.400*** |
| | | **SLA** | | | | |
| 16 | FormLABS | Form 1+ | 125 | 125 | 165 | 2578125 |
| 17 | FormLABS | Form 2 | 145 | 145 | 175 | 3679375 |
| 18 | DWS Lab | Xfab | Dim 180 | | 180 | 4578120 |
| 19 | 3D Systems | Projet 1200 | 43 | 27 | 150 | 174150 |
| 20 | XYZ Printing | Nobel 1.0 | 128 | 128 | 200 | 3276800 |
| | | ***Average*** | ***110.250*** | ***106.250*** | ***174.000*** | ***2857314.000*** |
| | | **DLP** | | | | |
| 21 | Autodesk | Ember | 64 | 40 | 134 | 343040 |
| 22 | Morpheus | Morpheus | 330 | 180 | 300 | 17820000 |
| 23 | SprintRay | MoonRay | 127 | 81 | 203 | 2088261 |
| | | ***Average*** | ***173.667*** | ***100.333*** | ***212.333*** | ***6750433.667*** |
| | | | | | | |
| | | ***Total Average*** | ***192.045*** | ***146.864*** | ***176.547*** | ***5831443.130*** |

With regard to the external dimensions of desktop 3DPs, I examined the average dimensions of relatively big size desktop 2D digital printers, and accordingly I specified boundary of maximum 550X550X650 mm, or maximum volume of 196,625,000 mm$^3$. Only 3DPs that are within the specified range were reviewed (15 material extrusion, 5 SLA, 3 DLP). I found lack of consistency regarding the external size of the reviewed 3DPs, but it seems like the developers were taking into consideration the suitability to home / office environment aspect.

**Table 2.4. – Machine size (mm), machine volume (mm$^3$), and Build Vol. / Machine Vol. ratio comparison between 23 desktop 3DP.**

| | Brand | 3DP | M.Length | M.Width | M.Height | Machine Vol. | Build Vol./ Machine Vol. Ratio |
|---|---|---|---|---|---|---|---|
| | | **Material Extrusion** | | | | | |
| 1 | Stratasys | Mojo | 630 | 450 | 530 | 150255000 | 0.014 |
| 2 | MakerBot | Replicator Mini | 295 | 310 | 385 | 35208250 | 0.036 |
| 3 | MakerBot | Replicator | 528 | 441 | 410 | 95467680 | 0.079 |
| 4 | MakerBot | Replicator 2X | 490 | 420 | 531 | 109279800 | 0.053 |
| 5 | MarkForged | Mark Two | 575 | 322 | 360 | 66654000 | 0.098 |
| 6 | FlashForge | Dreamer | 467 | 320 | 381 | 56936640 | 0.085 |
| 7 | FlashForge | Creator Pro | 467 | 320 | 381 | 56936640 | 0.086 |
| 8 | MakerGear | MakerGear M2 | 350 | 245 | 260 | 22295000 | 0.469 |
| 9 | Ultimaker | Ultimaker 2 | 342 | 357 | 388 | 47372472 | 0.224 |
| 10 | Ultimaker | Ultimaker 2 Extended | 342 | 357 | 488 | 59581872 | 0.265 |
| 11 | BQ | Witbox 2 | 508 | 393 | 461 | 92035884 | 0.136 |
| 12 | Zartax | Zartax M200 | 356 | 356 | 432 | 54749952 | 0.135 |
| 13 | CEL | Robox | 370 | 340 | 240 | 30192000 | 0.104 |
| 14 | Beeverycreative | BEETHEFIRST | 400 | 140 | 400 | 22400000 | 0.143 |
| 15 | LulzBot | LulzBot Mini | 435 | 340 | 385 | 56941500 | 0.064 |
| | | ***Average*** | ***437.000*** | ***340.733*** | ***402.133*** | ***63753779.333*** | ***0.133*** |
| | | **SLA** | | | | | |
| 16 | FormLABS | Form 1+ | 300 | 280 | 450 | 37800000 | 0.068 |
| 17 | FormLABS | Form 2 | 350 | 330 | 520 | 60060000 | 0.061 |
| 18 | DWS Lab | Xfab | 400 | 606 | 642 | 155620800 | 0.029 |
| 19 | 3D Systems | Projet 1200 | 228 | 228 | 356 | 18506304 | 0.009 |
| 20 | XYZ Printing | Nobel 1.0 | 280 | 337 | 590 | 55672400 | 0.059 |
| | | ***Average*** | ***311.600*** | ***356.200*** | ***511.600*** | ***65531900.800*** | ***0.045*** |
| | | **DLP** | | | | | |
| 21 | Autodesk | Ember | 325 | 340 | 434 | 47957000 | 0.007 |
| 22 | Morpheus | Morpheus | 550 | 350 | 520 | 100100000 | 0.178 |
| 23 | SprintRay | MoonRay | 381 | 281 | 508 | 54386988 | 0.038 |
| | | ***Average*** | ***418.667*** | ***323.667*** | ***487.333*** | ***67481329.333*** | ***0.075*** |
| | | | | | | | |
| | | ***Total Average*** | ***407.348*** | ***341.870*** | ***437.043*** | ***64626529.652*** | ***0.106*** |

Presently, material extrusion desktop 3DPs, are the most popular and widely offered for sale in the market. The main reasons for their popularity are the machines' price, the price and quality of the raw materials, hence the quality of the 3D printed parts, models and products. I found one more aspect that can explain the popularity of those 3DPs, which is the 'Volumes Efficiency Ratio' (VER). The VER represents how much the build volume takes from the total volume of the machine. There is a clear advantage to material extrusion 3DPs with VER of more than three times comparing to SLA desktop 3DPs, and almost twice more than DLP desktop 3DPs. I also examined the VER of Objet 24 and Objet 30 (Stratasys) Polyjet 3DPs, which were not included in the comparison tables, and their VER came out with average of 0.025, much below the compared 3DPs.

Main conclusion that stems from this interim summary, is the lack of standardization in the desktop 3DPs market. There is no standard that refer to, which

3DP can be marketed as desktop 3DP, and there is no standard regarding to the build volume. In cases when graphic designer designs something that need to be printed by desktop 2D digital printer, he/she relies on A4 standard paper as obvious standard format. No such thing, like the A4 (build volume in the 3DPs case), exists in the 3DPs market.

### *2.1.3. Market Effects Examinations*

**Berman (2011)**

Berman presents an overview of 3DPTs, with an emphasis on the current situation, i.e. utilizing these technologies to produce models, and as AMT. The comparison list (Figure 2.1H), presents the differences between the approach of Mass Customization (MC) in Mass Production (MP) system, and based on 3DPT manufacturing system. The parameters that were compared were: Manufacturing Technology, Supply Chain, Integration Requirements, Economic Benefits and Range of Products. The comparison table shows that there are many positive values in a system that is based on 3DPTs, which are more beneficial to consumers and the environment, relatively to the existing system.

| Characteristic | Mass Customization | 3-D Printing |
|---|---|---|
| Manufacturing Technology | Based on pre-assembled modular parts in different combinations or delayed differentiation. | Automated manufacturing based on CAD software and additive manufacturing. |
| Supply Chain Integration Requirements | Need for highly-integrated supply-chain management to ensure right goods at right times from multiple supplies. | Uses readily available supplies available from multiple vendors. |
| Economic Benefits | Ability to produce custom products at relatively low prices. Low inventory risk. Improved working capital management. | Ability to produce custom products at relatively low prices. Low inventory risk. Improved working capital management. |
| Range of Products | Computers; watches; windows; shoes; jeans. | Prototypes; mockups; replacement parts; dental crowns; artificial limbs. |

**Figure 2.1H – A comparison of mass customization and 3D printing. (P.157)**

Berman refers to 3 evolutionary stages, in which 3DP technologies already went through / will go through:

1. Use for production of models, by developers (engineers, designers, architects, etc.).
2. Production of high value products, by factories.

3. Production of products by users, in home environment.

The list (Figure 2.1I) presents properties of 3DPTs under three sections: Advantages, Importance, and Limitations.

Advantages of 3-D Printing in Comparison to Other Technologies

- Can economically build custom products in small quantities as if mass production were used. Sources of cost effectiveness include:
  - No need for costly tools, molds, or punches
  - No scrap, milling, or sanding requirements
  - Automated manufacturing
  - Use of readily available supplies
  - Ability to recycle waste material
  - Minimal inventory risk as there is no unsold finished goods inventory
  - Improved working capital management as goods are paid for before being manufactured
- Ability to easily share designs and outsource manufacturing
- Speed and ease of designing and modifying products

Important 3-D Printing Applications

Small Production Run Applications of 3-D Printing
- Mass-customized products
- Prototypes
- Replacement parts
- Medical/Dental applications

Medium Production Run Applications of 3-D Printing
- Bridge manufacturing

Current Limitations of 3-D Printing

- Higher costs for large production runs relative to injection molding and other technologies
- Reduced choice for materials, colors, and surface finishes
- Lower precision relative to other technologies
- Limited strength, resistance to heat and moisture, and color stability

**Figure 2.1I – Characteristics of 3D manufacturing. (P.158)**

In the summary of the paper, there is a reference to a futuristic status of 3DPTs. Suggested forecast claims that the reduction of raw materials, and 3DPs costs, will lead to integration of 3DP in home environment, and thus users will be able to print products in their homes. There is no reference to the types of printers that will be integrated in the home environment, i.e. whether consumers will want to have small printers that will enable 3D printing of small parts / spare parts only, or whether they will want to have big size 3D printer that can print large-scale products.

Even though Berman mentions desktop personal 3DPs as a personal manufacturing mean, there are no references to the affects in such a scenario, i.e. aspects like the elimination of the necessity to pack products, the on-demand manufacturing wide aspect, the elimination of most of the intermediaries and much more. There is also unclear general reference to the MC approach. The MC term, refers to several practices, in different levels, and the paper refers to it too generally.

**Gandhi et al. (2013)**

Gandhi et al. refer to the changing trend of the MC term, as a result of computers capabilities, the Internet, and other advance technologies (including 3D printing). They refer to the situation, in which 3DPT are owned by power centered sources, and therefore they present in a table (Figure 2.1J), a description of the required changes that need to be done, in order to successfully implement MC approach by these sources. The table is arranged according to the following fields: Marketing, Sales, Product/Service development, Manufacturing service operations, Supply chain, IT infrastructure.

| | Increase value to customer | Control cost of customization |
|---|---|---|
| **Marketing** | • Provide option for customers to market products to their friends in return for store credits | • Provide free marketing by giving customers opportunities to easily share and express their individualization experiences on digital media |
| **Sales** | • Turn those in customer-facing roles into customization advisers; turn "stores" into "showrooms"<br>• Use dynamic promotions to manage capacity | • Offer simple and fun online configurators to gather preferences |
| **Product/service development** | • Leverage big data and ancillary developers to develop and curate customization options, eg, via social media<br>• Curate "recommended configurations" | • Undertake modular approach in product development<br>• Tightly integrate new-product development with manufacturing/ service process design |
| **Manufacturing/ service operations** | • Implement modular approach with a limited number of standard baseline specs and a menu of options that limits complexity for consumers | • Postpone customization to latest possible point<br>• Build flexibility in low-capital-intensive process steps |
| **Supply chain** | • Provide visibility (via radio-frequency identification or scanning) to keep customers invested in "their" creation | • Catalog total cost to serve for each option and manage capacity accordingly |
| **IT infrastructure** | • Increase investments in customer-facing, data-warehousing, and data-analytics technologies<br>• Upgrade enterprise-resource-planning and legacy systems to manage additional complexity of product and service attributes<br>• Tightly integrate e-commerce and digital strategy with back-end IT<br>• Support operations with technology that helps control complexity of inputs | |

**Figure 2.1J – Exhibit 2. (P.9)**

It is clearly apparent that these mentioned required actions take into consideration the unique advantages of the cyber space. There is one important note that suggests postponing the customization to the latest possible point. This general suggestion can act as double-edged sword, because as mentioned previously, there are various MC practices that not necessarily fit every case.

**Petrick & Simpson (2013)**

Patrick & Simpson, refer in their paper to the radical change that 3DPs will generate in the products market. They emphasize the differences between the economies of scale, based on MP systems, and the economics of one-based-on, based on advance technologies (3DP). The table (Figure 2.1K) shows the differences between the economies, according to six categories: Source of competitive advantage, Supply chain, Distribution, Economic model, Design, Competition.

| | Economies of Scale | Economies of One |
|---|---|---|
| Source of competitive advantage | Low cost, high volume, high variety | End-user customization |
| Supply chain | Sequential linear handoffs between distributed manufacturers with well-defined roles and responsibilities | Non-linear, localized collaboration with ill-defined roles and responsibilities |
| Distribution | High volume covers transportation costs | Direct interaction between local consumer/ client and producer |
| Economic model | Fixed costs + variable costs | Nearly all costs become variable |
| Design | Simplified designs dictated by manufacturing constraints | Complex and unique designs afford customization |
| Competition | Well-defined set of competitors | Continuously changing set of competitors |

**Figure 2.1K – Economies of scale versus economies of one. (P.2)**

In addition, general analysis was conducted, according to 5 points: The 3D production Model, The Competitive Dynamics of 3D Printing, The Changing Nature of Design, Experimental Design and Localized Distribution and Printer Hubs.

In the conclusions of the paper, 5 phenomena that must be taken in consideration, were presented (a quote from the paper P.5):

1. There will be few clear boundaries in the design-build-deliver paradigm.
2. Design and production will be tightly coupled through experimentation.
3. Competitive advantage will reside in *both* designs that are simple to manufacture and assemble and designs that are highly customized and complex; the challenge

will be in arenas where manufacturers are seeking simple designs, and customers are seeking customized, complex products.

4. Proximity between supplier, manufacturer, and customer will matter, and localized production will be not only more feasible but more desirable.
5. Planning will go from long term to real time.

**Rayana & Striukova (2014)**

Rayana & Striukova refer to the effects of 3DPT, on business model that relates to the field of product consumption. The reference takes into account a futuristic situation, when 3DPs will be integrated in home environment, however, not only. They also describe a situation when 3DPs will be integrated in factories and printing shops. The diagram (Figure 2.1L) describes the positive feedback loop between the business model's components.

The Value delivery component, represent the option that 3DPs will be integrated in home environment. That means that if a user will own a 3DP, this stage will include a delivery of a suitable 3DP files through the Internet.

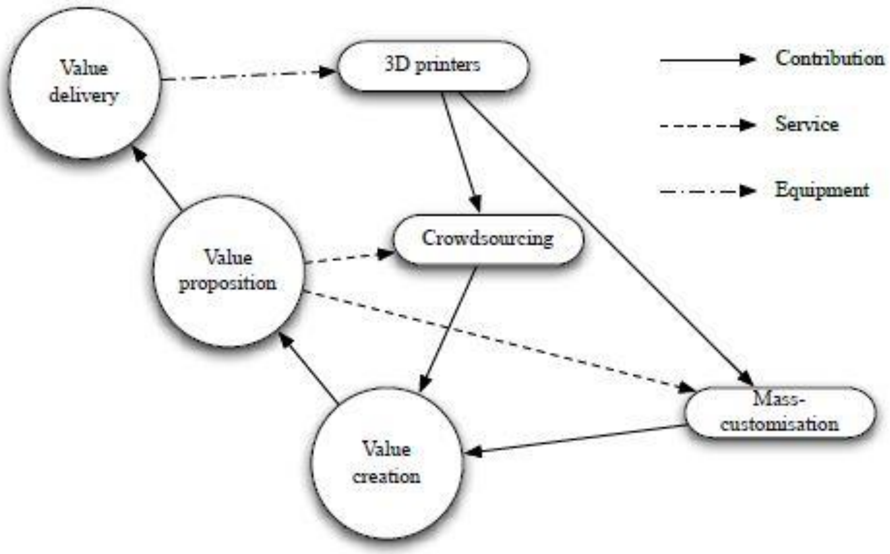



**Figure 2.1L – Positive feedback loop between business model components. (P.9)**

**Weller et al. (2015)**

Weller et al. refer in their paper to the impact of AMTs on the structure of the consumer market. The reference includes the integration of AMT (primarily the 3DPs) in systems, which implementing Flexible Manufacturing Systems (FMS), and there is a minimal reference to the existence of 3DP in home environment. Providing examples, and a sober analysis of the capabilities of AMT, have led to a series of tables that summarize the opportunities and limitations of the AMT, in technological and economical perspective (Figures 2.1M, 2.1N).

| Technological characteristics of AM | |
|---|---|
| **Opportunities** | **Limitations** |
| + Direct digital manufacturing of 3D product designs without the need for tools or molds | – Solution space limited to 'printable' materials (e.g., no combined materials) and by size of build space |
| + Change of product designs without cost penalty in manufacturing | – Quality issues of produced parts: limited reproducibility of parts, missing resistance to environmental influences |
| + Increase of design complexity (e.g., lightweight designs or integrated cooling chambers) without cost penalty in manufacturing | – Significant efforts are still needed for surface finishing |
| + High manufacturing flexibility: objects can be produced in any random order without cost penalty | – Lacking design tools and guidelines to fully exploit possibilities of AM |
| + Production of functionally integrated designs in one-step | – Low production throughput speed |
| + Less scrap and fewer raw materials required | – Skilled labor and strong experience needed |

**Figure 2.1M – AM technology's opportunities and limitations from a technological perspective. (P.46)**

| Economic characteristics of AM | |
|---|---|
| **Opportunities** | **Limitations** |
| + Acceleration and simplification of product innovation: iterations are not costly and end products are rapidly available | – High marginal cost of production (raw material costs and energy intensity) |
| + Price premiums can be achieved through customization or functional improvement (e.g., lightweight) of products | – No economies of scale |
| + Customer co-design of products without incurring cost penalty in manufacturing | – Missing quality standards |
| + Resolving "scale-scope dilemma": no cost penalties in manufacturing for higher product variety | – Product offering limited to technological feasibility (solution space, reproducibility, quality, speed) |
| + Inventories can become obsolete when supported by make-to-order processes | – Intellectual property rights and warranty related limitations |
| + Reduction of assembly work with one-step production of functional products | – Training efforts required |
| + Lowering barriers to market entry | – Skilled labor and strong experience needed |
| + Local production enabled | |
| + Cost advantages of low-wage countries might diminish in the long run | |

**Figure 2.1N – AM technology's opportunities and limitations from economic perspective. (P.47)**

With regard to the power centered sources that integrating AMTs in production systems, a table that analyzes 4 relevant principles of development and manufacturing process, is presented (Figure 2.1O).

| | |
|---|---|
| **Versatile manufacturing machine** | • On-demand direct digital manufacturing of 3D product models enabled<br>• End products are rapidly available at constant marginal cost (no economies of scale)<br>• Local availability of versatile manufacturing resources with standardized interface |
| **Customization and flexibility for free** | • Product designs can be customized without cost or time penalties in manufacturing<br>• Volume and product flexibility without cost or time penalties for machine setup or changeover<br>• No tools or molds needed |
| **Complexity for free** | • Higher design complexity without cost penalty in manufacturing<br>• Little design constraints for products<br>• No cost penalties for higher product variety |
| **Reduction of assembly work** | • Direct production of functionally integrated parts (e.g., moving parts, cooling system) possible<br>• Fewer production steps involved<br>• Lower manual intervention throughout production processes |

**Figure 2.1O – Key principles of production with AM technology. (P.48)**

In their conclusions, Weller et al. refer to the potential impacts of AM principles and their influence on manufacturing companies, and market structure (Figure 2.1P47). They also noted that there is lack of researches that relate to the fact of the ability to integrate 3DPs in home environment, hence that the user becomes also a manufacturer (partially or fully).

| AM key principles | Effects on payoff function | Effects on market structure | |
|---|---|---|---|
| | Payoff function as defined by Milgrom and Roberts (1990) | Product attribute address models | Game-theoretic models for technology choice |
| **Versatile manufacturing machine** | • Versatility enables firms to produce customized products on demand<br>• Total capital costs could be lower because product changes do not involve one-off costs | • AM enables strong economies of scope in product differentiation<br>• Market can be served along entire product range once entered | • Multiple, highly differentiated markets can be served at once; allowing split of fixed costs<br>• Fewer mobility barriers in serving more market segments may lead to increased competition |
| **Customization and flexibility for free** | • Customized products can be offered without penalties in manufacturing potentially resulting in price premium<br>• No time penalties for customization resulting in higher demand per product | • High product flexibility allowing firms to serve entire market without cost penalty<br>• Customers can all be served with most preferred good, while market prices can be lowered | • Participation in different market segments enabled, high incentives to increase flexibility<br>• Production is adjustable to fluctuating customer preferences |
| **Complexity for free** | • Product improvements and design changes can be carried out without cost penalties in manufacturing resulting in higher demand per product<br>• Higher design complexity without capital cost impact | • Negligible modification and re-anchoring costs of base product: higher variety can be offered<br>• Higher product variety without additional costs | • Incentives to raise a firm's degree of flexibility are increased as long as economies of scale do not lead to massive cost advantages of non-AM technology |
| **Reduction of assembly work** | • Total order processing time can be reduced<br>• Fewer defective batches due to less manual work requirements | • Negligible modification and re-anchoring costs of base product<br>• May reduce marginal costs for production of assembly-intensive products | • May reduce marginal costs for production of assembly-intensive products |

**Figure 2.1P – Key principles of AM and their potential effects on a manufacturing firm's payoff function and market structure models. (P.54)**

#### *2.1.4. Market Effects – Interim Summary*

The common denominator of all the reviewed references, is that they point on elaboration and simplification in all the aspects that assemble the value chain. The advantages and opportunities of 3DPT, as AMT, or as desktop personal 3DP (Table 2.5.), were summarized in a chart, according to four categories: Design, Manufacturing, Marketing and Distribution. Combining similar terms in each category have produced effects collection and insights as follow:

- **Design:**
  - Significant reduction in the duration of the design process.
  - Aspiration for modular / open architecture / optimized product design.
  - New design approaches and aesthetics.
  - Data collection through the cyber-space, more valued designs.

- **Manufacturing:**
  - Production capabilities dispersion among several independent sources.
  - On-demand direct digital manufacturing.
  - High manufacturing flexibility.
  - Reduction of assembly work.

- **Marketing:**
  - Marketing through users share and feedback.
  - Crowdsourcing as marketing tool.

- **Distribution:**
  - Cyber-space as distribution platform.
  - Delivery of suitable for 3DP file.
  - Supplies from multiple vendors.

**Table 2.5. – Advantages and opportunities of 3DPT as AMT / personal 3DP, according to the mentioned references.**

| | | Berman (2011) | Gandhi et al. (2013) | Petrick & Simpson (2013) | Rayana & Striukova (2013) | Weller et al. (2015) |
|---|---|---|---|---|---|---|
| Production chain | Design | - Speed and ease of designing and modifying products. | - Modular approach.<br>- Tight integration of new -product development with manufacturing.<br>- Aspiration to optimal design by collecting data through the cyber-space. | - Complex and unique designs afford customization. | - Open architecture design. | - Increase of design complexity.<br>- Change of product designs without cost penelty.<br>- Customer co-design of products |
| | Manufacturing | - Automated manufacturing.<br>- No need for costly tools, molds, or punches.<br>- No scrap, milling, or sanding requirements. | - Flexilble manufacturing process. | NR | - Not limited to one place | - Direct digital manufacturing.<br>- High manufacturing flexibility.<br>- Production of functionally integrated designs in one-step.<br>- Less scrap and fewer raw materials required.<br>- Reduction of assembly work.<br>- Local Production enabled.<br>- On-demand direct digital manufacturing.<br>- Lower manual intervention. |
| Supply chain | Marketing | - Easily designs share. | - Easily designs share.<br>- Users feedback as marketing tool<br>- User-marketer in return for store credits. | - Emphasize customization. | - Crowdsourcing as marketing tool, along with its purpose. | NR |
| | Distribution | - Readily available supplies available from multiple vendors. | - Visibility, to keep the customers invested in "their" creation. | - Direct interaction between local consumers / client and producer. | - Delivery of a suitalbe for 3DP file. | NR |

An interesting point is that all the references that regard to the limitations of the 3DPT, relate mostly to technical issues, e.g. "reduced choice of materials, colors, and surface finishes, lower precision relative to other technologies (I argue with that), limited strength, resistance to heat and moisture, and color stability" (Berman, 2011), "low production throughput speed, solution space limited to 'printable' materials (e.g., no combined materials and by size of build space), and training effort required (Weller et al., 2015). Weller et al., refer to another limitation, which is the missing of quality standard. This missing standard, which is one of a number of missing standards (as mentioned previously), is one of the obstacles that prevents from the 3DPs to make the breakthrough to the nonprofessional market. Without absolute values range of tolerances, designers and engineers cannot design multi-parts dynamic products. The absence of quality standard makes preplanned fit tolerances become irrelevant.

### *2.1.5. Socio-Environmental Effects*

Like every transformative change invention effects on way of life, beside its original purpose, 3DPT which initially directed to produce plastic parts for prototypes, have the potential to radically change many traditional / conventional aspects. Along with impacts on design and manufacturing, there might be other side effects on peripheral dependent aspects e.g., storage, recycling, energy consumption, etc.

**Barnatt (2013)**

Barnatt extensively reviewed 3DPT along with their peripheral effects. In chapter 6: 3D Printing & Sustainability, Barnatt points on six effected aspects: Empowering Localization, Digital Storage & Transportation, A Return to Product Repair, Improved Material Utilization, Material Recycling, and Complementary Technologies.

- Empowering Localization

This aspect relates mostly to the opportunity to use 3DPT as an element that will bring geographically closer production means, to where the outcomes supposed to be supplied. The current situation in which products are being manufactured and assembled in one place, and need to be shifted to another place, sometimes in the other side of the globe, requires use of transportation, hence localization of the manufacturing source will reduce, or even eliminate this requirement. The immediate consequence in this case, will be a huge saving of perishable energy sources, and I would add also the elimination of the need to heavily pack products, which will lead to saving in packaging raw materials that become waste, shortly after the purchasing of the product.

- Digital Storage & Transportation

As mentioned in the previous secondary sub-chapter (Market Effects), Barnatt refers to the opportunity to replace physical delivery by couriers, by a delivery of digital secured file to a nearby customer 3D printing shop. I would add that this operation can be done also in case that the customer owns desktop personal 3DP. Barnatt also points on the inevitable need to store stocks of products after manufacturing and before selling. This need is an outcome of the mass production system that produce products in high volume, and occasionally even not all the products are being sold. On-demand manufacturing by 3DPs can clearly eliminate this need, and solve this current unsolvable problem. I would add also that on-demand manufacturing can also reduce the need for storage in private homes. There is an opportunity for people to print whatever they need for specific purpose and after use, they will be able to send the unrequired product for recycling i.e., if a person has to host twenty people for BBQ, this person can 3D print twenty plates, cutlery set, glasses etc., and afterward send it to recycle, without the need to store them before, or after the event.

- A Return to Product Repair

This aspect relates to a controversial issue that many people believe that it is a manufacturers' conspiracy. Barnatt refers to past times, when products were designed to endure, and were repaired when parts got broken, unlike present times in which people prefer to buy new products in same cases. The mass production system lowered the prices of products, and along with technological developments it brought people to throw away working products, or broken products that could be repaired. The phenomenon is mostly observed in Japan, where people throw almost brand-new products, because of new improved products, which are offered for sale. This phenomenon had led manufacturers to design less durable products, rather not because of a conspiracy, but because of how people behave. 3DPT can definitely bring back times when people will prefer to fix certain broken products, because of the availability of spare parts, but it will not stop this phenomenon completely.

- Improved Material Utilization

Conventional manufacturing means produce a lot of raw materials waste. The unique ability of 3DPs to build parts, and not reshape blocks, saves a lot of waste that comes out from milling, drilling etc. Moreover, the ability of 3DPs to build solid parts with inner construction, without losing their strength, can also save large quantity of raw materials. Barnatt refers more widely to this aspect, and brings more examples of how companies use this advantage of 3DPTs by integrating 3DPs as AMT.

- Material Recycling

This important issue, which relates not only to 3D printing, can be implemented in certain 3DPTs, and by that it can be aligned with the global trend. Material extrusion and DMLS technologies use recyclable raw materials, but the rest of the technologies operate in such a process that make the final raw material non-recyclable. Barnatt mentions interesting innovative invention of a desktop machine that reshape thermoplastic waste into ready-for-reuse raw material, and this kind of function can be integrated, in the future, in 3DPs. Such an option will bring new process of in home recycling (like some people produce fertilizer from organic waste).

- Complementary Technologies

By referring to 3DPTs as complementary technologies, Barnatt points on other uses rather than producing parts and products, e.g. food printing and 3D printing for medical purposes. Since 2013 (the year of the publication of the book), experiments in 3D printing of biological tissues were done, and uses like printing dental implants and other implants that replace missing bones, became practical methods.

**Lipson & Kurman (2013)**

Lipson & Kurman refer extensively in their book to many aspects that relate to 3D printing. They refer in particularly to effects on design, and present many examples of 3D printed products and other outputs. As mentioned in the 'Research Motivation' chapter, most of the revolutionary designs are done using biomimetic approach. This advanced approach reflects a fascinating combination of natural structures based on an optimized humans' design and engineering. In chapter 12 – 'Ownership, safety, and new legal frontiers', they note negative aspects along with controversial issues that need to be considered, and should bother all of us.

- **Printing weapons** – Luckily the common people still have not adopted 3DPs, because this option is already on the table, and it does not seem like governments are doing something about it (I'm not sure they can, and I'll not open this matter).

- **Printing drugs** – The reference relates mostly to a futuristic scenario in which 3DPs will be able to synthesize chemicals and 3D print customized medicines. In the same manner, people will be able to 3D print unsupervised narcotic and psychotic drugs, hence obtain them much more easily than today.

- **Consumer safety** – One of the big advantages that consumers usually enjoy from companies, is that companies design and manufacture products under safety regulations. For example, in kids' gun toys, designers are not allowed to produce more than 1.5 J kinetic energy. The absence of awareness to regulation in design can lead, even not deliberately, to injuries, fires, etc.

- **Quality assurance –** It can be argued, but another thing that consumers benefit from products that produced by companies, is the reputation issue. Companies assure at list, minimal quality, because they produce stocks and aspire to sell all the manufactured products. This kind of integrity, and minimal care is not assured in a word of independent designers who can share designs without fear from the reputation sword.

- **Copyrights -** The combination of computer, Internet and 3DP can produce series of copyrights and patents violations, or even just false credits issues. Another moral issue that needs to be figured out is how to solve, and practically regulate.

- **Taxes income** – Prof. Yuval Noah Harari, a lecturer at the Department of History, Hebrew University of Jerusalem, mentioned in a TV panel that the form of states is changing. Instead of leading, democratic countries governments are now expected to properly manage. As a result of all the series of transformative change inventions of the computer, Internet, 3DPTs, and the autonomic machines, along with other advance developments and scientific discoveries, people will tend to identify themselves, and gather around ideas, and less by citizenship (this is an already ongoing process). The influential power of governments will decrease, and maybe, one of the reasons might be the reduction in taxes incomes, as a result of an adaptation of 3DPs by the common people. The fact that masses can potentially own advance automatic manufacturing means, might cause to reduction in VAT income from products, and other incomes from fuels taxes, income tax from labors, all kind of fees including customs, etc.

## 2.2. Product Design Methodologies

In order to formulate a product design methodology for desktop personal 3DP, a review of leading product design methodologies was made. The review focused on the factors that formulate the methodologies and the way they were constructed. The review starts from references that were published since 1995, and which carefully were selected with consideration of their references to methodologies that were formed previously. The book 'Engineering Design – A Systematic Approach" by Pahl and Beitz – Second English Edition (1996), was reviewed, but will not be presented in the literature review. This book refers extensively to design methodologies and mentions previous systematic approaches (P.16), but it is more engineering design oriented. Therefore, I preferred to rely on Roozenburg and Eekels (1995) that included relevant outcomes form the first edition of this book (1984).

### *2.2.1. Methods and paradigms*

**Roozenburg & Eekels (1995)**

Roozenburg & Eekels refer extensively to methods of product design with orientation for product designers. They funneled their references to the product's development process, from the general business perspective down to detailed design methodologies.

I would add, at this point, that the book refers to professional product developers, and all the presented diagram, methods and case studies, relies on organizational combined work, based on professional managers, designers, engineers, business men marketers, manufacturers etc. This remark has its importance in context to the research work, since a scenario in which the manufacturing mean exists in the hand of the user (3DP), requires re-examination of the presented methodologies and ideas. The absence of standardization and regulation in the 3D printing market, along with possibilities that the cyber-space enables (regarding to almost every aspect), necessitate to revalidate the conventional methodologies, or to construct new methodologies.

In part I section number 2 they refer in generally to the life cycle of a product, and more specifically, to the product development process, as part of a general business development process. They present the general components of the value chain that assemble the general business plan, as follow: "basic and applied research, design and development, market research, marketing planning, production, distribution, sales and after sales service" (P.9). The General structure of the product's development process, or the as they named it - the innovation process (Figure 2.2A), demonstrates in general perspective, the general strategic milestones in the process. This structure elaborated into detailed structure diagram (Figure 2.2B), which places the product design stage in the heart of the process. The presented diagram is a linear one, and it does not reflect lawfully the product's development process, it simply shows linearly the direction of the progress.

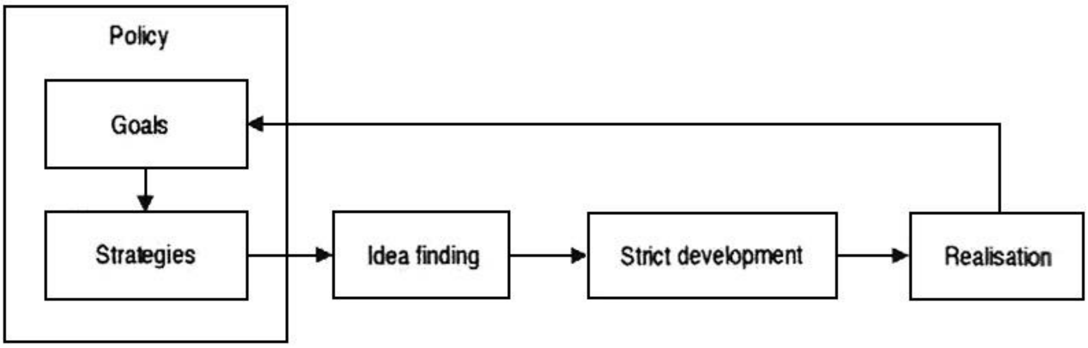



**Figure 2.2A – The structure of the innovation process. (P.12)**

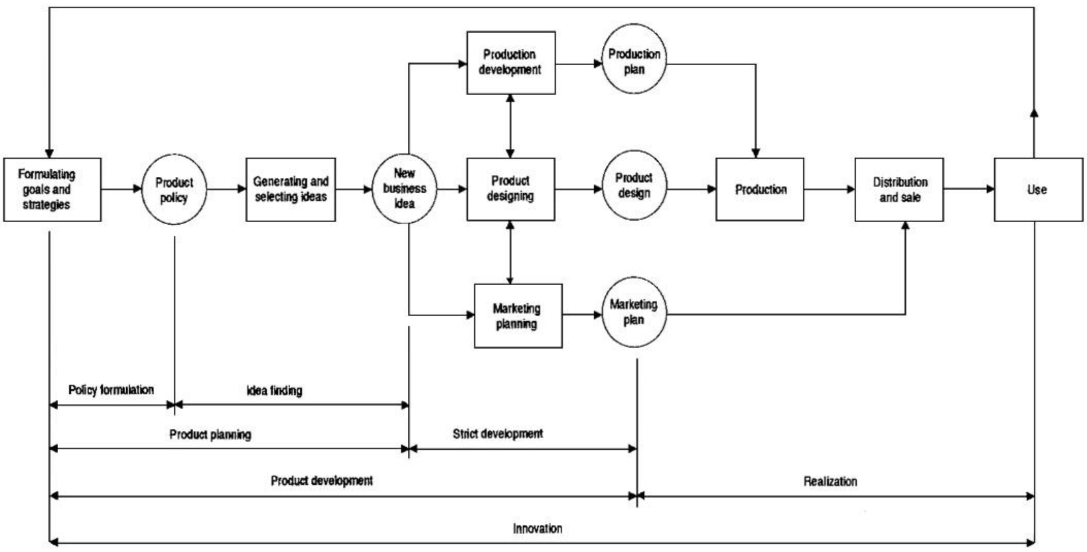



**Figure 2.2B – The phases of the innovation process. (P.13)**

Further to the mentioned processes, Roozenburg and Eekels scoped the 'strict development' stage, which starts with a 'new business idea', continues in parallel with 'production development', 'product designing' and 'marketing planning', and ends in the 'production plan', 'product design' and the 'marketing plan' stages. They developed and formed the 'technical development process' stage (as part of the 'product designing' and the 'production development' stages) into a diagram (Figure 2.2C) that presents it as an iterative process. Prior to the presented diagram, a simpler diagram was constructed, in order to place correctly and understand the effect of every variable. Only after that, the more elaborated diagram was presented.

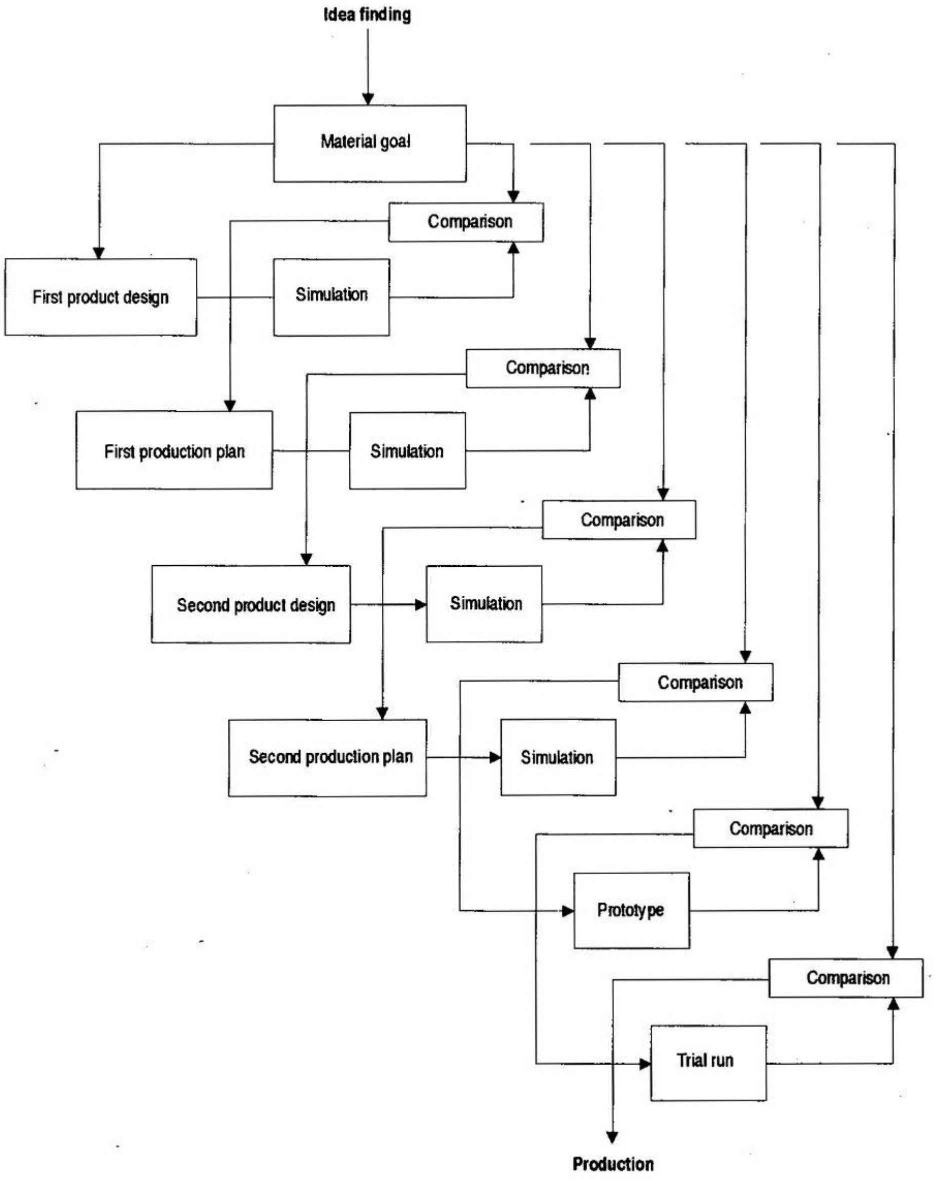



**Figure 2.2C – Technical development as an iterative process. (P.20)**

In quite a similar way, they constructed a diagram that presents the 'commercial development' as iterative process, they combined it with the 'technical development process', and formed a diagram, which they named the 'Product development as a whole' interactive flow diagram (Figure 2.2D). The shape of the bordered half circle (they call it a sink) represents a point in which "two information streams ought to be combined to be able to further process the result of the combination" (P.23). The numbers represent decision points, where decisions be should made according to three options: proceed to the next stage, go backward to previous stage, or stop the project.

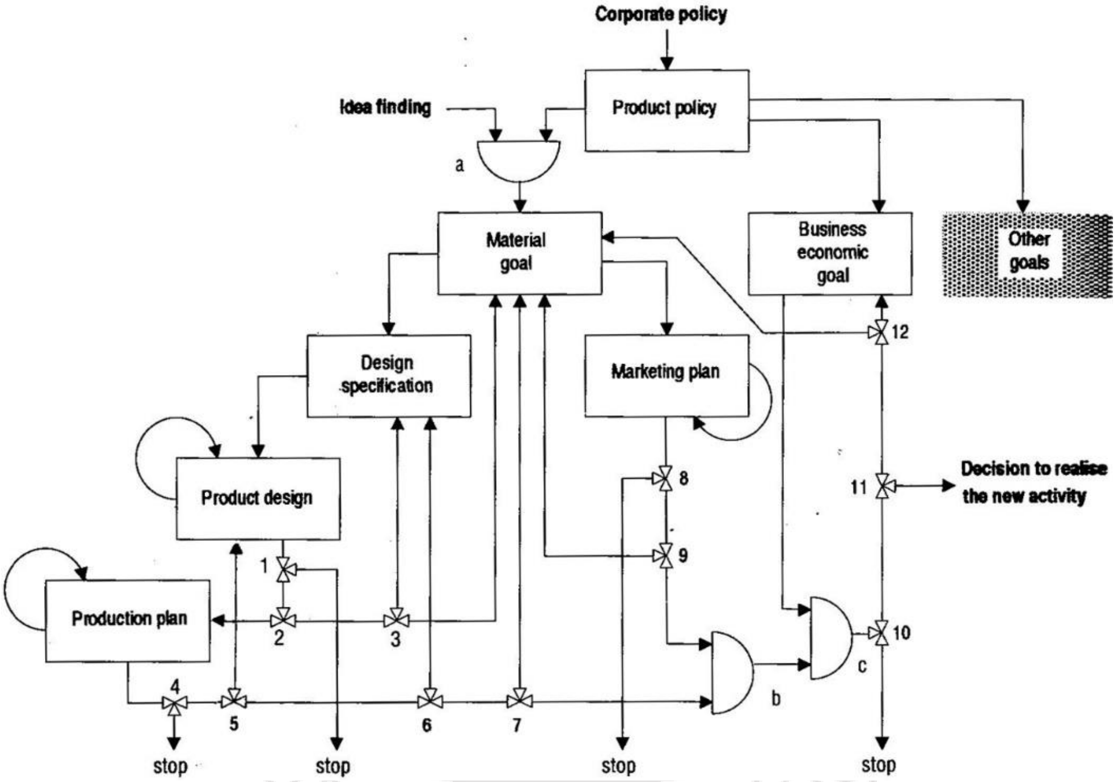



**Figure 2.2D – Product development as a whole. (P.24)**

In part I section number 3 'Design Methodology', Roozenburg and Eekels define and explain the title of the section as follow:

**"Design methodology is a science of methods that are or can be applied in designing…the word 'methodology' has two meanings. The first meaning is: a science of study of method, i.e. the description, explanation ad valuation of methods. The second meaning of 'methodology' is: a body of methods, procedures, working concepts and rules employed by a particular science, art or discipline…. In design methodology, there are two principal questions: (a) what is the essential structure of designing? and (b) how should the design process be approached to make it effective and efficient?" (P.29).**

In continuation to this definition, a deep reference, regarding to methods, was made. Starting from a logic differentiation between science and technology methodologies, through how to ensure that there is a necessity for a new methodology, clarifying related concepts, classifying methodologies, and ending with the place of using methods in an organization with its effectiveness.

In part II section number 5, 'The Structure of the Design Process', Roozenburg and Eekels mention 3 types of design process methodologies models. The first one is the 'problem-solving' empirical model, the second is the 'phase' model, and third is also a 'phase' model, with regards to more aspects beside the design of the product. With regard to the 'problem-solving' first model, and according to the mentioned principals that De Groot (1969) and Hall (1968) presented, a diagram of the basic design cycle (Figure 2.2E) was presented. At this point I would add that the first model is less relevant for use for construction of a design methodology for desktop personal 3DP. The relevancy of this model is correct for any need to solve problem during the design process, but it is not instructing how to design for the mentioned purpose.

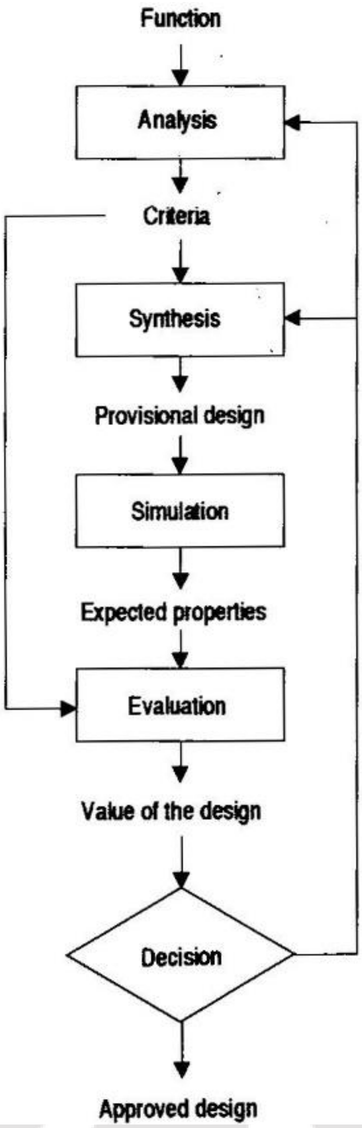



**Figure 2.2E – The basic design cycle. (P.88)**

With regard to the second model, Roozenburg and Eekels mention methodologies that were constructed by French (1971), Pahl and Beitz (1984), Hubka/VDI Guideline 2221 (1987), Pugh (1961), Ulman (1992), and van den Kroonenberg and Siers (1992). The three most adopted phases models were presented (Figures 2.2F, 2.2G, 2.2H), and as can be seen, the models comprise stages that relate to the product design process only, without indicating factors that were included in product development process models (Figure 2.2D). Basically, including the production development and the marketing factors, along with the product design stage is what makes the difference between the second and the third phase models. "Commercial and manufacturing considerations are largely seen as constraints (established in the specification), within which designer seeks the best possible form for the product" (P.111). In a case of a scenario in which the end user / customer's own, or have access to 3DP, the manufacturing factor becomes very specific, and it should not be considered anymore as a bank of solutions (unlike in all the second phase models there were formed until now).

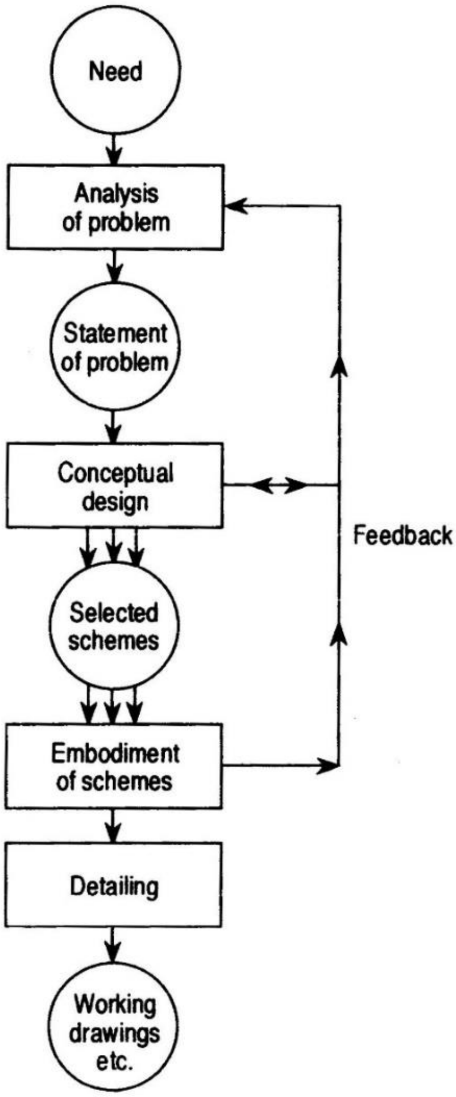



**Figure 2.2F – The Phases of the design process according to French. (P.103)**

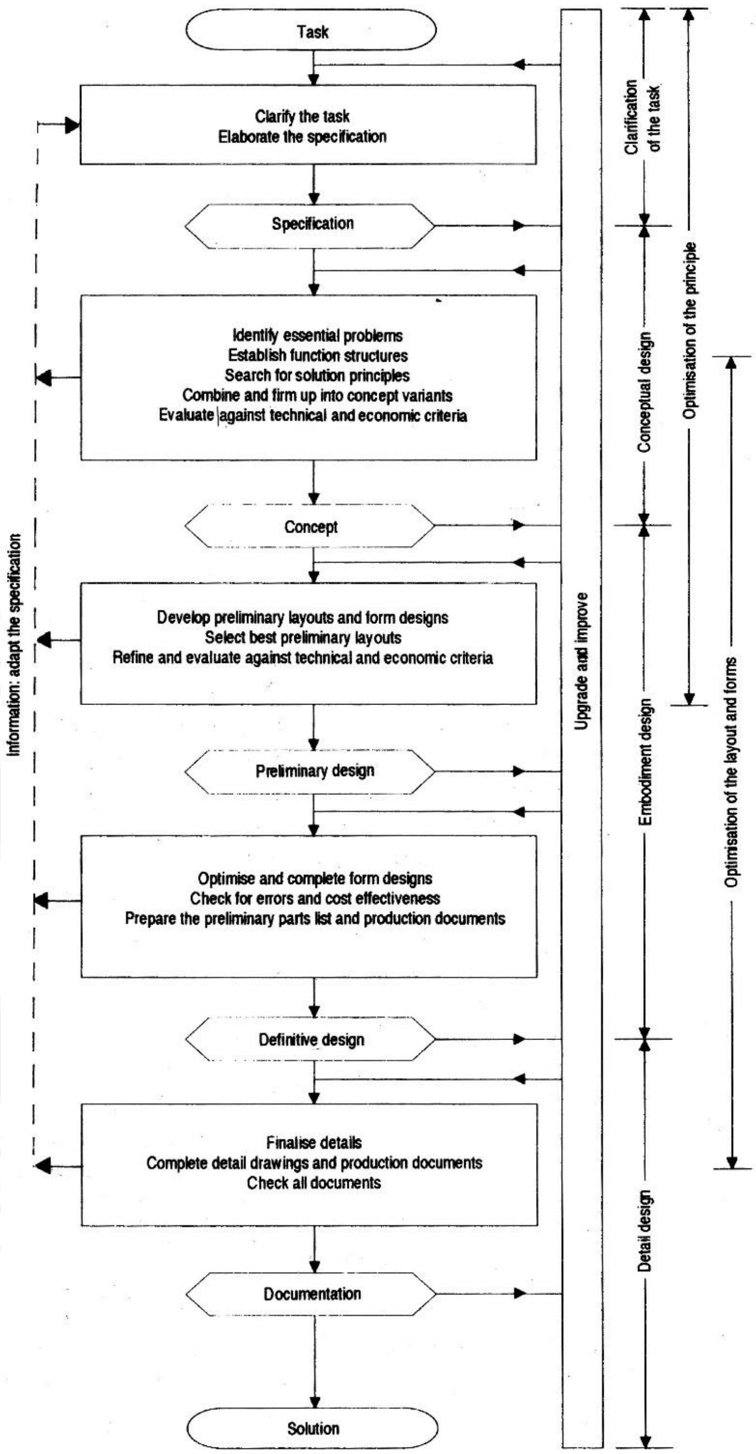



**Figure 2.2G – The phases of the design process according to Pahl and Beitz. (P.104)**

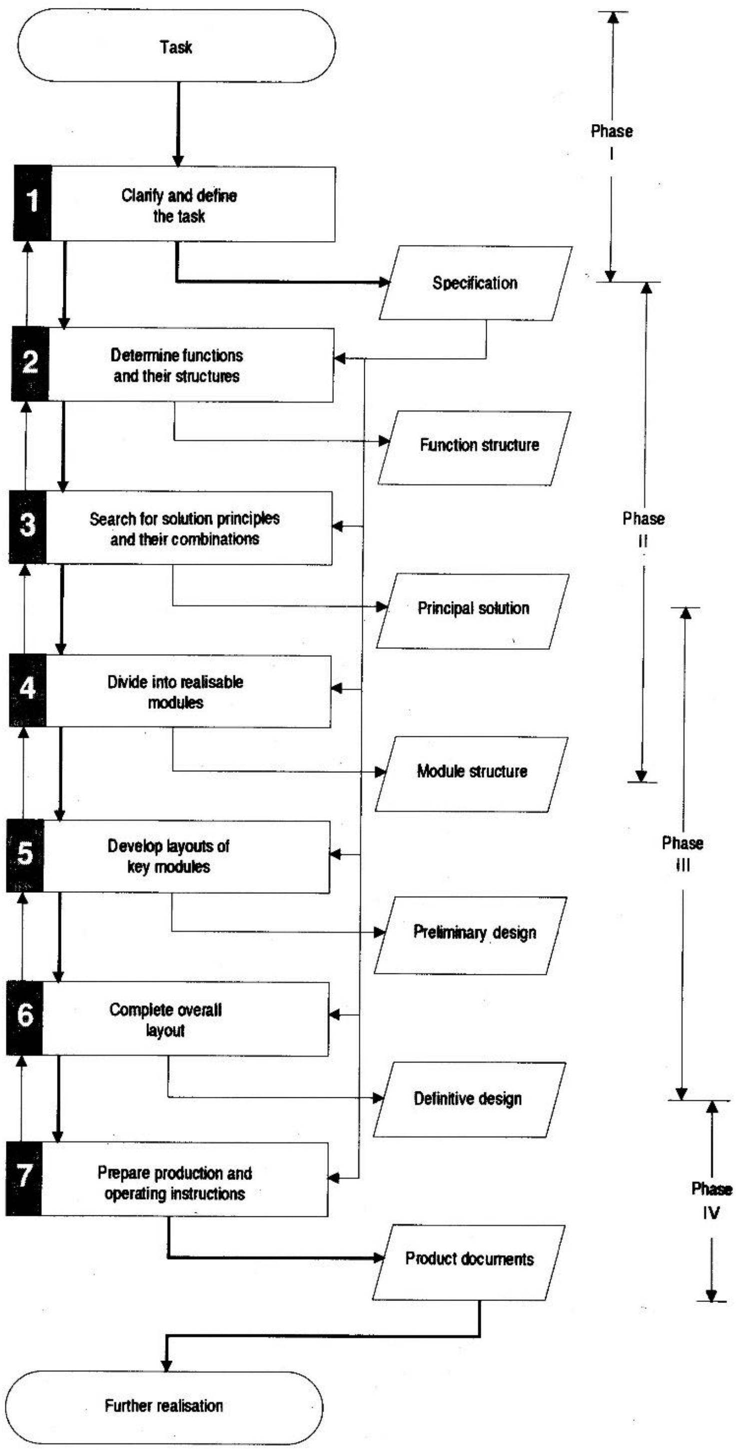



**Figure 2.2H – General approach to design according to VDI 2221. (P.108)**

**Baxter (1995)**

Baxter refers broadly to all the aspects that involve in the product development process, with emphasize on the design process. At the first chapter, he listed six demands that are required from the industrial designer of the future (P.4):

- Multi-skilled
- Fanatically 'customer-oriented'
- Deeply committed to systematic design methods
- Knowledgeable about a wide range of manufacturing business
- Comfortable in marketing, design and engineering disciplines
- Accomplished at creative problem solving

In chapter 2 'Principles of new product development', Baxter refers to the product development process, as a whole process that includes the marketing, the design and the manufacturing processes. Accordingly, he presents a model that linearly trying to describe an iterative process (Figure 2.2I).

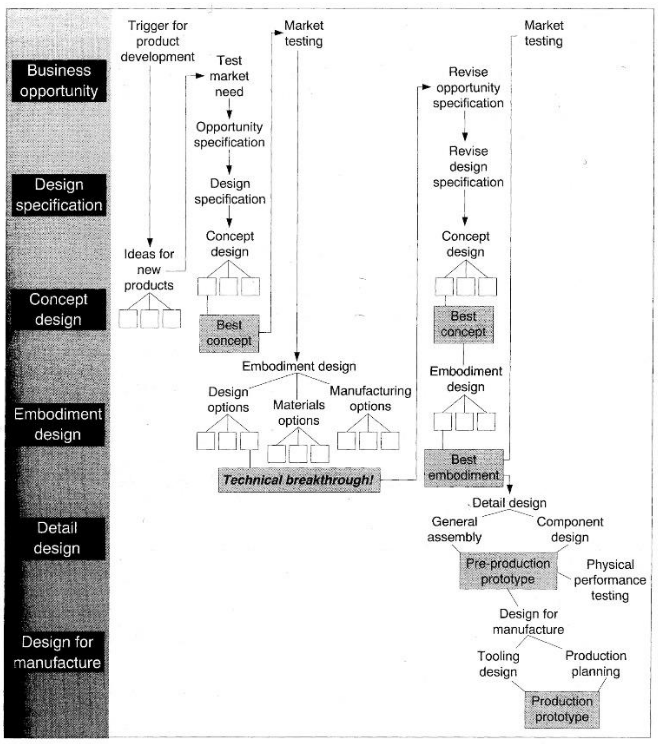



**Figure 2.2I – Design activities at different stages of product development. (P.19)**

Further in the book, Baxter explains about every stage in the product development process, and presents linear phase models for each phase. Two examples for this type models can be seen in Figures 2.2J and 2.2K.

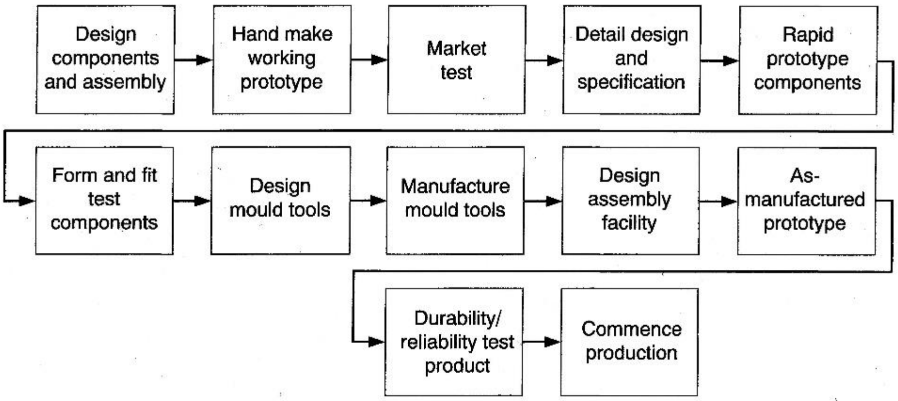



**Figure 2.2J – Linear sequence of events in product development. (P.266)**

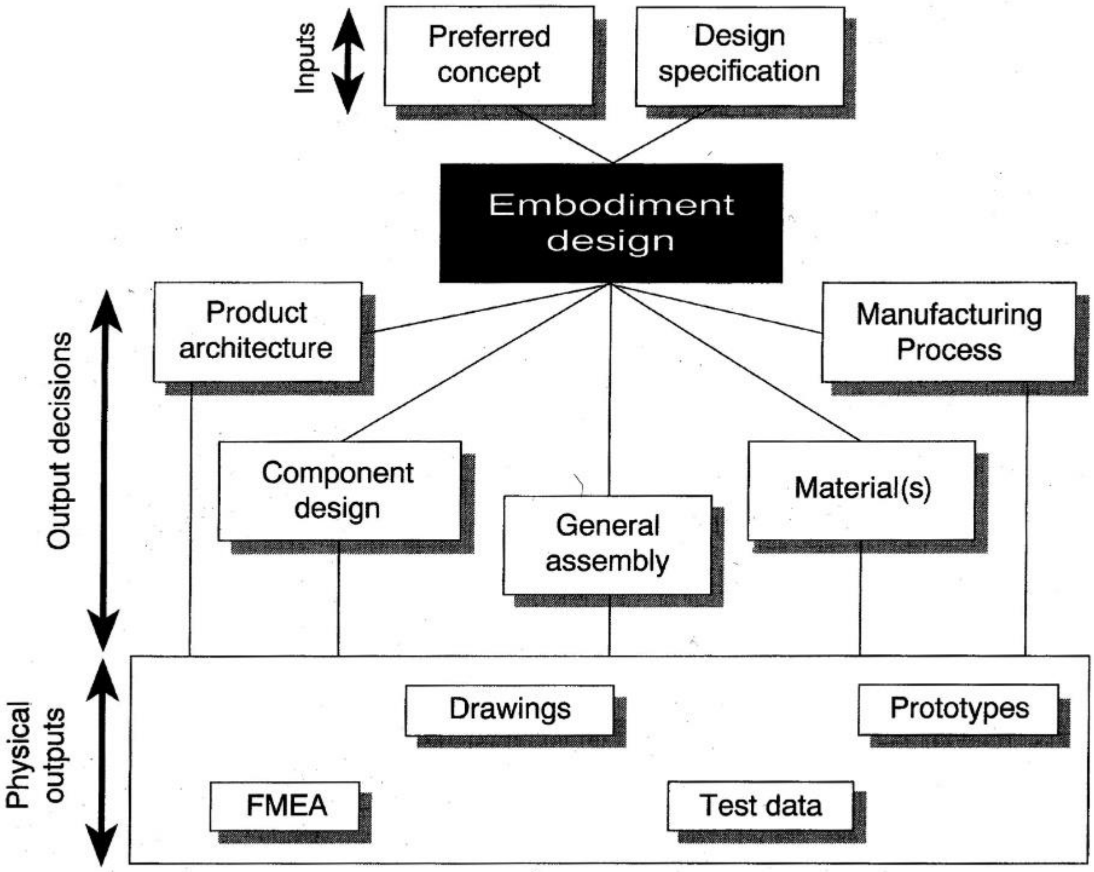



**Figure 2.2K – Inputs and outputs in the embodiment design process. (P.272)**

**Bürdek (2005)**

At the beginning of the section 'Development in Design Methodology, Bürdek quotes (P.251) Christopher Alexander (1964), who listed four reasons why design process needed its own methodology:

- Design problem had become too complex to treat them purely intuitively.
- The amount of data required to solve design problems had increased so rapidly that one designer working alone could not collect, let alone process, them all.
- The number of design problems had increased rapidly.
- Totally new design problems were emerging at a faster rate than previously, so ever fewer design problems could be resolved by referring back to long-established practice.

Further at this section, Bürdek reviewed variety of design process methods.

- Christopher Alexander Method (1964).

  One of the earliest method that were formed for design process, and emphasized the relationship between the form and its context. The method was designated to solve complex design problems, by breaking down the problems into their components. "Alexander developed a method for structuring a design problem (defining the context) and then using the resulting hierarchical composition to develop the form" (P.253). This decomposition and then composition method (Figure 2.2L), is mostly in use for alternatives creation, at one of the initial stages in the design process.

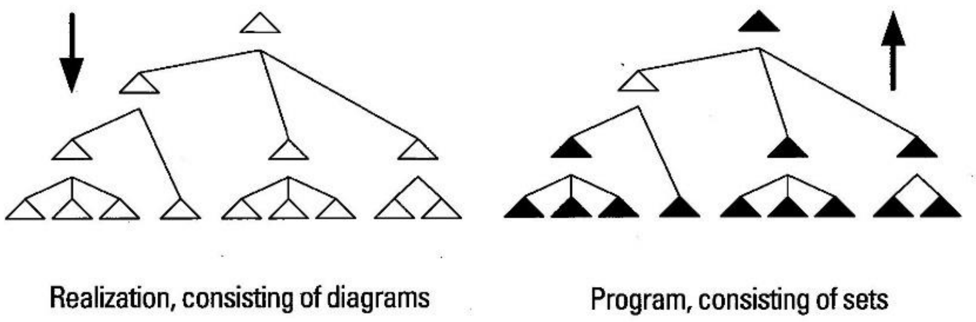



**Figure 2.2L – Decomposition und Composition according to Christopher Alexander. (P.253)**

- Bürdek (1975)

Citing from a book that he wrote, 'Introduction to Design Methodology', Bürdek presents a model that was presented in that book (Figure 2.2M), and belongs to the 'problem-solving' type of models (according to Roozenburg and Eekels). In addition, there is an interesting reference to the paradigm shift that happened in the 70th, and which changed the design process approach, from a deductive (from the outside in) to an inductive (from the inside out) approach.

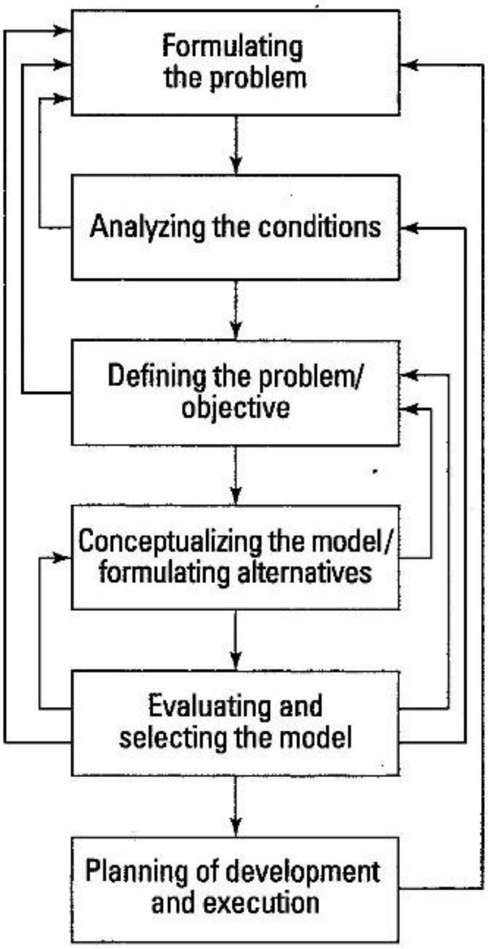



**Figure 2.2M – Model of the design process. (P.255)**

The rest of this section in the book refers to sub-methods in the design process, e.g. mind mapping, scenario techniques, mood charts, target group determination through milieus, and product clinic. All these methods were reviewed, but will not be presented, because of lack of relevancy to the research work.

*2.2.2. Product Design Methodologies – Interim Summary*

Out of the review that was made, and in context of the product development process, I have noticed that there are three types of methodologies. (1) General process methodologies that use integrative models to show how two, or more separate methodologies interact. (2) Specific process methodologies that relate to one coherent subject, e.g. the design process, the marketing process, etc., and which use subjective models to present the phases of the specific process. (3) Sub-specific process methodologies that relate to one phase in the second model, or to a peripheral issue that has effect on the process, and/or does not obligatory, e.g. creativity and other ideation techniques. Figure 2.2N presents the hierarchy of the models.

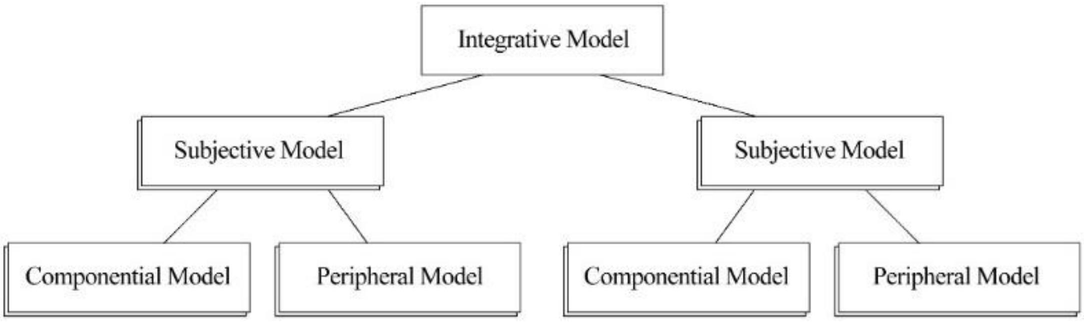



**Figure 2.2N – Hierarchical relation between Types of models.**

Despite the fact that I chose to present in the review structural models, methodologies can be explained also by literal description, linearly, or iteratively.

In context to the research work, no methodologies that relate specifically to desktop personal 3DPs, were found. Desktop personal 3DP is a game changing factor, and the fact that the user becomes the manufacturer as well, requires re-examination of the structure of the known methodologies. In addition, according to the reviewed subjects, I would say that there is at least one clear reason why the common people do not adopt the personal 3DPs. The reason is poor product design. I will refer to it extensively later, but I would add at this point that 3DPs are not user friendly (for the common people), and I do not refer to aesthetics.

An interesting taxonomy matrix (Figure 2.2O) shows that the 3DPs and their market are in a diversification status. That status can explain many of the gaps that exist between the promises to the current situation.

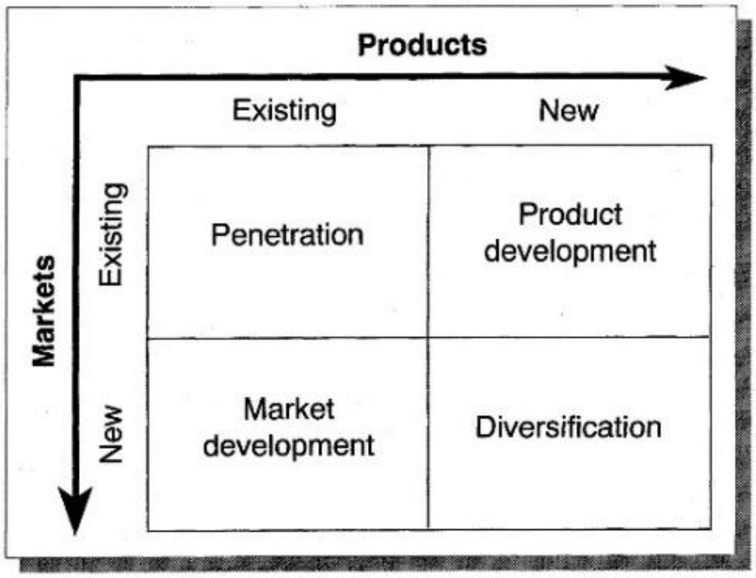



**Figure 2.2O - Ansoff matrix for exploring business development opportunities. (Baxter, 1995 – P.117)**

## 2.3. Mass Customization

The term Mass-Customization (MC) was first coined by S. Davis (1987), and it was defined as an ideal in which "the same large number of customers can be reached as in mass markets of the industrial economy, and simultaneously treated individually as in the customized market of pre-industrial economies" (P.169). This ideal, along with other paradigms and tools that were developed, until recent years, referred mostly to a scenario in which the abilities to research, develop, manufacture, market and distribute were in the hands of a power centered sources, such as firms, factories, companies, etc.

The research work will re-examine the term MC, from a perspective of a presence of 3DPs in home environment. A situation that will change the rules, due to the fact that the means of production will be in the hands of the users. The mere fact that the means of production (fully or partially) will be in the hands of the users, will shift the ability to implement MC, from the manufacturing sources to the development and the marketing sources.

In this chapter, the review will comprise examinations, researches that were studied so far.

### *2.3.1. Methods and paradigms*

**Pine (1993)**

Pine refers to the term MC, as an opportunity that could provide an advantage to business source, in a competitive market. Pine analyzed the term and defined it in different ways. The differences were according to the abilities of companies and manufacturers to flex the development, production, sales, marketing, and delivery processes, in front of an aspiration to enable the customer to get exactly what he needed and expected. "While the practitioners of MP share the common goal of developing, producing, marketing, and delivering goods and services at price low enough that nearly everyone can afford them, practitioners of Mass Customization share the goal of developing, producing, marketing, and delivering affordable goods and services with enough variety and customization that nearly everyone find exactly what they want" (P.44).

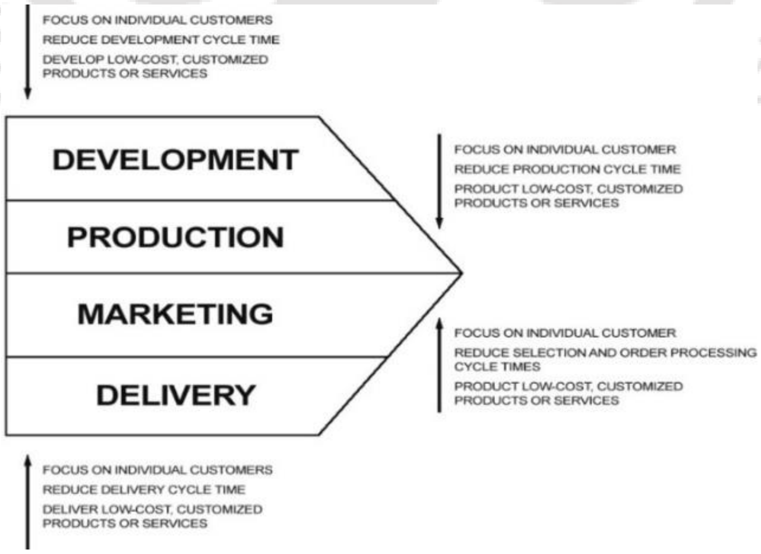



**Figure 2.3A – Culmination of Changes in an Organization to Mass-Customize Products and Services. (P.214)**

Another reference that defines the goal of MC, was described as follow: "…providing tremendous varied and individual customization, at prices comparable to standard goods and services". Figure 2.3A shows the basic value chain of a product, or a service life cycle, and the actions that need to be taken in order to enable MC.

Figure 2.3B presents a product change-process change matrix that generates four situations. The purpose of this matrix is to clarify in which situation, MC can be implemented.

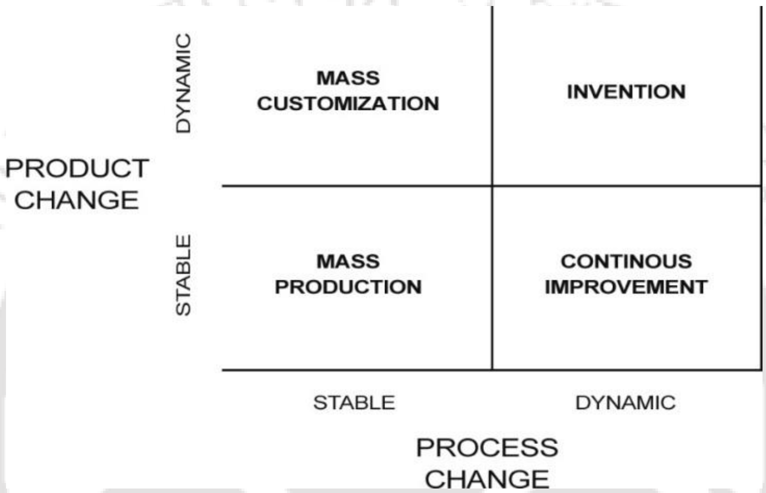



**Figure 2.3B – Product-Process Change Matrix. (P.218)**

**Ross (1996)**

Ross mentions trends, and techniques that were invented at the mid-80s of the past century, as the factors that enabled elaboration of manufacturing processes. Thus, these developments enabled companies to adopt an approach to product development according to customer's needs. Examples of companies that implemented this approach, e.g. Motorola and the Pagers, National Bicycle Industrial Co. in Japan, Rakeigh Industries in the UK, IBM, were given and shortly reviewed. Ross also refers to three types of industries that implement principles of MC: Business process focus, Information technology, and Customer focus industries.

"There are number of ways of providing mass customers with high choice (Figure 2.3C). The most competitive (and most challenging) for manufacturing company is to be capable of providing 'core mass customization', as it will have both the direct understanding of its customers and their requirements and the ability to fulfil them." (P.262).

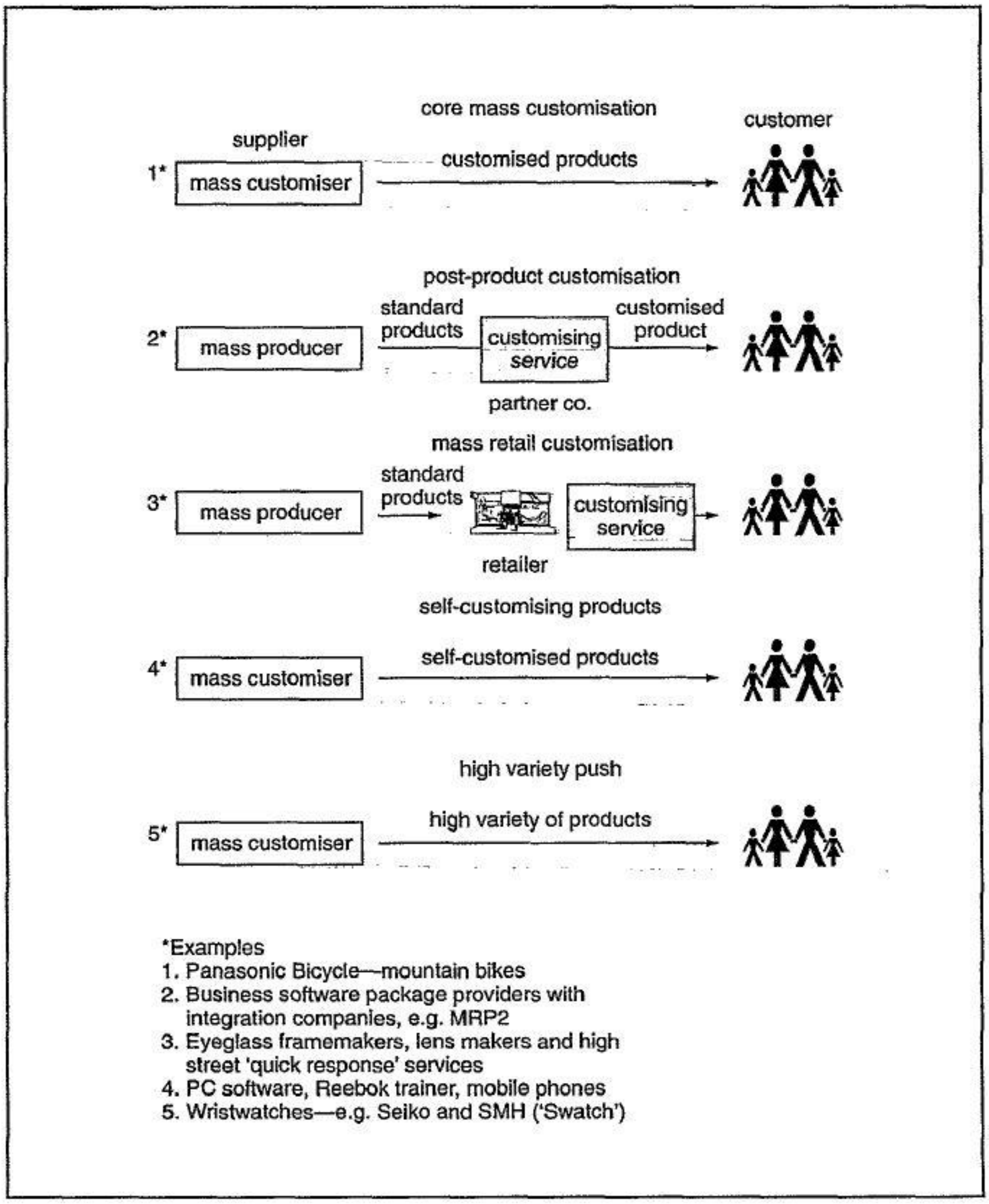



**Figure 2.3C – Methods of providing customers with choice on mass basis. (P.262)**

**Lampel and Mintzberg (1996)**

Lampel and Mintzberg present a simplified model of the main factors that combine the value chain of the design to distribution process. According to the ability to implement MC approach in each factor, they present five possible models (Figure 2.3D), and they named them as follow:

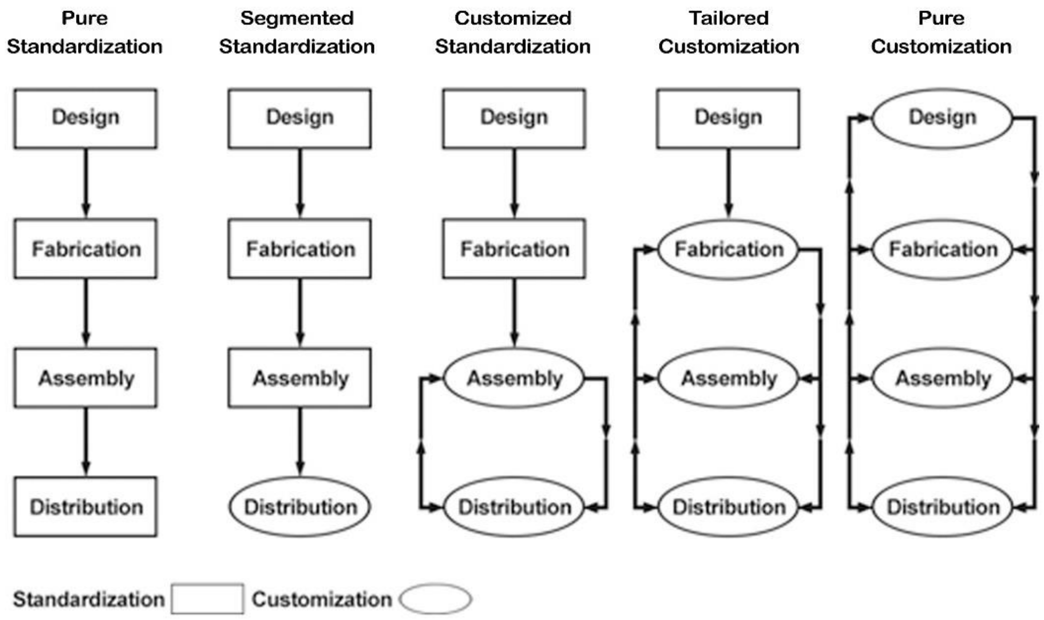



**Figure 2.3D – A Continuum of Strategies. (P.24)**

**Pine / Gilmore (1999)**

In their book, Pine & Gilmore extend the term MC and sort it in the context of the relationship between the product and its representations (packaging, product name, etc.). Their starting point was an ideal that can provide the user exactly what he needs, in front of the ability of the power centered sources to fulfill this aspiration. Figure 2.3E shows the relationship between the product and its representation, and according to the variables of each one of them, they categorized four types of MC approaches.

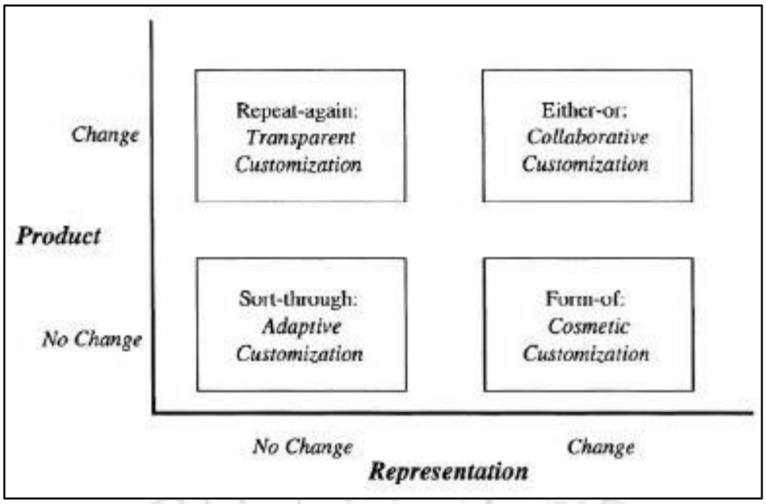



**Figure 2.3E – Approaches to customization (types of sacrifice). (P.132)**

**Duray et al. (2000)**

Duray et al. present four factors that assemble the value chain of the 'from design to use' process (design, fabrication, assembly, and use). They divided the factors into two groups, according on their dependency to each other, and examined each group by its ability to allow the user to be involved in it. Accordingly, Figure 2.3F presents a taxonomy matrix, which classifies types of customers. The paper and its conclusions were based on empirical analysis and classification of 126 mass customizers.

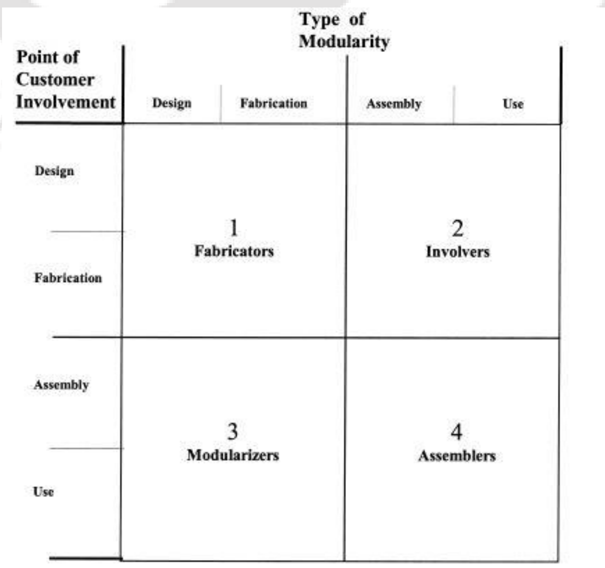



**Figure 2.3F – Matrix grouping of mass customization configurations. (P.612)**

**Piller (2000)**

Piller divides the term MC into 2 categories: Soft Customization and Hard Customization. The Soft Customization category refers to the possibility to adjust and to make changes for the user in a standard manufacturing process system, when the consumer has the ability to be involved only in the research, development, engineering design and sales stages. The consumer does not have any involvement in the production processes. Products that belong to the category of the Soft Customization, present a limited range of products that enable adjustments for the user, by the user (self-customization), by the seller (point-of-delivery customization), or by providing a service that provides a sense that the product has been customized for the user (service customization). Products that belong to the category of the Hard Customization enable changes and interventions in the production process and / or offer modular products, so it can be assembled into a product, customized for the user, by selecting the appropriate standard components that fits to the user's needs. In addition, more details sub-categories refined the general categories (Figure 2.3G).

| ***Soft Customization***:<br>Customization based on fully standardized manufacturing processes | ***Hard Customization***:<br>Customization starts within the manufacturing processes |
|---|---|
| **Self customization**<br>Create customizable products and services | **Customization-Standardization-mix**<br>Either the first or the last activities of the value chain are customized within the factory, while keeping the others standardized |
| **Point-of-delivery customization**<br>Customization of a standardized product at the point-of-delivery | **Modular product architectures**<br>Modularize components and combine them to customized products |
| **Service customization**<br>Customize services around standardized products and services | **Flexible customization**<br>Using flexible manufacturing systems for production of fully customized products without higher costs |

[1]**Figure 2.3G – Mass customization strategies. (P.251)**

[1] Source: Blecker et al. (2005), P.17.

**Da Silveira et al. (2001)**

Da Silveira et al. performed a comparative analysis based on a review of the theories that were offered by Pine & Gilmore (1997), Lampel & Mintzberg (1996), Pine (1993) and Spira (1996). They present in their paper, a general comparative framework that represents a quantified value chain according to eight categories (Figure 2.3H): Design, Fabrication, Assembly, Additional Custom Work, Additional Service, Packaging and Distribution, Usage, and Standardization.

| MC Generic Levels | MC Approaches (GILMORE and PINE, 1997) | MC Strategies (LAMPEL and MINTZBERG, 1996) | Stages of MC (PINE, 1993) | Types of Customization (SPIRA, 1996) |
|---|---|---|---|---|
| 8. Design | Collaborative; Transparent | Pure Customization | | |
| 7. Fabrication | | Tailored Customization | | |
| 6. Assembly | | Customized Standardization | Modular Production | Assembling Standard Components into Unique Configurations |
| 5. Additional Custom Work | | | Point Of Delivery Customization | Performing Additional Custom Work |
| 4. Additional Services | | | Customized Services; Providing Quick Response | Providing Additional Services |
| 3. Package and Distribution | Cosmetic | Segmented Standardization | | Customizing Packaging |
| 2. Usage | Adaptive | | Embedded Customization | |
| 1. Standardization | | Pure Standardization | | |

**Figure 2.3H – Generic levels of Mass Customization. (P.5)**

In the paper's conclusions, they indicate that studies and paradigms which were written on MC, were based on an analysis of individual cases, and on educated guesses by those who were dealing with this matter in the academic aspect. In addition, they sharpen the issue of implementing the idea of the MC as a flexible matter, which can be applied at various stages, partially or fully.

### MacCarthy et al. (2003)

McCarthy et al. Presents a comparative analysis between the models of Lampel and Mintzberg (1996), Ross (1996), Alford et al. (2000), Duray et al. (2000), Da Silveira et al. (2001), Gilmore and Pine (1997), by relying on case studies of companies, or areas that implemented MC at various levels (Figure 2.3I).

| | NBIC | Motorola | European bicycle | Computer | Commercial vehicle |
|---|---|---|---|---|---|
| Lampel and Mintzberg (1996) | Tailored customization + customized standardization | Customized standardization | Customized standardization + tailored customization | Customized standardization | Tailored customization + pure customization |
| Ross (1996) | Core customization | Core customization | Core customization | Core customization | Core customization + post-product customization |
| Alford et al. (2000) | Optional | Optional | Optional | Optional | Core |
| Duray et al. (2000) | Involver | Assembler | Assembler | Assembler | Fabricator |
| Da Silveira et al. (2001) | Fabrication + assembly | Assembly | Assembly + fabrication | Assembly | Design |
| Gilmore and Pine (1997) | Collaborative | Collaborative | Collaborative | Collaborative | Collaborative |

**Figure 2.3I – Classification comparison. (P.293)**

As a conclusion of comparative analysis, MacCarthy et al. present a categorical model of application types of MC (P.297):

***Mode A: Catalogue MC:*** A customer order is fulfilled from a pre-engineered catalogue of variants, produced using standard order fulfillment processes.

***Mode B: Fixed resource design-per-order MC:*** A customer order is fulfilled by engineering a customer specific product, produced through standard order fulfillment processes.

***Mode C: Flexible resource design-per-order MC:*** A customer order is fulfilled by engineering a customer specific product, and produced through modified order fulfillment processes.

***Mode D: Fixed resource call-off MC:*** A customized product is designed for a customer, to be manufactured via standard order fulfillment processes in anticipation of repeat orders.

***Mode E: Flexible resource call-off MC:*** This mode is the same as Mode D except that the order fulfillment activities are modifiable.

In the summary table (Figure 2.3J), the modes represent the factors that mainly categorize the relationship between the producer / manufacturer and the consumer, while sorting the study cases, according to the shown arrangement.

| | A | B | C | D | E |
|---|---|---|---|---|---|
| | Catalogue | Fixed resource design-per-order MC | Flexible resource design-per-order MC | Fixed resource call-off MC | Flexible resource call-off MC |
| Temporal relationship | | | | | |
| Product design | Per family | Per order | Per order | Per product | Per product |
| Product validation/ manu. eng. | Per family | Per order | Per order | Per product | Per product |
| Once-off/call-off | — | Once-off | Once-off | Call-off | Call-off |
| Fixed/modifiable order fulfilment resources | Fixed | Fixed | Modifiable | Fixed | Modifiable |
| Classification of case studies | NBIC, Motorola, Computer, Commercial vehicle | | | European Bicycle | Commercial vehicle |

**Figure 2.3J – Mode summary. (P.299)**

**Hu (2013)**

Hu reviewed three paradigms: Mass Production, Mass Customization and Personalization. He highlighted the main differences between the personalization paradigm and other paradigms, according to the following characteristics (P.6):

"***Open Architecture Products:*** Product personalization rely on an open product platform that allows various modules, including user designed modules to be integrated together.

***Personalization Design:*** Consumers are participating in the design process at different levels. A number of designers are much more likely to be novices who bring with them significant differences that are important to them.

***On-demand Manufacturing System:*** To ensure rapid response to the consumer demand, the manufacturing system must provide flexibility in fabricating personalized product features and modules and assembling these modules with other manufacturer supplied modules.

***Cyber-physical System:*** To support the distributed personalization design, collaboration and on-demand manufacturing, computational tools integrated with the physical design and manufacturing system will be necessary."

Hu presents a diagram (Figure 2.3K), which shows that based on technological developments, e.g., the computer, the Internet and the 3DP, the personalization paradigm has the potential to expand the market to maximum condition, compared to the other paradigms.

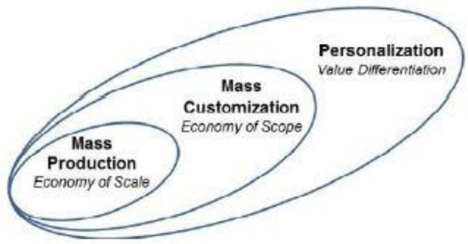



**Figure 2.3K - Goals of the manufacturing paradigms. (P.7)**

The possibility to enable user involvement in product design, might cause engineering failures, thus Hu noted that an "advanced analysis tools will be needed to verify safety and reliability of these highly-individualized products and perform human-in-the-loop simulation" (P.7). The table (Figure 2.3L) presents a comparative summary of the three paradigms according to four categories: Production Goal, Desired Product Characteristic, Customer Role, and Production System.

| | *Mass Production* | *Mass Customization* | *Personalized Production* |
|---|---|---|---|
| *Production Goal* | ***Scale*** | Scale<br>***Scope*** | Scale<br>Scope<br>***Value*** |
| *Desired Product Characteristics* | Quality<br>***Cost*** | Quality<br>Cost<br>***Variety*** | Quality<br>Cost<br>Variety<br>***Efficacy*** |
| *Customer Role* | Buy | ***Choose***<br>Buy | ***Design***<br>Choose<br>Buy |
| *Production System* | Dedicated Mfg Systems (DMS) | Reconfigurable Mfg Systems (RMS) | On-Demand Mfg Systems (OMS) |

**Figure 2.3L - Key differences between mass production, mass customization and personalized production**. **(P.7)**

**Kull (2015)**

Kull refers to computers and the Internet as the motors that have the potential to enable implementation of MC approaches. He mentions that the Internet has become a reliable contact source, which enables direct connection between companies and users (by using PCs, Smartphones & Tablets). According to this claim, Kull presents a paradigm of the integration between the consumer, the supplier, and the process that links them (Figure 2.3M). There is a reference to the possibility to use 3DPTs, but it mostly refers to the possibility to integrate 3DPTs as an AMT.

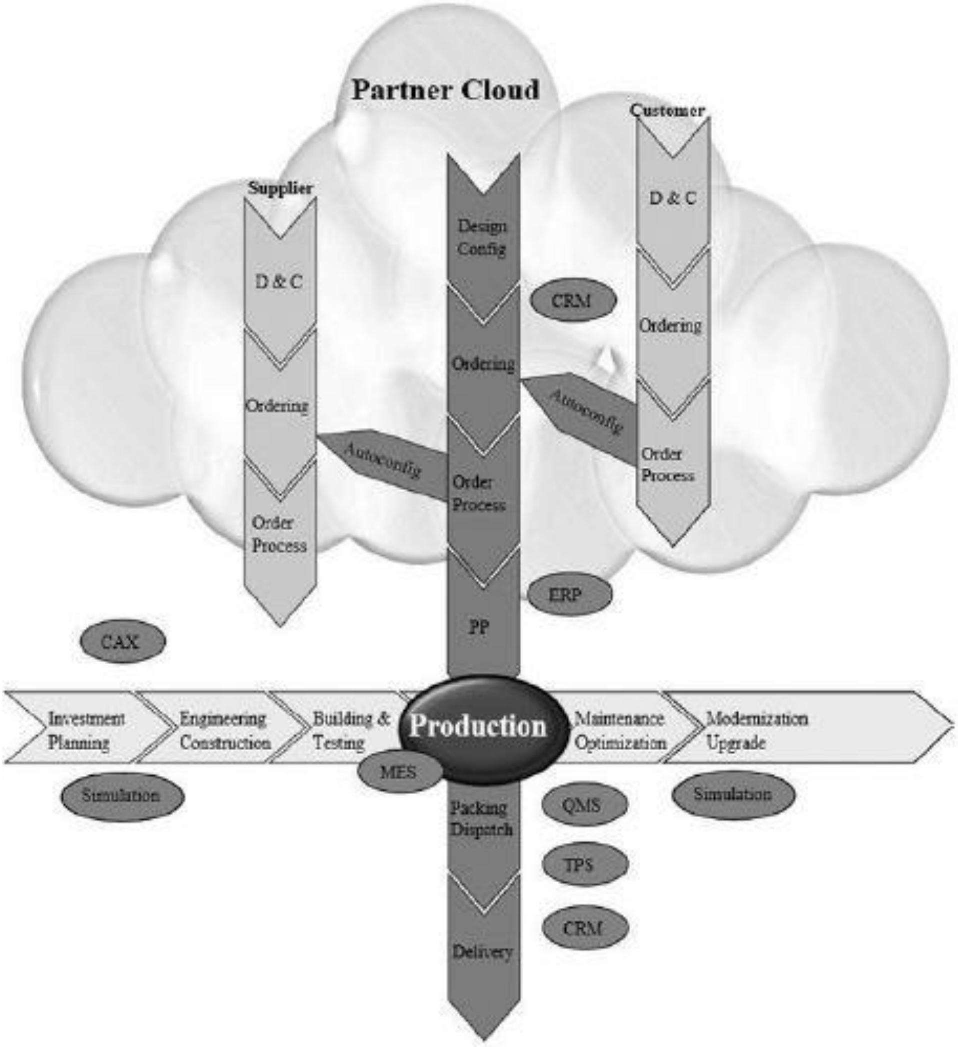



**Figure 2.3M - Horizontal and vertical integration in mass customization. (P.5)**

*2.3.2. Studied cases*

**Kotha (1995)**

**National Bicycle Industrial Co. (Panasonic) – Japan (1989)**

Kotha's reference regarding the 'National Bicycle Industrial Co.' (NBIC), presents a unique case of a successful attempt to produce customized bicycles. NBIC established two collaborative factories, which mass-produced standard bicycles and mass-customized bicycles. Figure 2.3N demonstrates the workflow of the production process at the custom factory.

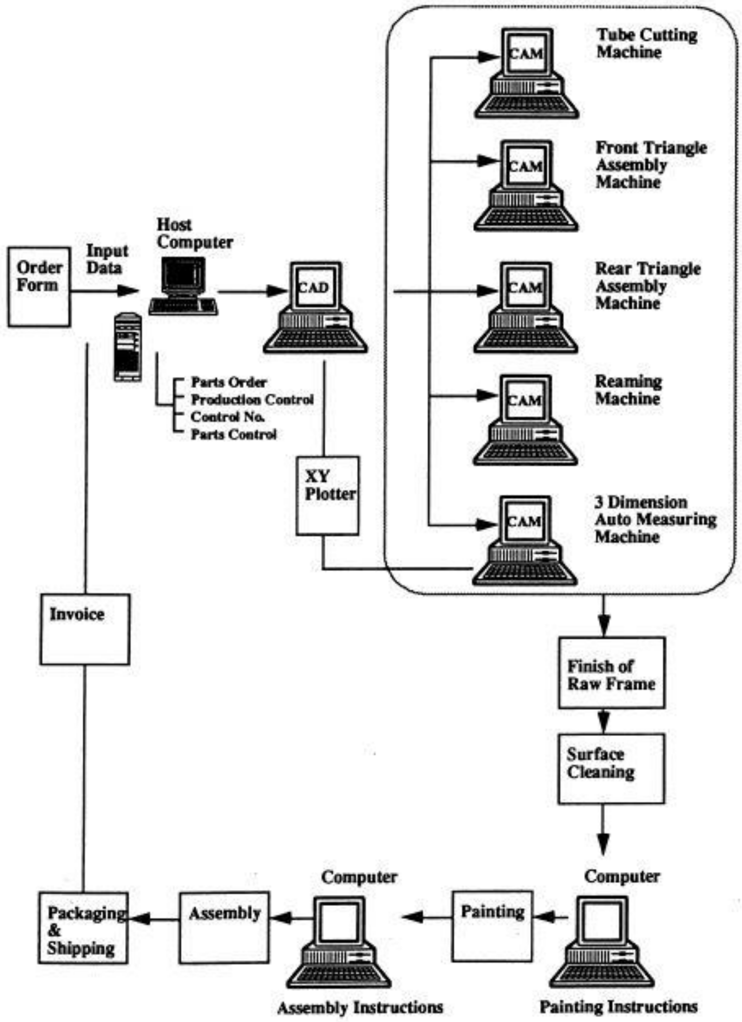



**Figure 2.3N – The production process at the custom factory. (P.29)**

In order to justify the economic production of affordable customized bicycles, NBIC developed an integrative process between the mass-production and the mass-customization factories, based on computerized system and the 'Panasonic Ordering System' (POS). Figure 2.3O presents the interactive process between the two sub-factories.

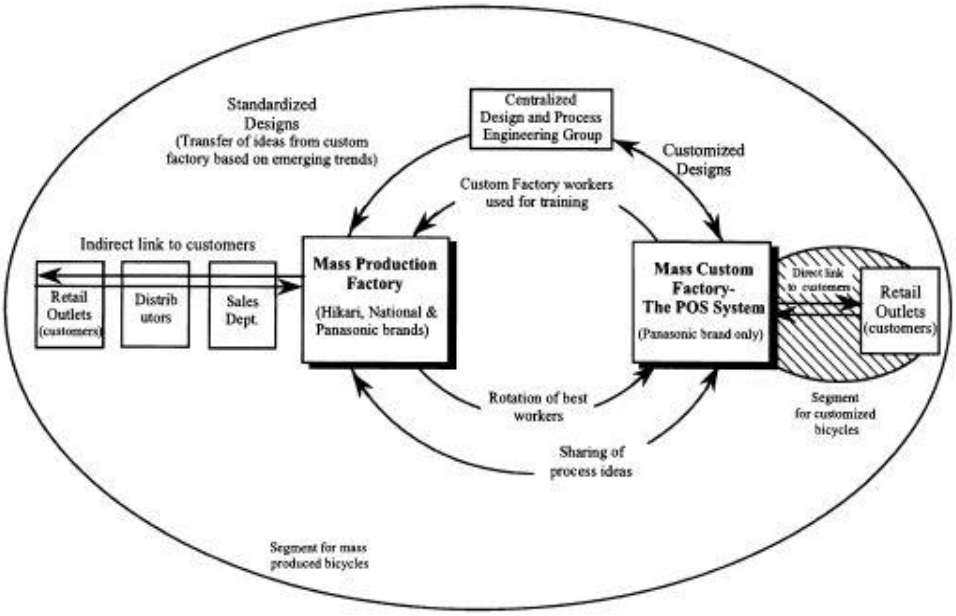
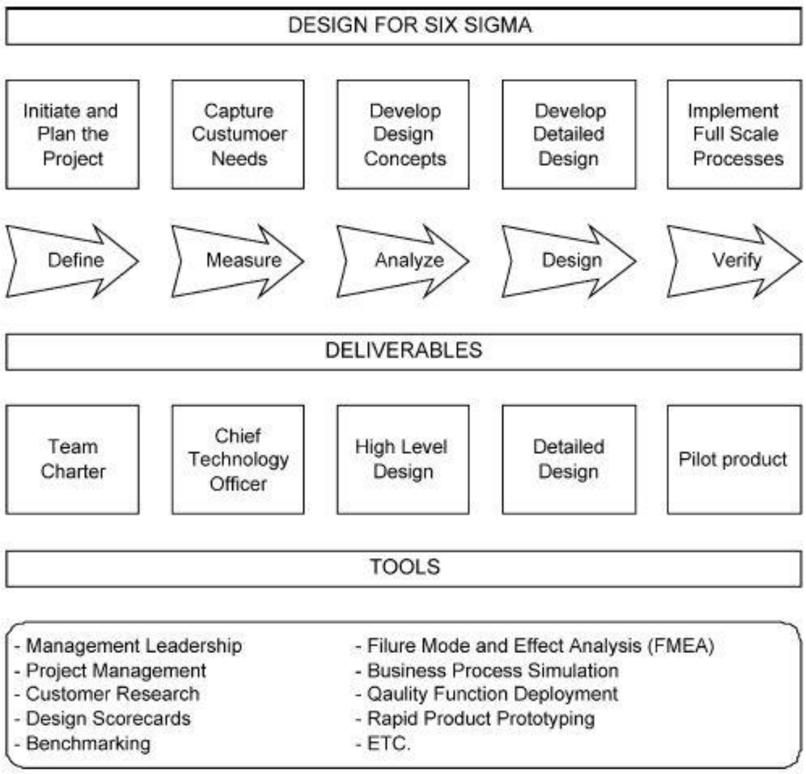



**Figure 2.3O – The interaction between mass-customization and mass-production systems. (P.33)**

**Rosenthal & Tatikonda (1993); Eastwood (1996); Kwak & Anbari (2004)**

**Motorola Pagers**

Motorola produced highly successful unique pager. The uniqueness was the ability to customize the pagers, externally and internally, according to the customer's specifications. Similarly, to NBIC case, Motorola relied on mass-production factory in Singapore which was producing sub-assembly standard components, and on custom factory in Florida, which was in charge on the customized final assembly. The whole process was managed according to 'Six Sigma' method (Figure 2.3P).



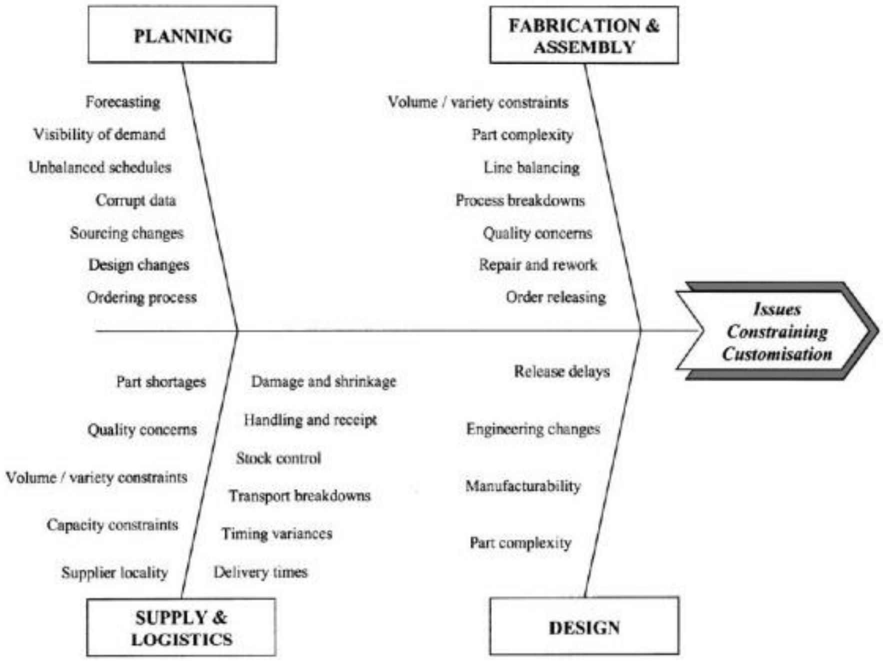

**[2]Figure 2.3P - Five Step DFSS process (P.3)**

**Van Hoek & Weken – SMART (1998); Alford et al. (2000); Alizon et al. – Ford and the Model T (2009)**

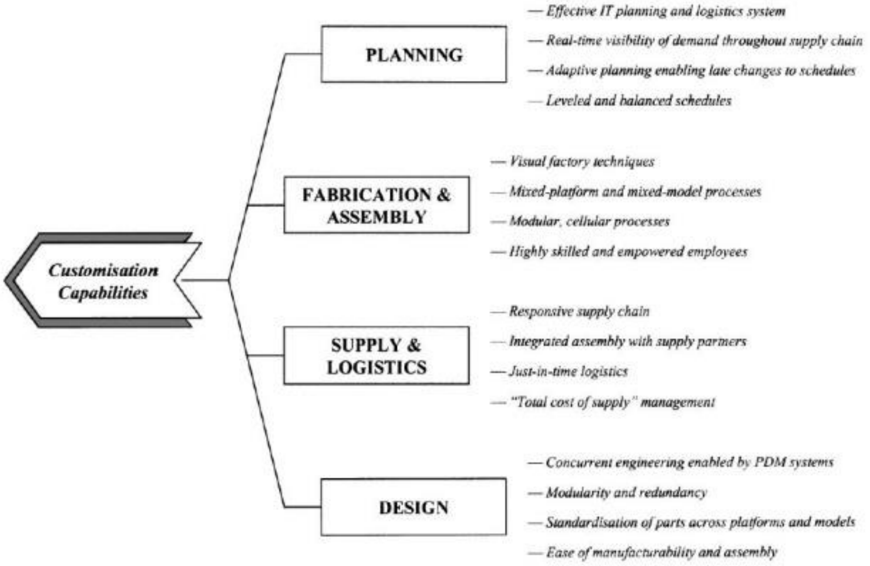
**Automotive Industries**

The automotive industry has broad experience in customization. Basic functions like the seat adjustments, mirror adjustments, air conditioning, etc. are all meant to be customized by the user. The authors mentioned above, refer to customization in the automotive industry, but unlike Weken (1998) and Alizon (2009), Alford et al. (2000) present general perspective with reference to customization in the design, manufacturing and the distribution phases. According to Alford et al., Figure 2.3Q shows issues that constraining customization, and Figure 2.3R shows the capabilities for mass customization.

[2] Source: Kwak and Anbari (2004).




[3]Figure 2.3Q - Issues constraining customization.




[4]Figure 2.3R – Capabilities for mass customization.

[3] Source: Alford et al. (2000) P.107.
[4] Source: Alford et al. (2000) P.108

**Ramaswamy (2008)**

**Nike ID program**

Ramaswamy reviews innovations that were made by Nike, in order to create significant competitive advantage. One innovation that has become very popular among other companies is the use of the DART model (Figure 2.3S) for sharing information and for providing the ability to directly connect with the company**.** Another significant development by Nike was the establishment of the Nike ID program that enabled users to aesthetically customize their snickers, by using the Nike+ co-creation platform (Figure 2.3T).

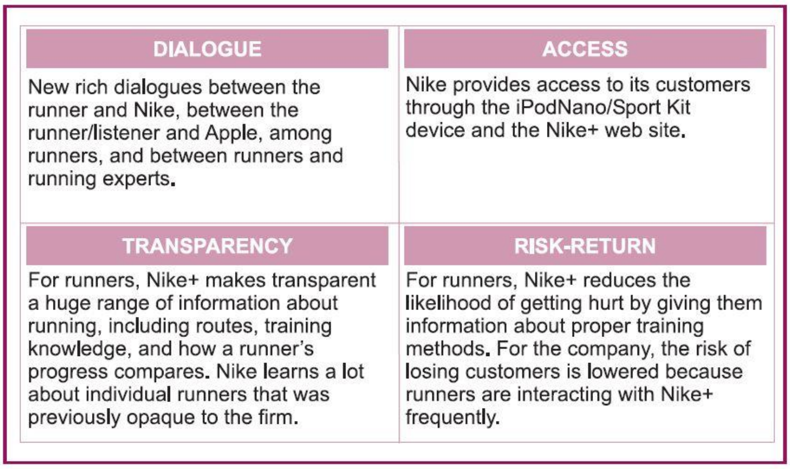



**Figure 2.3S - The DART model. (P.11)**

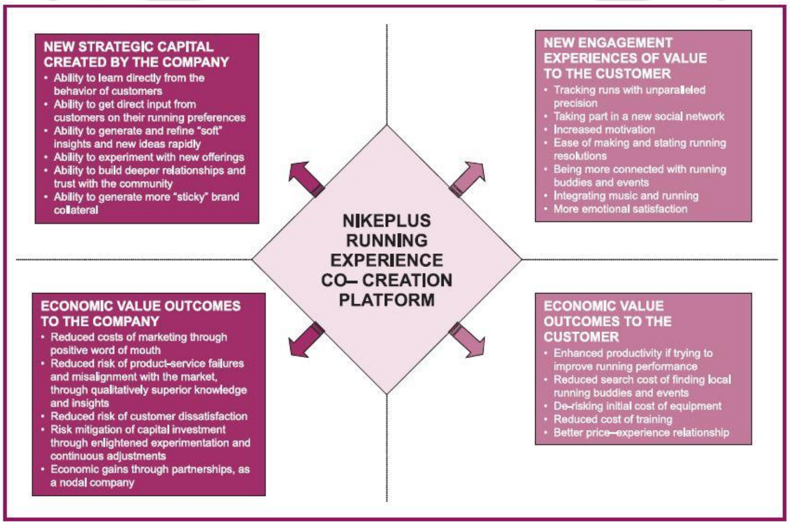



**Figure 2.3T - X-map of co-creation value: NikePlus. (P.13)**

*2.3.3. Unstudied cases*

**Prosthetic hand for children**

The designer Pat Starace design of a prosthetic hand (Figure 2.3U), inspired by the 'Iron-Man' comics and movies figure, for children with congenital defect in their hand. CBS's '60 minutes' TV program presented a similar case, of Paul MacCarthy who has a son without hand fingers. MacCarthy designed and 3D printed a prosthetic hand, and the impact was revolutionary. The kid gained popularity among other kids, and instead of being a focus of ridicule has become just a normal kid.


**Figure 2.3U - 'IRON MAN' Child Prosthetic Hand.**

This case demonstrates a most positive impact that 3D printing can create. Besides the obvious contribution, the fact that the design was designated for 3DP, enables modification of the prosthetic hand very easily for any other child who has a similar condition. There are more cases in the medical field where 3DPT enabled to get results that could not have been reached before, e.g. production of perfectly fit implants (especially missing / broken bones, and teeth).

**Nervous System (3D-Printed Jewelries)**

'Nervous System' is a design studio that was founded in 2007 by Jessica Rosenkrantz and Jesse Louis Rosenberg. The studio offers few Meta designed jewelries (Figure 2.3V), which the customer can customize, or I would prefer to say design, in this case, according to his / her personal taste. A unique dynamic interactive online design platform (Figure 2.3W) enables the customer to design the desired jewelry in four levels: (1) the physical dimensions, (2) the aesthetics design, (3) material selection, (4) color selection. This case represents a pure customization model (Lampel and Mintzberg, 1996). After the customer completes the design and places an order, the studio 3D prints the customized jewelry and deliver it to the customer.

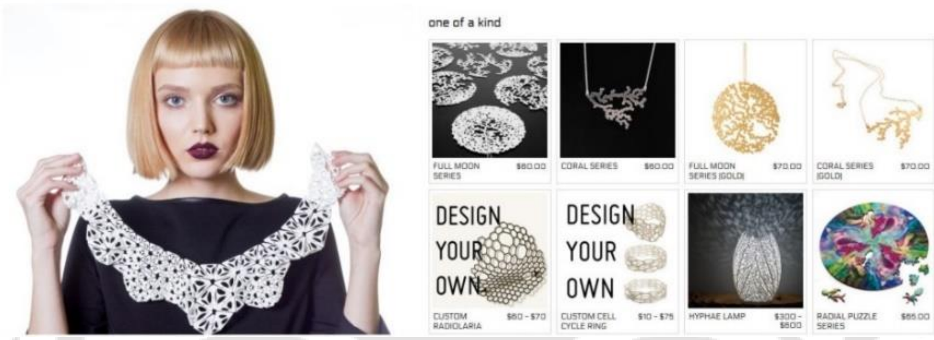



**Figure 2.3V – Jewelries collection.**

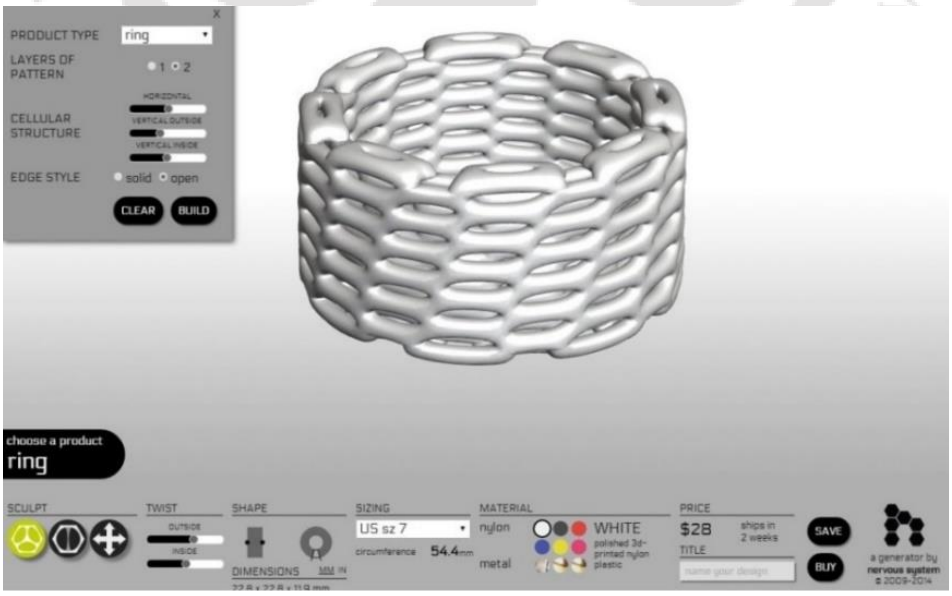



**Figure 2.3W – The dynamic interactive online design platform.**

**Normal (3D-Printed Earphones)**

Normal offered customized earphones that were assembled from standard parts, combined with one 3D printed adapter, which was manufactured according to each user's outer ear space. Normal launched an app that enabled each user to take picture of his / her ear, and send it to the company. A special software analyzed the picture, and converted the shape of the outer ear space to a 3D model of the customized adapter. The concept failed, and nowadays Normal no longer offers this type of earphones.


**Figure 2.3X – Exploded view of Normal's earphones.**

**Mini Cooper**

Mini Cooper automotive company enables customers to customize their pre-ordered car through a unique platform (Figure 2.3Y) that shows the changes online. This type of customization matches the customized standardization model (Lampel and Mintzberg, 1996) and the mass customizer model (Ross, 1996), because it relies on mass production system with modules. Nothing is made especially for the user. The uniqueness comes from the combination of standard options.

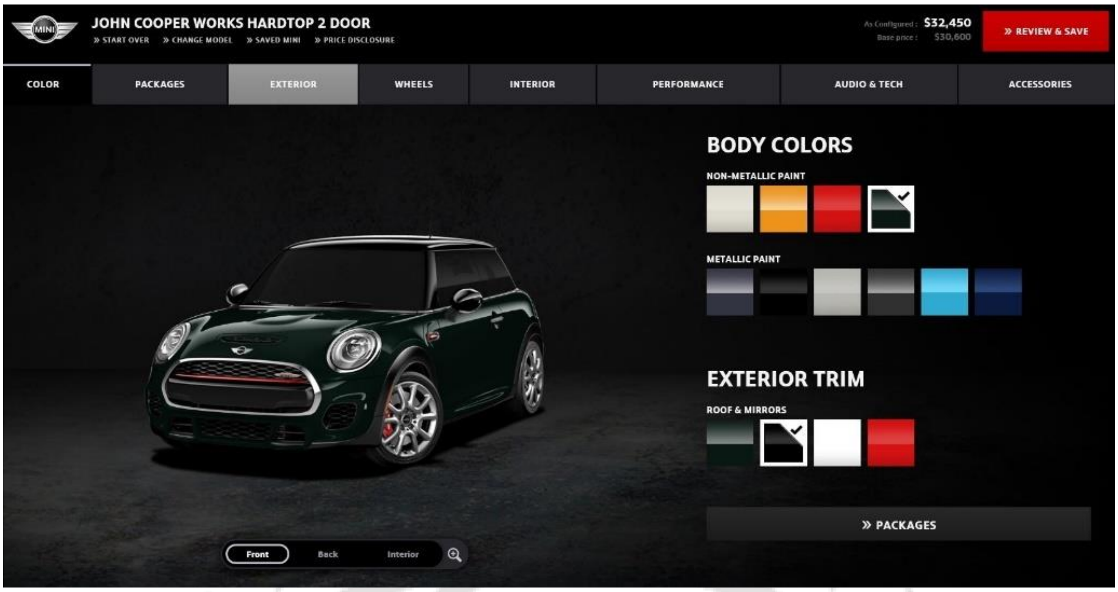



**Figure 2.3Y – Mini Cooper's customization platform**

### *2.3.4. Mass Customization – Interim Summary*

Technological advancements (mostly computers) at the mid 80's of the 20th century, significantly expanded production capabilities, and significantly shortened the production time of mass produced parts. These advancements enabled the development of the MC approach, which intended to provide competitive advantage to companies in a competitive market. Since the MC idea was firstly introduced (Davis, 1987), market processes were re-examined, and paradigms with models that describe processes of real, or potential cases were formulated. The main intention of the re-examinations was to better comprehend and understand the sources of success, failure points, and the mutual effects on the product development process, for implementation of MC approach.

Research into MC can be divided into two groups: (1) research that was made before the beginning of the 21st century, (2) research that has been made since the beginning of the 21st century until today. The research at the end of 20th century refers to center powered sources as the only source that enables degrees of MC. Since center powered sources are responsible for all the life cycles of the product, prior to its sale, and sometimes even later, all research naturally addressed that.

Blecker et al. (2006), presented a comparison table of the main paradigms and strategies that referred to the subject of MC (Figure 2.3Z) until the beginning of the 21st century.

| | Pine/Gilmore (1999) | Duray et al. (2000) | Piller (2000) | Da Silveira et al. (2001) | MacCarthy et al. (2003) |
|---|---|---|---|---|---|
| Research type | Empirical investigation | Empirical research and validation | Literature research and 101 case studies | Literature research | Literature research and 5 case studies |
| Exclusiveness between strategies | Available | Available | Not available | Available | Available |
| Main classification perspective | Product/ representation | Point of Customer involvement/ modularity | Customer involvement in value chain | Customer involvement in value chain | Product design/ repetition of orders/ resources |
| Easiness of attribution | Easy | Not easy | Not easy | Not easy | Easy |
| Specification of application suitability | None | None | None | None | None |

**Figure 2.3Z – Comparison between the classification models for mass customization.**

Recent research has begun to address scenarios of integration of computers, Internet and 3DPs, as an option that must be taken in consideration, when looking at the products market. However, references to a scenario of integration of 3DPs in home environment, is still missing.

## 2.4. User Involvement

Companies that deal with development of products and services, tend to involve end users in the development process. The main reason for this is to gain competitive advantage by developing products that fulfill the users' needs as much as possible. Research shows that user involvement, in the development stage, and especially in the design process and/or the final assembly stages, increase significantly the value of the product, and creates an emotional bond between the user and the product. The mass production system enables the user to be involved in two main phases: the research and the development phase, and the final assembly phase. The involvement of the user at the final design and the production phases, is almost impossible in mass production systems, but there are systems that specialize in production of Taylor made products (especially for professional end users, rich people and B2B market).

Integration of desktop personal 3DP in home environment, has the potential to enable user involvement in almost every stage in the product development process, since changes that the user will make to the design, in order customize it, do not require any adjustments and changes in the production and the distribution systems.

The intention of the review was to study the field of user involvement, in order to find values that might fit to a product design for desktop personal 3DP methodology.

### *2.4.1. Methods and paradigms*

**Kaulio (1998)**

Kaulio reviewed in his paper, methods and approaches that involve consumer / end user, in the product development process (partially quoted from the paper – PP. 144-146):

**"QFD (Quality Function Deployment)**

QFD is a dominating approach in a TQM (Total Quality Management) organization (Akao, 1990; Eureka & Ryan, 1988; Hauser & Clausing 1988; Sullivan, 1986; Ullman, 1992). This Method, or rather methodology, is described as ***"a system to assure that customer needs drive the product design and production process"*** (Sullivan, 1986). QFD prescribes a process model and, by specifying information needed in order to fill the matrices, implicitly specifies and suggests data collection methods. ***The design process is guided by 'the voice of the customer'. However, the involvement of customers themselves occurs only in the initial phase of the product design process.***

**User-oriented product development**

User-oriented product development is a human factors/ergonomics engineering approach to product design (Dahlmsn, 1986; Rosenblad-Wallin, 1983, 1985, 1988). This approach is characterized by:

- ***a problem analysis of user/use requirements with a starting point in the use situation, leading to the formulation of 'user requirements';***
- ***a transformation of these user requirements into measurable engineering requirements;***
- ***an iterative design where prototypes are tested by users and modified by designers.***

**Concept testing**

Concept testing is an approach that aims to involve customers in the conceptual design phase, preferably known as the concept evaluation phase (Acito & Hurstad, 1981; Moore, 1982; Page & Rosenbaum, 1992). Stimulus materials, such as paper-and-pencil sketches, models, mock-ups and prototypes of the product-to-be, are recommended, in addition to verbal communication. (In this paper, the term concept test is limited to the phases before the existence of a working prototype.) Ideally, the presentation of a concept should offer a realistic description of the proposed product(s), in order to facilitate specific responses from customers. It is recommended that this step be supplemented with later prototype evaluations, e.g. beta testing.

## Beta testing

Beta testing can be described as an approach applied in the latter phases of the product design process, and aims to determine if the product does what it is designed to do in the customer environment (Dolan & Matthews, 1993; Nielsen, 1993). Beta testing is frequently used in software engineering. Usually, working prototypes are placed with selected customers in order to test the influence of 'environmental factors', as well as the level of customer satisfaction. The results from these tests are used in order to refine the product further and to eliminate 'bugs'. Since beta testing is a field test, comments on the product have to be collected through observations or in retrospective studies. It is recommended that beta testing should not be the only method for feedback from customers, because beta feedback would arrive too late to be of as much use as results from earlier evaluation methods (Nielsen, 1993).

## Consumer idealized design

Consumer idealized design is described as "a process for involving consumers in the actual design of new manufactured goods or services" (Cincianntelli & Magdison, 1993). The approach deals mainly with the conceptual design and requirement analysis phase of product development, and focuses on involving users in the early phases of the product design process. The process is conducted as a group exercise similar to that of focus groups. The participants must be carefully selected representatives of the target market. Several groups of ordinary consumers, composed of different market segments, are recommended for best results. The basic idea behind the approach is to get the customers to forget existing products and ignore the feasibility of new designs. The session begins with a blank sheet of paper and ends up with

- A (new) design.
- A list of articulated requirements.
- A record of the underlying reasons for the design choices.

The facilitator's role during the group exercise is to guide the participants towards their ideal and away from what they perceive as obstacles. The customer's role is to identify basic requirements, and actively to find new solutions to their own problems and requirements.

### Lead user method

This approach is described as a methodology composed of the lead user concept integrated with market research techniques (Herstatt & von Hippel, 1992; Urban & von Hippel, 1988). The aim is not, primarily, to establish requirements, but to elicit specific 'solution data' from lead users. Lead users are "users who face needs that will be general in the marketplace-but face them months or years before the bulk of the marketplace encounters them", and they are also "positioned to benefit significantly by obtaining a solution to those needs" (Urban & von Hippel, 1988). The method passes through a four-step process:

(1) Specifying lead user indicators;

(2) Identifying lead user groups;

(3) Generating concepts (products) with lead users;

(4) Testing lead user concepts on ordinary users.

Critical points in the method are the selection of lead user indicators and lead users. On the one hand, the designer's/researcher's role is dominated by the composition of the problem to be solved by managing the group of lead users. The lead users, on the other hand, are actively involved in the process of finding solutions to their own problems.

### Participatory ergonomics

Participatory ergonomics is an approach used in industrial ergonomics and architecture (Noro & Imada, 1991). The basic idea is that the workers/users themselves actively partake as designers, generate ideas and design their (own) working environment or living space. The key element in participatory ergonomics is the participation of end-users in small group activities. By being engaged in the process of change, people can actively contribute to the solution of their own problems. Since participatory ergonomics is mainly used for improvements in workplaces, the context of its application has been within company changes, i.e. no study has been reported that deals with the design of mass market products."

Kaulio present a graph (Figure 2.4A), of all the phases of the product development process, and where every user involvement method could be implemented.

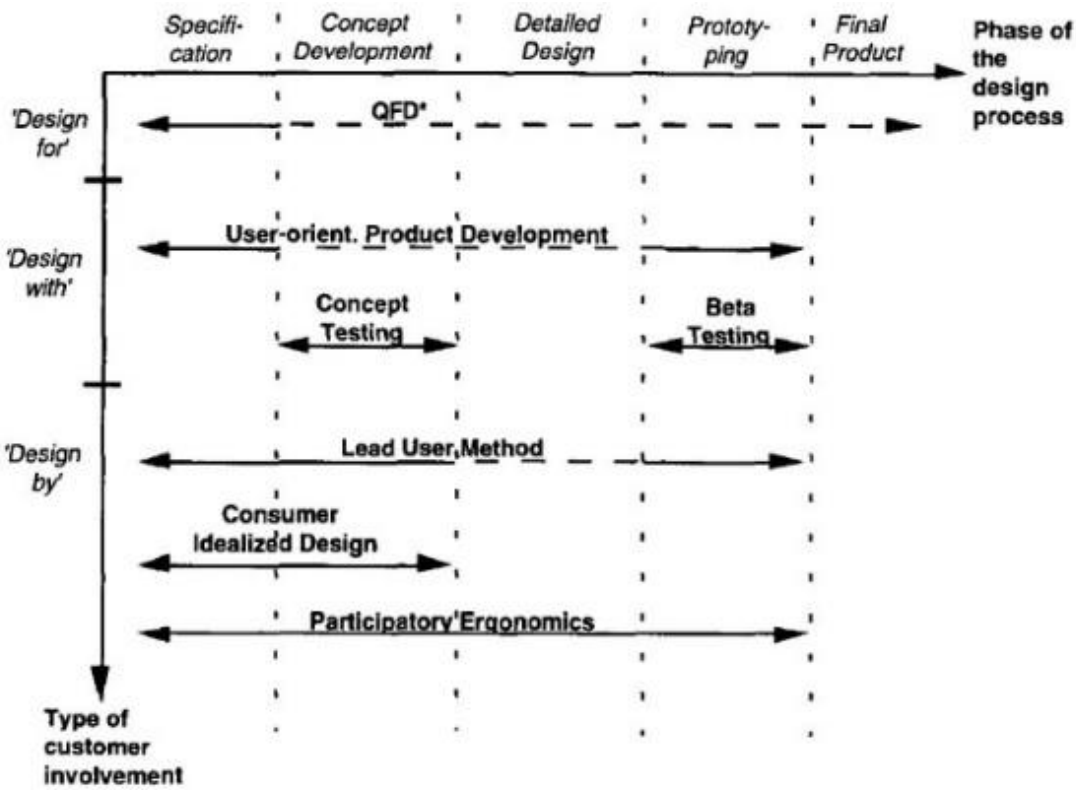



**Figure 2.4A - The methods reviewed related to a framework.**

**Kujala (2003)**

Kujala presents literary sources which presented surveys and interviews relating to user involvement in development of products / services. The table (Figure 2.4B) shows the cases that were presented in the literary sources, and it gathers all the obstacles and the benefits that arose from the possibility to enable user involvement in the development process of the product / service.

| | Design context | Obstacles | Benefits |
|---|---|---|---|
| Grudin (1991b): a survey and interviews of over 200 interface designer, conversations and experiences | Product development in large organizations | • Motivating the developers were challenging.<br>• Identifying appropriate users was difficult.<br>• Obtaining access to users and motivating the users.<br>• Developers did not know how to benefit from user contact and how to obtain feedback from existing users.<br>• Not enough time. | The benefits were out of the focus of the paper. User involvement is believed to be necessary in order to understand user requirements. |
| Wilson *et al.* (1996): a questionnaire of 25 practitioners | Not reported | In the preparation phase:<br>• Users lacked information as to what the designers needed to know.<br>• Users lacked information about what design process meant.<br>In the design phase:<br>• Little consensus across users, the problem was in finding compromises between groups.<br>• Users introduced new concepts, and there were generally too great a volume of feedback.<br>In the evaluation phase:<br>Overall:<br>• Users became more exacting.<br>• There were often too many user groups. | In the preparation phase:<br>• Users provided information and feedback.<br>In the design phase:<br>• Users identified interaction issues, which had to be addressed by users within the specific application domains, provided ideas and offered a practical view.<br>In the evaluation phase:<br>• Involvement from users, comments, feedback, suggestions, commitment, criticism, acceptance, improved usability, learning by designers and project leaders.<br>• The feedback brought the user interface closer to task<br>Overall:<br>• Users were satisfied.<br>• Users accepted the design. |
| Wilson *et al.* (1996): a longitudinal study of a one design project, interviews of designers | In-house | • Users had to be educated about design.<br>• Users were unaware of implementation constraints.<br>• Designers spent lots of time contacting users and arranging meetings. | • Users provided useful information and ideas.<br>• Users helped define the scope of the project.<br>• The system from the customers point of view, was improved.<br>• Users were happy with the results.<br>• Users learnt about their job and organization. |
| Wilson *et al.* (1997): a longitudinal study of a one design project, interviews of designers and users | In-house | • Limited time for the first phase of the design.<br>• Users were very busy.<br>• Some users lacked confidence or motivation and were reluctant to talk to the designers.<br>• Some users did not understand the task model used.<br>• Users were unaware of implementation constraints. | • Users were eager to participate, because they wanted to influence on the outcome. (The benefits were out of the focus of the paper.) |

**Figure 2.4B – The obstacles and benefits of user involvement.**

The table (Figure 2.4C) presents positive and negative effects that arose from the review.

| | Design context | Negative effects | Positive effects |
|---|---|---|---|
| Barki and Hartwick (1991): a survey of 105 users | In-house | | • User participation had a positive, although nonsignificant correlation with system usage ($r = 0.17$). Participation correlated statistically significantly with personal relevance of a system to its users ($r = 0.36$). |
| Baroudi *et al.* (1986): a survey of 200 production managers | Varied information systems | | • User involvement in the development of information systems enhanced statistically significantly system usage ($r = 0.28$) and the user's satisfaction ($r = 0.18$). |
| Foster and Franz (1999): a questionnaire of 87 users and 107 analysts | Varied information systems | | • Users' self perceptions of participation had a moderate significant correlation to system acceptance ($r = 0.42$ and 0.32 for acceptance indicators of functional features).<br>• Analysts' perceptions of user participation correlated strongly and significantly with all indicators of acceptance ($r = 0.81$, 0.75, 0.55 and 0.50). |
| Heinbokel *et al.* (1996): a longitudinal field study of 29 projects | External and in-house | User participation in software development was associated with project difficulties:<br>• lower overall success ($r = -0.47$);<br>• fewer innovations ($r = -0.40$);<br>• lower degree of flexibility ($r = -0.44$);<br>• lower team effectiveness ($r = -0.45$). | |
| Keil and Carmel (1995): an interview of development managers of 17 companies | Product development and in-house | | • More successful projects employed more direct links to users and customers. |
| McKeen and Guimares (1997): interviews and questionnaires to users and developers from 151 projects | In-house business applications | | • Positive and significant relationship between user participation and user satisfaction was found ($r = 0.42$). User participation was never dysfunctional in these 151 projects. |

**Figure 2.4C – A summary of the effects of user involvement on system success.**

**Veryzer and de Mozota (2005)**

Veryzer & de Mozota discuss in their paper the new product development process (NPD), and possible effects of consumer involvement on the process. The paper presents differences between the traditional approach of mass production that advocates the study of the user, and the user-centered design approach that advocates in user involvement (Figure 2.4D).

| Traditional Approach | User-Centered Design |
|---|---|
| • Technology driven | • User driven |
| • Component focus | • Solutions focus |
| • Limited multidisciplinary cooperation | • Multidisciplinary team work |
| • Focus on internals architecture | • Focus on externals design |
| • No specialization in user experience | • Specialization in user experience |
| • Some competitive focus | • Focus on competition |
| • Development prior to user validation | • Develop only user validated designs |
| • Product defect view of quality | • User view of quality |
| • Limited focus on user measurement | • Prime focus on user measurement |
| • Focus on current customers | • Focus on current and future customers |

[a] Adapted from Vredenburg, Isensee, and Righi (2002, p. 2).

**Figure 2.4D - Comparison of User-Centered and Traditional Approaches.**

The table (Figure 2.4E) present the phases of the new product development process, and the required actions that need to be performed in each phase. The table does not address to limitations of production.

| Phases/Gates | Stage-Gate™ (Cooper, 1998 ) | Design in NPD (Ulrich and Eppinger, 2004) |
|---|---|---|
| Phase/Gate 1 | Ideation<br>Initial screening | Exploration<br>Consider product platform and architecture<br>Assess new technologies and new needs |
| Phase/Gate 2 | Preliminary investigation<br>Market assessment<br>Technical assessment<br>Business assessment | Concept development<br>Investigate feasibility of product concepts<br>Develop industrial design concepts<br>Build and test experimental prototypes |
| Phase/Gate 3 | Detailed investigation<br>Market research<br>Users needs and wants studies<br>Value in use studies<br>Competitive analysis<br>Concept testing<br>Detailed technical assessment<br>Manufacturing appraisal<br>Detailed financial analysis (ends with business case) | System level design<br>Generate alternative architectures<br>Define major sub systems and interfaces<br>Refine Industrial design |
| Phase/Gate 4 | Development<br>Product development (money gate) | Detail design<br>Define part geometry<br>Choose materials<br>Assign tolerances<br>Complete ID documentation |
| Phase/Gate 5 | Testing and validation<br>In house product testing<br>Customer test of products<br>Market test | Testing<br>Reliability test<br>Life testing<br>Performance testing<br>Regulatory approvals<br>Implement design changes |
| Phase/Gate 6 | Market launch<br>Trial production<br>Precommercialization business analysis<br>Production startup<br>Market launch | Production ramp-up<br>Evaluate early production output |

[a] Adapted from Borja de Mozota (2003a, p. 135).

**Figure 2.4E - Phases of the New Product Development Process.**

Since the paper clearly advocates user-centered design approach, it ignores difficulties and obstacles that the mass production system must deal with. With regard to the user-centered design approach, Veryzer and de Mozota present a diagram of the main points that must be taken in consideration, in order to create successful new product development process, according to the user-oriented design approach (Figure 2.4F). The diagram divides the process into two main stages: process and product.

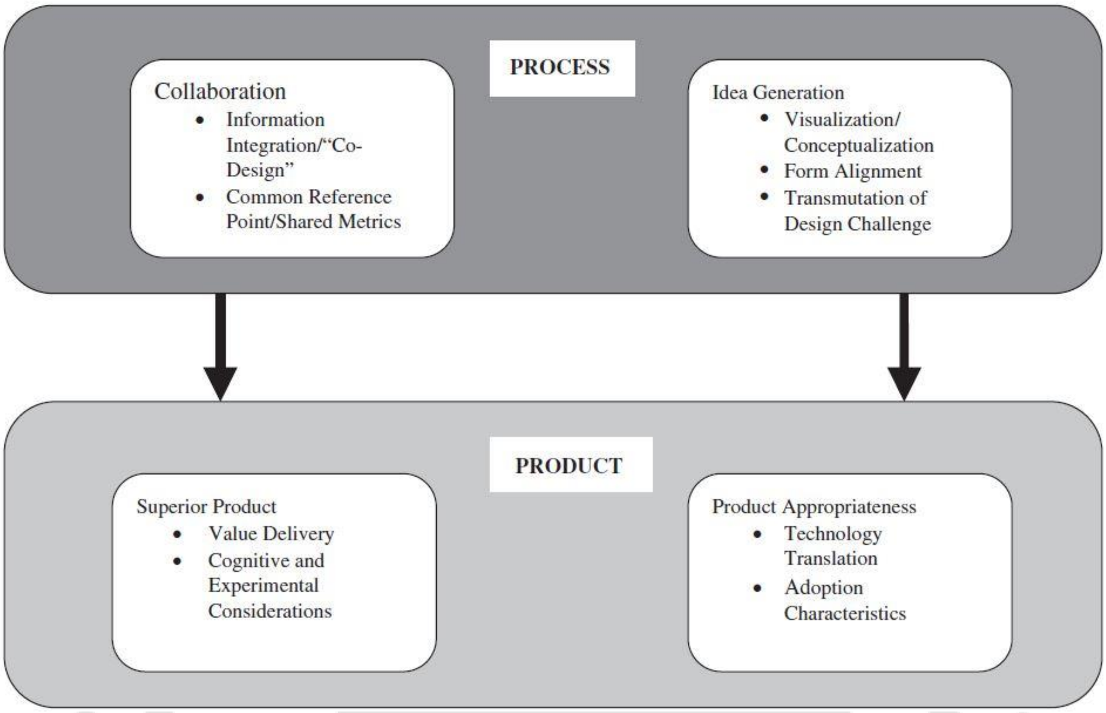



**Figure 2.4F - User-Oriented Design Impact on NPD.**

In addition, a chart that present a linear product development process was presented (Figure 2.4G).

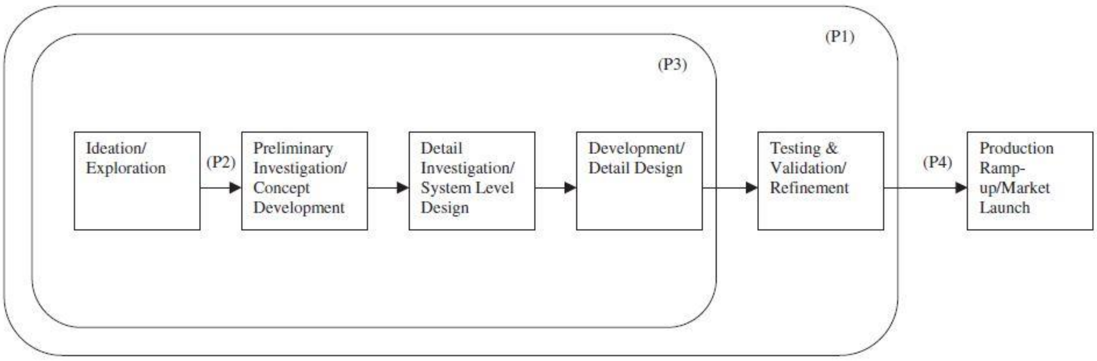



**Figure 2.4G - User-Oriented Design Propositions.**

**Steen et al. (2007)**

Steen et al. propose the term 'Human-Centered Design (UCD), a term that encompasses the relationship between the product developers, and the end users. They characterize the term according to four characteristics (P.2):

1. "The active involvement of users for a clear understanding of user and task requirements.
2. An appropriate allocation of functions between users and technology.
3. Iteration of design and evaluation processes.
4. Multi-disciplinary approach"

In addition, they present an overview of types of studied user involvement methods (partially quoted from the paper, PP. 6-12):

*"Participatory design*

The move of participatory design (Schuler and Namioka 1993; Muller and Kuhn 1993) is of **end-users towards, and into, the research and design process.** Participatory design has its roots in the 1970's in Scandinavia, and was initiated by trade unions who saw offices becoming automated by computers, and strived for more democratic values in the work place and for workers' emancipation. Participatory design is about providing people who will be using a system a voice in the process of design, evaluation and implementation of a system which they will be using. 'It attempts to examine the tacit, invisible aspects of human activity [and] assumes that these aspects can be productively and ethically examined through design partnerships with [end-users]' (Spinuzzi 2005). In participatory design, end-users are treated as experts – often experts in doing some specific work – and it is attempted to bring their knowledge and their skills (tacit knowledge) into the development process.

***Ethnographic fieldwork***

There is a tradition of conducting fieldwork – applied social science, inspired by ethnography or ethnomethodology – in order to inform or inspire product development. The ethnographic move is about researchers and designers going 'into the field' – often to work places – to better understand people via observations and interviews. The ethnographic move is meant to be descriptive (rather than prescriptive) and to foreground and emancipate the end-users' perspective.

***Contextual design***

In contextual design (Beyer and Holzblatt 1998) the ethnographic move complemented with a move into the design process. It is a technique to help researchers and designers observe people doing tasks in their natural context (often a work context) and then to apply pragmatically their findings in the design of a system (often an ICT application). After that, these observations are interpreted by a multi-disciplinary team and the findings are directly applied to the articulation of functional requirements for a system to be developed. The observations are clustered along different perspectives, such as: what end-users do; how they communicate; the roles that power and culture play; the artefacts which they use; the physical environment in which activities take place.

***Lead user approach***

Many ideas for new products originate in the heads and hands of innovative end-users or 'lead users' (Von Hippel 1988; Von Hippel et al. 1999; Von Hippel 2005). Lead users are users who have 'two distinguishing characteristics: (1) They are at the leading edge of an important market trend(s), and so are currently experiencing needs that will later be experienced by many users in that market. (2) They anticipate relatively high benefits from obtaining a solution to their needs, and so may innovate.' (Von Hippel 2005, p. 22). Lead users experience a problem or need which they cannot fulfil with a current product and create innovative solutions, applications or modifications. Lead users can be invited to help researchers and designers to jointly develop improvements to existing products or to develop new products. An important difference with participatory design is that the lead user approach is oriented towards pragmatic and commercial goals (rather than towards democracy or emancipation).

***Empathic design***

The basis movement of empathic design is that of researchers and designers moving towards end-users, of trying to get closer to their live and work, of trying to empathize with them, with their experience and emotions. There are different versions of empathic design, varying from a business-like approach (Leonard and Rayport 1997) to a more creativity-like approach (Koskinen and Battarbee 2003). There is a broad variety of techniques, which are often combined in one project, for example: observing (or 'shadowing') potential end-users or via role-playing parts of potential end-users' lives (Aldersey-Williams et al. 1999; Iacucci et al. 2000; Iacucci and Kutti 2002; Oulasvirta et al. 2003; Svanaes and Seland 2004). The goal of empathizing on an emotional level with somebody else can be (slightly) different from *describing* another person in more detached terms as is done in (traditional) ethnography. The researchers' and designers' knowledge – or better: *experience* – is privileged in empathic design. Although they go towards end-users and interact with them, it is the researchers and designers who attempt to experience something.

***Co-designing***

In co-designing (Sanders 2000; Sanders 2002) or co-creation potential or future end users are invited, together with researchers and designers, for all sorts of workshops, and they are provided with tools to jointly *create*. The focus is on jointly articulating ideas, on playing with concepts, on making and evaluating sketches, on jointly tinkering with mock-ups and prototypes. Sanders (2000) distinguishes between three approaches: 'what people say' in marketing research, 'what people do' in applied ethnography, and 'what people make' in participatory design. Knowledge of end-users and knowledge of researchers and designers are brought together, similar to participatory design, with the goal of creating knowledge about some future and desirable situation and products. Ideas about this future situation and this future product are privileged. Co-designing can be thought of as a mixture of participatory design and empathic design."

Steen et al. present a map of the six methods that were reviewed with their orientations (Figure 2.4H).

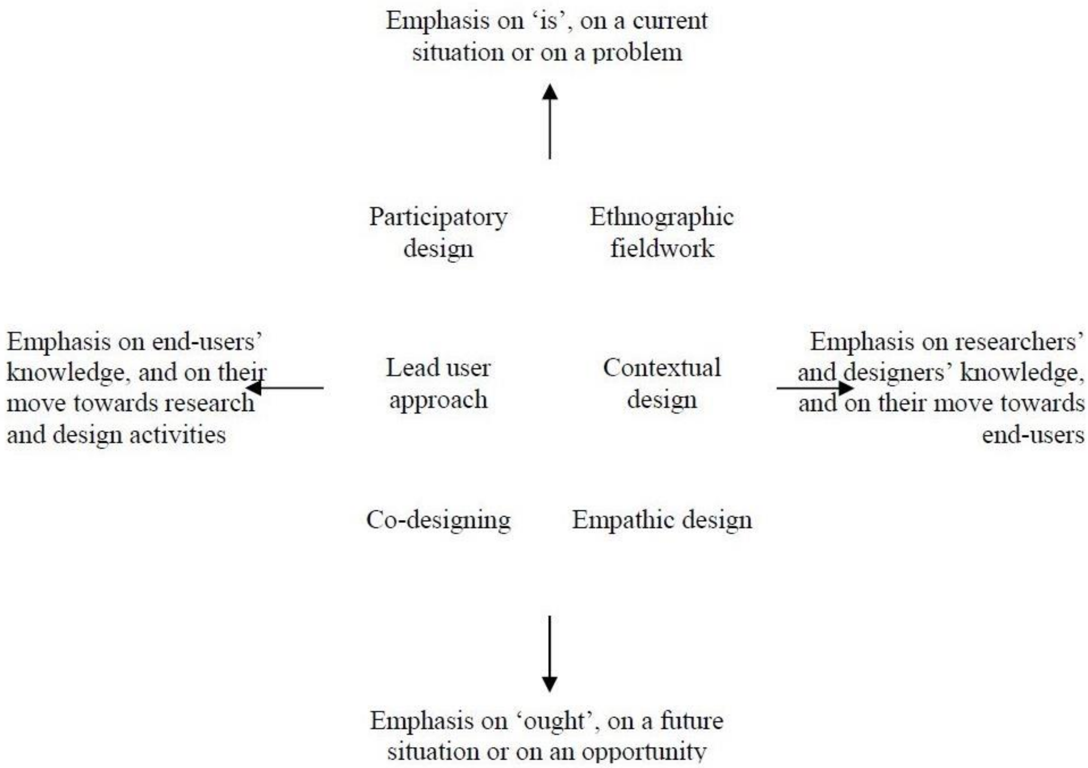



**Figure 2.4H - Different human-centered design methods and practices**

**Zhang et al. (2015)**

Zhang et al. relate to user involvement in context of the current trend of Open-Architecture Product (OAP). The reference takes into account the computer, and the Internet as sources of communication between the power-centered sources, and the end user. Zhang et al. refer to the computerized platform as an option that enable to provide CAD modules, and Virtual Reality (VR) modules.

Accordingly, Zhang et al. present a diagram that theoretically shows the architecture of a system based on indirect involvement design (Figure 2.4I), and a diagram of the structure of VR based user interface. (Figure 2.4J).

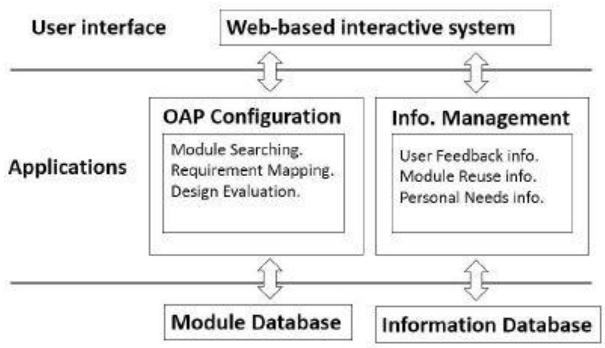



**Figure 2.4I - System architecture of indirect involvement design.**

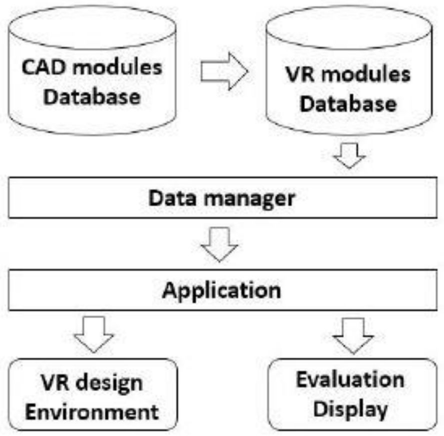



**Figure 2.4J - Structure of a VR-based user involvement interface.**

### *2.4.2. User Involvement – Interim Summary*

The review of the user involvement methods, indicates that most cases refer to the user involvement aspect, as a factor that need to be integrated in a system that relies on mass production systems. Thus, the level of the involvement stays limited to the stages of the development and / or the final assembly of the product. Up to date references, take into account the possibility of increasing the level of the user involvement, through computers and the Internet, but neither one of the methods refer to cases in which 3DP will be integrated in home environment.

A scenario of integration of 3DPs in home environment, along with the possibility to use 3DPT as AMT, can create a significant change in the relationship between the user and the product. Therefore, the research work will address this existing gap, and will refer to the involvement of the user, in the context of this scenario.

# CHAPTER 3

# RESEARCH QUESTIONNAIRE

## 3.1. The Rationale

In general perspective, the three main factors that constitute the newborn desktop personal 3D printing market are the source of the design, the product, and the user. As can be seen in Figure 3.1A, which represents a simplification of the process that combines these three factors, the source of the design (independent designer / company / design studio / etc.) uses the cyber-space to present the design to potential customers, and if a consumer buys a product, the virtual design moves from the cyber-space to the real world by being manufactured by a manufacturing source, or by the user himself.

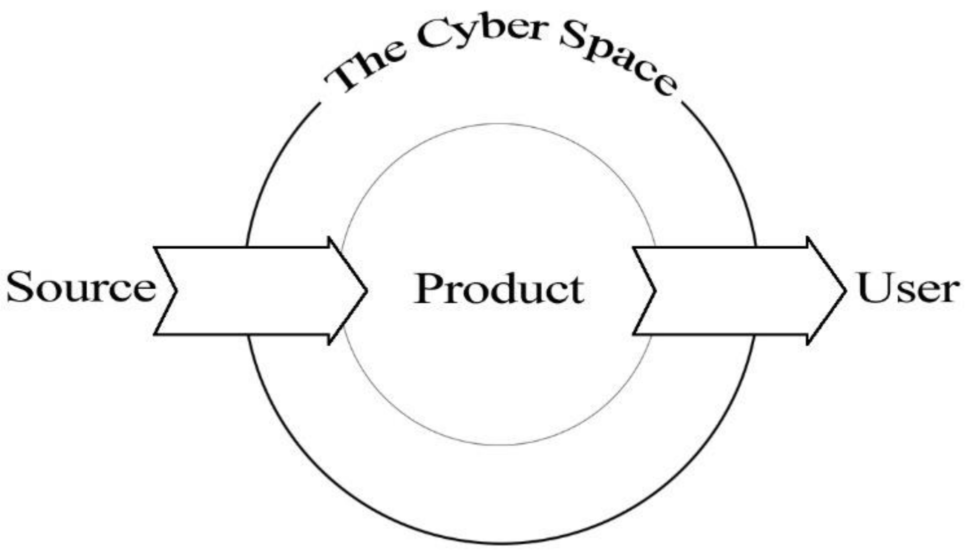



**Figure 3.1A – The general process that relates between the three main factors that construct the desktop 3D printing market.**

The few literary sources that refer to those factors, in context of 3DPTs, tend to focus on technical issues, impacts on manufacturing systems, and on general market structure issues. Most of the references refer incidentally to desktop 3DPs as self-manufacturing mean, and no research that examines how potential users perceive desktop personal 3DPs were found.

The rationale behind the questionnaire, derives from the research questions (Q2 and Q2.1), and from research objective number 5. The current situation shows a clear gap with some unanswered questions pertaining to the fact that the common people do not find practical interest in desktop personal 3DPs, despite the fact that in the past few years, they became accessible and affordable. The missing part from the literature review, is the 'voice' of the potential user, and thus, the purpose of the questionnaire was to examine how the common people perceive desktop personal 3DP.

## 3.2. The Theoretical Basis

As mentioned above, the questionnaire was designed primarily to answer two of the main research questions, Q2 and Q2.1:

Q2 – What type of personal 3DP people will want to have, if any?

Q2.1 – Will a person with personal 3D printer prefer to 3D print standard, or customized products, or it depends on the type of the product?

### *3.2.1. The General Structure*

Regarding the first question, and according to the conclusions of the *'3DPTs Technical Review*' sub-chapter, there is lack of standardization in the desktop 3DPs market. There are 3DPs that fit for desktops, and there are few other 3DPs, which were not presented and were not included in Tables 2.3 and 2.4 (pp.39-40), e.g. 3D Systems CubePro (FFF), and Stratasys Objet 24, and 30 (Polyjet), which do not fit to be put on desktops, but can be integrated in home environment. Therefore, I have decided to present three options only:

1. Common 3DP – small size desktop personal 3DP.
2. Makers 3DP – large size personal 3DP (suitable for home environment).
3. None

The second question relates to the user involvement in the design aspect, and it should be kept in certain correlation with the first question. For that matter, and in order to answer accurately as possible the second question, in context of the first one, I have decided to follow Hu's (2013) 'personalization paradigm's' four principles ('Open Architecture Products', Personalization Design, On-demand Manufacturing system, and Cyber-Physical System). The rationale to rely on Hu's 'personalization paradigm' derives from its ability to cover the whole range of the possibilities that the products market can offer to customers, starting from standard mass produced, up to high levels of mass customized products. Despite the fact that Hu's paradigms represent three market segments, which covers all the possibilities, they do not define in high resolution, levels of customization in the customization and the personalization segments. Therefore, I had to search for an empiric model that refer to the levels of the customization aspect, and which matches Hu's paradigms. I found that Lampel and Mintzberg strategies (1996), could fill this gap, but I had to refer to these strategies with relevancy to 3DP. Thus, in comparison to Lampel and Mintzberg strategies (Figure 2.3D, p.91), I changed the status of the design phase to an 'open architecture design' status (except in the 'Pure Standardization' strategy, which remained as the representative of the conventional method), and the status of the fabrication phase to a flexible-manufacturing-abilities status (as personal 3DP, or as AMT). The new form of the strategies, (Figure 3.2A), had to be reexamined according to the new status of the mentioned phases, which means checking its relevancy to the first question, and the matching to Hu's paradigms.

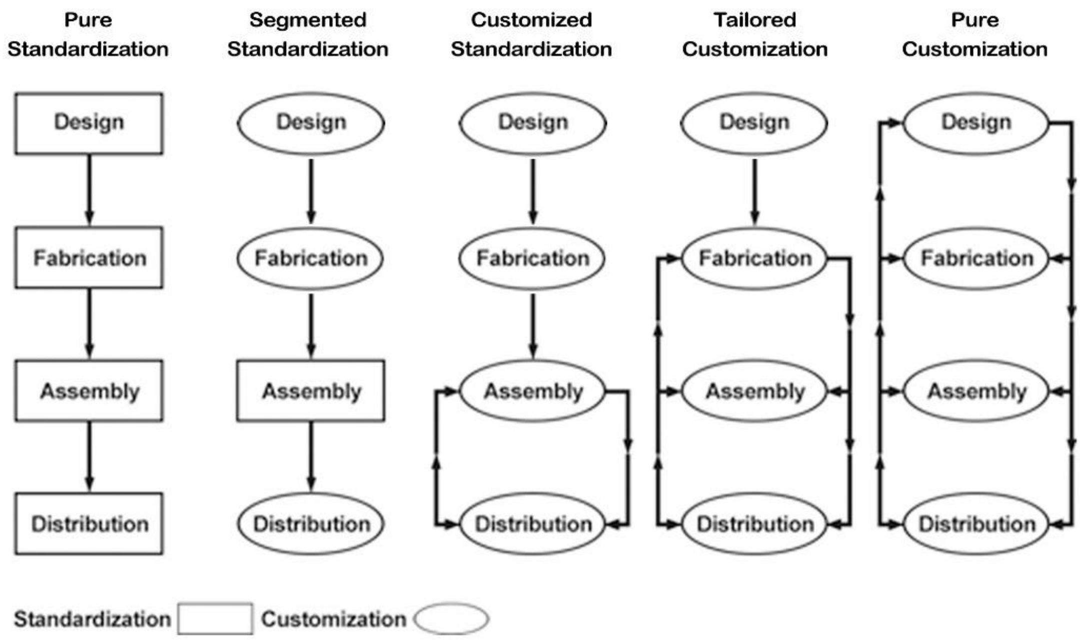



**Figure 3.2A – Adjusted representation of Lampel and Mintzberg strategies.**

**Pure Customization:** This model fits to Hu's 'personalization paradigm' (according to Figure 2.3K, p.77), and it can be integrated with the 'Makers' 3DP option. This option represents a scenario in which the whole process is being implemented in the customers' home environment, and by taking in consideration the described iterative process, this option should provide the customer full independency in all the phases. The meaning of the independence is the absence of reliance of the customer on any factor, beside the initial virtual design. The adjusted form of the model represents a process which starts with a virtual open architecture product, then proceed to the domestic fabrication and the assembly phases, and the last distribution phase becomes irrelevant in its position, as no distribution is required, beside the need to deliver a suitable for 3DP file between the design and the fabrication phases.

**Tailored Customization:** This model fits to Hu's 'personalization paradigm', and it can represent the 'Common' 3DP option. According to the described iterative process, this option would enable to 3D print only few parts out of an offered product, and the rest of the product is needed to be manufactured by industrial flexible manufacturing system. In this case, the customer relies on the design and the manufacturing sources, and therefore, the distribution phase becomes a relevant aspect.

The three other models do not allow customer access to manufacturing mean (3DP), and they represent common MC and one general standard widespread practical strategies. Accordingly, I had to open the 'None' option to three more options:

**Customized Standardization:** This option fits to Hu's MC paradigm, and it should enable the customer to customize and assemble the product. This option represents two MC practices e.g. 'Ikea' and other DIY companies that enable user involvement in the final assembly phase, and 'Nervous System', 'Nike' and other companies, which enable user involvement in the design phase. A combination of these two practices can be found in the PC's market, and in less utilitarian products, e.g. 'Mr. Potato' and other modular toys.

**Segmented Standardization:** This option fits to Hu's MC paradigm, and it should enable the customer to customize the product only. As mentioned above, this option represents MC practices that enable the customer to be involved in the design phase.

**Pure Standardization:** This option fits to Hu's mass-production paradigm, and it should offer the customer collection of standard products. This option eliminates all forms of practices of 3DPs, and it represent the most familiar and conventional strategy.

As can be seen, the titles of the strategies remained the same as Lampel and Mintzberg titles. I found that despite the new constrains, there are no contradictions if the reference to the fabrication phase is made according to the source that holds the manufacturing mean, i.e. standardization = industrial and customization = personal. Although the new constrains changed the status of the design and the fabrication phases in the 'Tailored Customization', 'Customized Standardization', and the 'Segmented Standardization' strategies, they remained loyal to realistic scenarios. Therefore, according to the reexamination along with the mentioned considerations that were presented, the general structure of the main question that should answer both Q2 and Q2.1 questions has been formed as can be seen in Figure 3.2B.

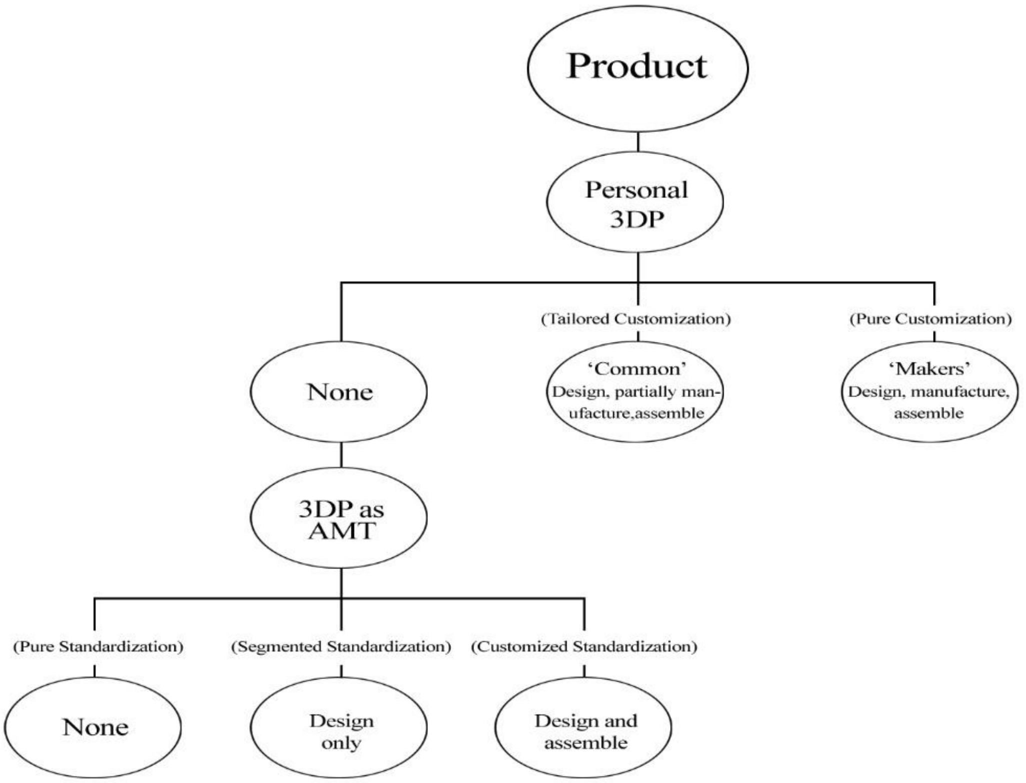



**Figure 3.2B – The general structure of the main question.**

### *3.2.2. Modulation, Customization and Personalization*

In favor of the completion of the expected value of the variants of the general structure, in correspondence to Hu's paradigms, and in order to shed some light on Q1, I needed to decide on a product that will fit to the following demands:

1. The research addresses the common people. Therefore, the product should be familiar and cross-genders, which men and women, young and old can easily identify with.

2. In order to emphasize the differences among the 'Makers', 'Common' and the 'None' options, the product should be big size, so that only the 'Makers' option will be compatible for its fully manufacturing, and assembled, so that the 'Common' option will be compatible for manufacturing of few parts of it.

3. 'Product personalization relies on an open product platform, allowing various modules to be integrated together. Comparing with product family design methodology mass customization's arena which consists of common modules and customized modules, a personalized product usually has one more personalized module that allows customers to create and design. The module is integrated with common modules and customized modules in the open architecture. All these modules can be easily assembled and disassembled by applying the standard mechanical, electrical, and informational interfaces. Product design may contain partial or all of the three types of modules due to the consideration of anticipated value, manufacturability, and cost of the product' (Tseng and Hu, 2014). Accordingly, and in context of personal 3DP, the product should represent open architecture principles.

The first demand had led to further literature review, and despite the fact that no researches and studies were found on how the common people perceive desktop personal 3DPs, or how they perceive themselves as manufacturers, some references that address self-design, or co-design issues were found (von Hippel, 2001; Wind and Rangaswamy, 2001; Dahan and Hauser, 2001; Kamali and Loker, 2002; Randall, Terwiesch and Ulrich, 2003; Tseng and Piller, 2003; Franke and Piller, 2004; Dellart and Stremersch, 2005; von Hippel, 2005; Baldwin, Hienerth and von Hippel, 2006;

Franke and Schreier, 2010; Moreau and Herd, 2010). Moreover, since the product should enable coverage of all Hu's paradigms, other references that promote 'open architecture products' ideology, and/or take into account 3DPs, (along with other manufacturing means) as one of the means that carry the ability to democratize the products market, were also reviewed (Van-Abel et al., 2011; Maldini, 2012; Anderson, 2012; Koren et al., 2013; Kull, 2015).

Few examples of real-life open architecture products were mentioned, such as boards for windsurfing (von Hippel, 2001), computers (Dell and others), bicycles (National Bicycle and Cannondale), CDs (CD Now), vitamins (Acumin), designer jeans (Levi's), and newspapers (Wall Street Journal Personal Journal), (Wind and Rangaswamy, 2001). Dahan and Hauser (2001) presented six web-based customer input methods for different levels of customized products, and depicted examples e.g. instant camera, crossover vehicles and copier finisher. Kamali and Loker (2002) presented a computerized platform that enable 3 levels of customization (Control Condition, Limited Customization Treatment, and Advanced Customization Treatment) for shirts. Randall, Terwiesch and Ulrich (2003) compared between 'parameter-based system' and 'needs-based system' approaches by using customizable laptop and came out with general conclusion that the 'needs-based system' approach fits mostly for novice consumers, and 'parameter-based system' approach fits mostly for experts. Franke and Piller (2004) had proved again that customized products are preferred by consumers comparing to standard products, and they showed it by comparing how much people willing to pay for standard and customizable watches. Baldwin, Hienerth and von Hippel (2006) referred to the natural course of products developments by lead users, and how industrial source can exploit it for the benefit of development of better commercial products. The case study that they referred to, was a kayak for rodeo kayaking. Franke and Schreier (2010) analyzed which factors prompt customers to attribute value to products they design themselves. They examined the studied issue by using real MC toolkit (http://www.wildemasche.de), and according to the three factors (Preference Fit, Process Effort, and Process Enjoyment), they compared how much people are willing to pay for self-designed scarf and standard one. Moreau and Herd (2010) conducted practical sociological research, which examined how comparison with others influence consumers' evaluations of their self-designed backpack.

At this point I would note that all the reviewed cases relied on mass production, or small-series professional manufacturers, and did not take in consideration presence of personal manufacturing mean (3DP or others). As a result of that fact, each reference examined customizable products with varying degrees of customization, based on the abilities of a mass / professional manufacturer to flex the manufacturing process. Additionally, the reference to the design phase was accordingly, without any reflection of abilities that desktop personal 3DP can offer. Therefore, I have decided to refer to the design phase so that it will reflect the abilities of 3DPs, according to 'Nervous System' concept (P.85), which embodies all the values that were mentioned in Hu's (2013) personalization paradigm and the definitions that were set by Tseng and Hu (2014). Hence, regardless to the type of the product that will be selected, the design process should represent user involvement in three general aspects, as follow:

1. **Modulation:** The ability to enable the user to do manipulations on the general shape of the product / component. In real-life, this ability needs to be supported by an integrative engineering failures prevention feature (does not exist).

2. **Customization:** The objective ability to modify the design according to physical variants of each potential user. In order to implement this option, the user must provide personal physical data, e.g. height, weight and other anthropometric data.

3. **Personalization:** The Ability to enable the user to determine aesthetic values according to his personal taste, e.g. color, graphics and text. In real-life, this is the most prevalent customization option, since it is the easiest to implement action for series manufacturers.

### *3.2.3. The Product*

Out of all the products that were examined at the additional literature review, and according to the first demand, six general types of products were found as suitable for the common people: computers (including laptops), garments (shirts, pants and scarves), watches, backpacks, cameras, and bicycles. By taking in consideration 3DPs as the manufacturing mean, the watches, the cameras and the bicycle remained theoretically, as the most relevant products, since computers contain too many non-3D printable components, and although there have been attempts to produce 3D printed garments by designers e.g. Iris van Herpen, Neri Oxman and Danit Peleg (appendix 3.2.3A), these attempts were not designed for everyday wear but only for the catwalk. According to the second demand, the bicycle remained as the only relevant option, since watches and cameras are not big enough to emphasize the difference between the 'Makers' and the 'Common' options. The bicycle option has also several relative advantages upon the other products, since it is deeply perceived as customizable transportation mean (the absolute majority of the standard bicycles are customizable), and it has familiar iconic shape with understandable revealed functional mechanisms. Moreover, there are also precedential cases of open architecture tailored made bicycles (NBIC), and 3D printed bicycle components, e.g. the collaborative project of 'Shapeways' and 'Montague Bike', the 3D printed titanium alloy frame by the British company 'Empire Cycles', Luna 3D printed bicycle by Omer Sagiv, and more (appendix 3.2.3B).

In order to ensure that the bicycle could be the representative products that the questionnaire will examine to show how the common people perceive 3DPs, I had to check the followings:

1. Which components are suitable for 3D printing?
2. Which components could be excluded from the general assembly, in favor of emphasizing the difference between big size 3DPs (the 'Makers' option) and desktop personal 3DPs (the 'Common' option).
3. How the modulation, customization and personalization (MCP) factors can reliably be implemented in each component, in favor of examination of the correlation between the preferable type of 3DP to the required levels of openness of the architecture of the product.

With regard to the first clause, additional literature review about bicycles and their structural components was conducted (Wilson, 2004; Heine and Praderes, 2009; Hadland and Lessing, 2014; Hallett, 2014). Due to the fact that bicycle has many essential and non-essential components, a concern that it could cause a congestion, which could blur the focus from the 3DPs, had led to an initial step that divided all components into categories of functionally required components (FRC), and supplementary components (SC), (Figure 3.2C). The FRC were selected according to the indispensable dependency of the bicycle functionality on them, and they were divided into 3 sub-categories: Basic Functional Components, User Adjustment Components, and Mechanisms. The SC list was comprised from the remaining components, which the bicycle can be properly operated by human, even without them, and they were divided into 2 sub-categories: Enhancers (lights, suspensions and mud flaps), and Accessories.

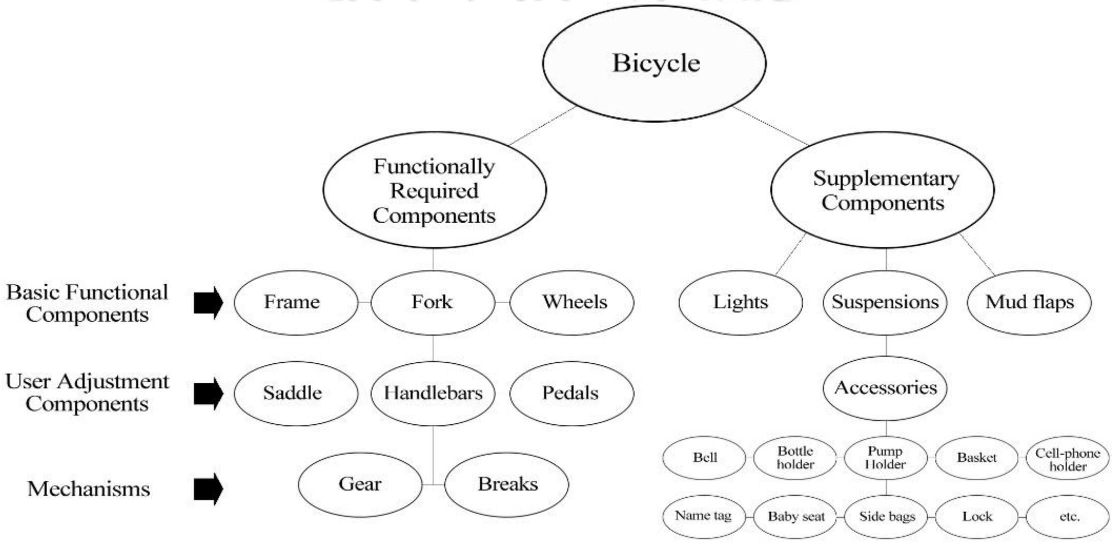



**Figure 3.2C – Categorization of bicycle components.**

In order to examine engineeringly which components could be 3D printed by a desktop size 3DP, or by a big size 3DP, I have consulted with [5]Dr. G. Mazor, [6]Dr. Y. Biton, and [7]Prof. K. Munshi, and the conclusion was that theoretically, beside the light bulbs, all the components are 3D printable (by taking in consideration all the available commercial technologies). By referring specifically to a desktop size 3DP, the conclusion was that all the components, including the big size components, e.g. all the 'Basic Functional Components', the suspensions, the mud flaps, and few of the

[5] Guide - Dean of Mechanical Engineering at SCE – College of Engineering, Israel.
[6] Advisor - Senior faculty at SCE – College of Engineering, Department of Mechanical Engineering, Israel.
[7] Advisor – Prof. Emeritus at the Industrial Design Center – Indian Institute of Technology, Mumbai, India.

accessories, can all be manufactured by it, and function properly. It is just a matter of creative segmental design, which is a challenge that nobody faced until now.

With regard to the second clause, and by taking in consideration the conventional familiar design, I had to compare between the general external dimensions of each component to the average build volume dimension of commercial desktop personal 3DPs (Table 2.3. p.39). In favor of this comparison, additional review of cybernetic standard bicycle shops (dimensionbikeproducts.com, electrabike.com, en.author.eu, performancebike.com, and more), and cybernetic customizable bicycle shops (villycustoms.com, missionbicycle.com, republicbike.com, and more), was conducted, and it was discovered there are many types of general designs of bicycles and bicycle components for different purposes, e.g. leisure, racing, challenging maneuvering, mountaineering, etc., and accordingly, for different end-users. Since the common people tend to use bicycle mostly for leisure purposes, or other non-challenging riding purposes, I decided to focus on inner-city bicycles for leisure purposes and for non-challenging utilitarian purposes, e.g. inner-city touring, go to school / work, fitness, visit friends, etc. The comparison between the general external dimensions of the bicycle components to the average build volume dimensions of the reviewed desktop personal 3DPs has found that the 'User Adjustment components' and few of the accessories (bell, name-tag, most of the holders, etc.), are the most relatively suitable components for manufacturing by using desktop personal 3DP, and therefore they should represent the 3D-printable-by-the- user components, under the 'Common' option.

With regard to the third clause, since bicycles have many components, and the questionnaire is able to examine the correlation between the preference of 3DP and the level of the user's desired modifications by representing only few components, I have decided to balance the expression of 3DPs and the selected type of bicycle as the representative product, by focusing on the FRC components, and the most basic SC components (the mud flaps and the lights).

In favor of the examination of how the MCP factors can reliably be implemented in each component, an assessment table was created (Table 3.1.), and as can be seen, the 'User Adjustment Components', the frame, and the fork, are the only components that can represent all the MCP factors. The 'Mechanisms', the 'Enhancers', and the wheels were found as eligible to represent the modulation, and the personalization aspects only, since they have no dependency on the user's physical data.

**Table 3.1. – Examination of the representation of the MCP factors.**

| Category | Component | Modulation | Customization | Personalization |
|---|---|---|---|---|
| **Basic Functional Components** | **Frame** | Shape | Dimensions | Color |
| | **Fork** | Shape | Dimensions | Color |
| | **Wheels** | - Size<br>- Spokes shape<br>- Tire tread pattern | - | - Rims color<br>- Spokes color |
| **Mechanisms** | **Gear** | Levers shape | - | Color |
| | **Breaks** | Levers shape | - | Color |
| **User Adjustment Components** | **Saddle** | Shape | Dimensions | Color |
| | **Handlebars** | Shape | Dimensions | Color |
| | **Pedals** | Shape | Dimensions | Color |
| **Enhancers** | **Mud flaps** | Shape | - | Color |
| | **Lights** | Type | - | Color |

### 3.2.4. *General Perception*

With reference to research objective no.5: *'to examine how potential home users perceive 3DP, in order to better understand the market gap…from the perspective of the potential user'* (p.24), I have decided to add separate general section, which will purely examine by direct questions, how the common people as potential users perceive 3DPs. The essence of the general perception was conceived from the DIY literature sources along with additional literature review (Paulos, 2009), and from the literature review of the questionnaire's theoretical basis sub-chapter, with emphasize on the factors of how much people are 'willing to pay' (Franke and Schreier, 2010), and the user's level of expertise (Randall, Terwiesch and Ulrich, 2007).

In favor of the presentation of the correlation among the 'type of 3DP' options, the 'willing to pay' (WTP) factor, and the user's level of expertise factor, I formed a diagram (Figure 3.2D) that graphically presents the different states of the perception. The edge cases (Figure 3.2E), represent ten endpoints that should reflect the gap between the potential user characterization along with the willingness to pay factor, to the 3D printing market.

The first row on the left side of the diagram **(Amateur-Makers-Minimum)** represents a hypothetical anti-market endpoint of an amateur user position, who wants big size 3DP that theoretically capable to 3D print almost everything, and expect to get it for free. The second row on the left side of the diagram **(Amateur-Makers-Maximum)**, represents a hypothetical pro-market position of an amateur user who wants large size 3DP, and is willing to pay the offered market price. The first raw on the right side of the diagram **(amateur-None)**, represents an off-market position of a person who does not want to have any 3DP. Generally, the first and the third rows represent anti-market, or the off-market states, and the second row, along with the forth row, represent the pro-market states.

The expected answers from the questionnaire, which should reflect the general perception, are expected also to reflect the hypothetical gap between different users' characteristics to the market (out of the participant's perceptive). While the combination between the user's level of expertise and the type of 3DP defines the characteristic of the participant, the right vertex in each triangular diagram should define the dynamic WTP factor, hence represent the perception by the level of proximity to anti-market / pro-market states.

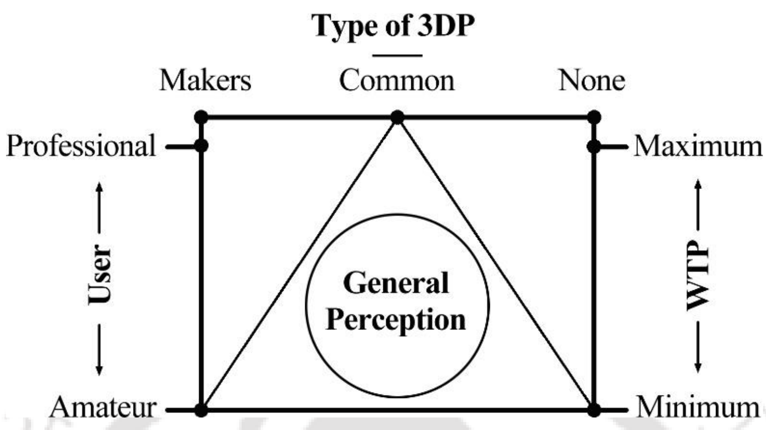



**Figure 3.2D – A Descriptive diagram that presents the correlation among the three factors of the general perception.**

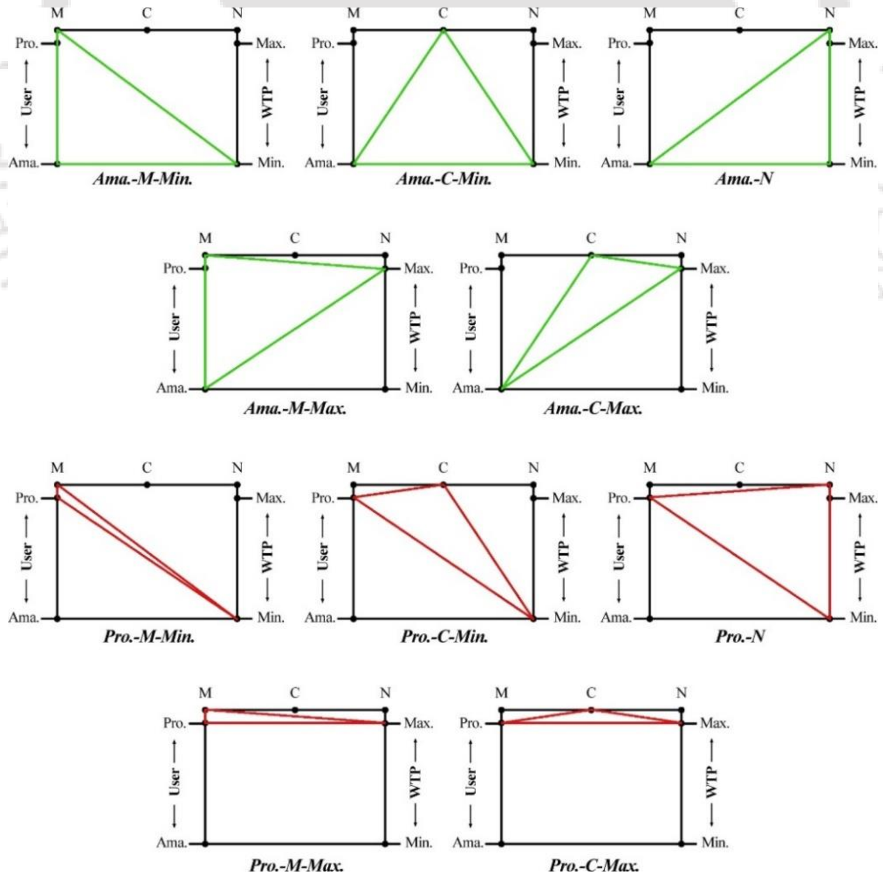



**Figure 3.2E – General perception - endpoints diagrams.**

## 3.3. The Design of the Questionnaire

Based on the theoretical context, the questionnaire was designed to refer to the three main issues, and the correlation among them:

**Issue no.1:** Which type of 3DP the participants, as representatives of the common people, will prefer, if any.

**Issue no.2:** According to the preferred type of 3DP, what will be the level of the theoretical manipulation on the design?

**Issue no.3:** According to the preferred type of 3DP, how the participants, as representatives of the common people, perceive 3DPs.

With regard to the selection of the bicycle as the representative product, I have decided to put costume on the questionnaire of an imaginary bicycles shop's form. The costume was not invented to blur or hide the questionnaire, but rather to friendly mediate between the theoretical bases of the questions to the participants. Additionally, the design was made so that the questionnaire will be available for distribution by printed copy, and/or by cyber form.

***The first page*** (Figure 3.3A) was designed to introduce to the participants an imaginary company (D-Bicycle), and the context of the questionnaire.

***The second page*** (Figure 3.3B) contained to two general questions:

**GQ$_1$. Which type of 3DP do you think (the participant) you will own?**

Regarding the general structure of the main question (Figure 3.2B, p.129), and by taking in consideration the categorization of the components of the bicycle (Figure 3.2C, p.134), the optional answers were divided into three options as follow:

I. **Common 3DP** - A small size 3DP that enables to print only few parts (saddle, handlebars, pedals, and few accessories). The rest of the components will be 3D printed at D-Bicycle's workshop and will be delivered to the user by courier (Tailored Customization).

II. **Makers 3DP** – A big size 3DP that enables to print all the components. The user will 3D print and assemble the bicycle by himself. D-Bicycle will provide manuals (Pure Customization).

III. **None** – The 'None' option was divided to three user-perspective sub-options:

i. To customize the bicycle, but that D-Bicycle team will 3D print, assemble, and ship it as finalized product (Segmented Standardization).

ii. To customize the bicycle, but that D-Bicycle team will only 3D print and ship it. The user will assemble it by himself (Customized Standardization).

iii. To buy standard bicycle from a catalog (Pure Standardization).


**Figure 3.3A – The first page of the questionnaire.**

## *D-Bicycle*

*Enjoy the world of **3D-Printing***

### Introduction

***D-Bicycle*** is a new entrepreneurship that believes in democracy and sustainabilty. We believe that **3D-printing Technologies** herald new times, when each person will be able to customize his products, along with consideration about the environment.

***D-Bicycle*** will enable you to customize your bicycle in 3 levels, depends on the type of the 3D-printer that you will own.
Please mark the type of 3D-printer that you think that you'll own:

○ **Common 3D-Printer** - A small size 3D printer that enables to print only few parts (saddle, handlebars, pedals and few accessories).The rest of the components will be 3D printed at our work-shop, and will be delivered to you by courier.

○ **Makers 3D-Printer** - A big size 3D printer that enables to print all the components. You will 3D print and assemble your bicycle by yourself. Manuals are available on ***D-Bicycle*** website.

○ **None** - I prefer to:
- ○ customize my bicycle, but I would like that ***D-Bicycle's*** team 3D print, assemble, and shift it to me.
- ○ customize my bicycle, but I would like that ***D-Bicycle's*** team 3D print all the components, and shift it to me. I prefer to assemble it myself.
- ○ buy standard bicycle from catalog.

### Personal details

Reference no. DB-__________

Gender: M / F

Age: _________

Height:______ (Meters)

Weight:______ (Kg)

Occupation:_______________

Riding frequency:

Nunber of days _____ / month

Riding purpose:
(Multi Choice is permitted)

○ Leisure & tourism ○ Get to work / School

○ Fitness ○ Other:____________________

E-mail address:____________________________________

**Figure 3.3B – The second page of the questionnaire.**

**$GQ_2$. Personal details.**

This general question relates to the characterization of the participants, and it has four purposes:

I. To collect typical data, so that the expected results could be classified and analyzed accordingly (age and gender).

II. Since the general characteristic of the participants of the questionnaire should naturally converge into adults (15-years-old, and above), who use inner-city bicycles for leisure purposes, e.g. tourism, get to work / school, etc., I have added hidden filter questions (riding frequency, and riding purposes), to ensure that only participants' responses, who follow the general characteristic, will be taken in consideration.

III. As part of the costume, to induce a sense of a real bicycle shop that has advance customization abilities (height, weight, and occupation).

IV. To have the ability to contact the participants, in case of further questions, or clarifications (e-mail address).

***The Third Page*** (Figure 3.3C) was designed to respond to **'Issue no.2'**, based on the theoretical basis of the **'Modulation, Customization and Personalization'** sub-chapter (p.130), and Table 3.1. (Examination of the representation of the MCP factors, p.136).

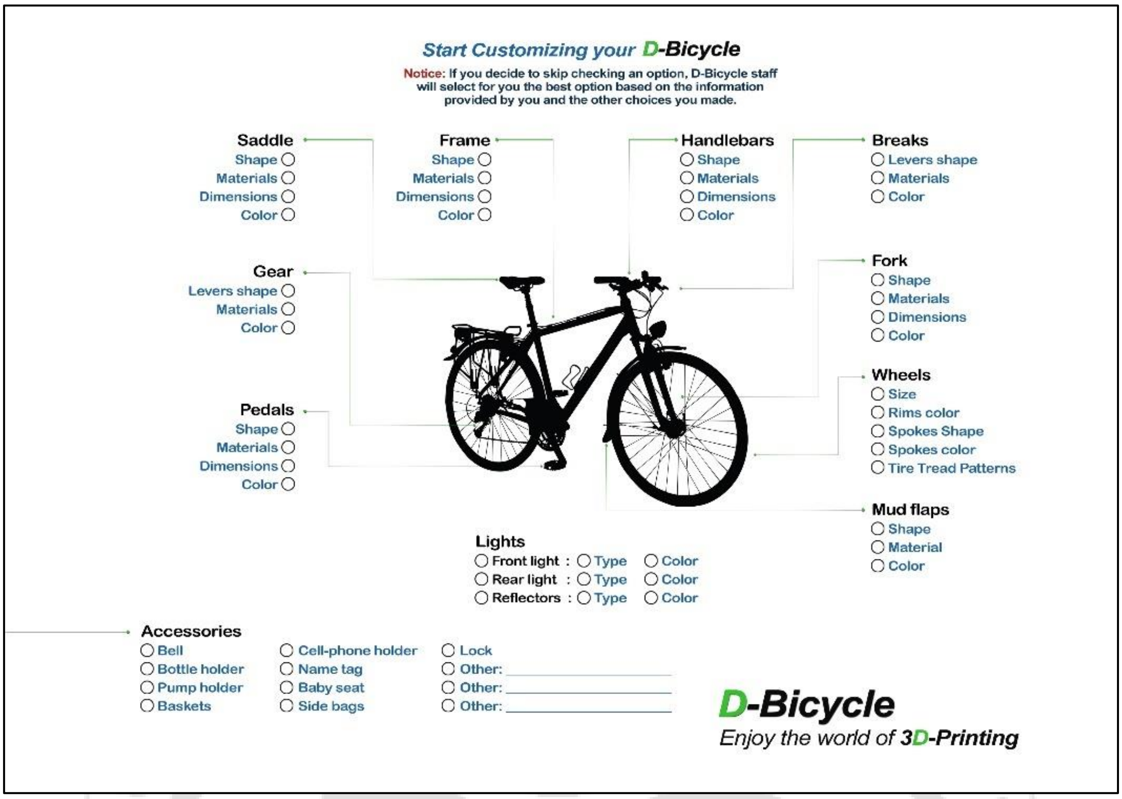



**Figure 3.3C – The third page of the questionnaire.**

A scenario of which a consumer owns a manufacturing mean (3DP), comprises also issues that relates to the raw material. The designer designs parts according to specific raw material properties, and the consumer can hold a bank of raw materials, which not necessarily match to the specific raw material that was selected by the designer. On one hand, the designer can specify which raw material should be in use, but on the other hand, the consumer might ask for a design that fits to his immediate available raw materials. Thus, additionally to the insight of the theoretical basis, I have decided to add a 'Material' option for most of the components, in order to examine whether there is awareness to the raw material aspect.

Additionally, I have decided to add a list of accessories, just to strengthen the sense of the real-shop-costume that can supply all the components.  The list was not added for examination purposes, and no MCP factors were attached to neither one of the accessories.

***The fourth page*** (Figure 3.3D), was designed to respond to **'Issue no.3'** based on the theoretical basis of the **'General Perception'** sub-chapter (p.137). With reference to the descriptive diagram (Figure 3.2D, p.138), I have added the two missing factors (the first factor is the type of 3DP that the participant marked as preferable).

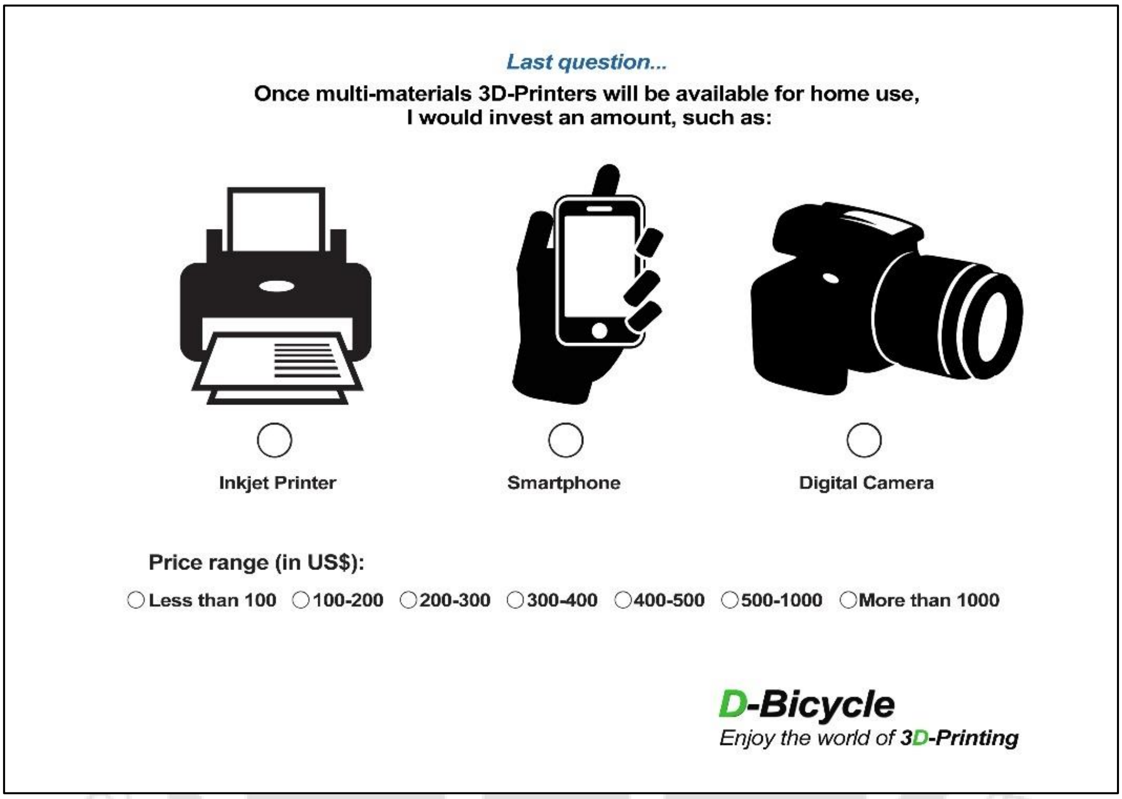



**Figure 3.3D – The fourth page of the questionnaire.**

The factor that refer to the WTP aspect is represented by a prices-scale. The user's level of expertise factor is represented by three icons that list different type of products with different required level of expertise:

- **Inkjet Printer:** Symbolizes a product (in this case a pure manufacturing mean) that requires minimum level of expertise from the user, and it represents participants that perceive themselves as amateurs.

- **Smartphone:** Symbolizes a product that has more significant place in everyday life, and in order to get the most out of it, the user should gain certain level of expertise. Since this product can only be modified and customized by the user by guided actions (installing and operating desired applications), and not open for hardware modifications, this option represents participants that perceive themselves as semi-professional users.

- **Digital Camera:** Symbolized a hobby tool that people choose to own. These people, most likely, are willing to invest spare money on it, and have good understanding of how this tool works. Thus, this option represents participants that perceive themselves as professional users.

## 3.4. Questionnaire Hypotheses (QH)

The questionnaire hypotheses derive directly from the expected outcomes, based on the insights from the general theoretical basis of the general research, and from the theoretical basis of the questionnaire.

With reference to the first general hypotheses **($H_1$)** of the general research (p.40), with correlation to the first general question **($GQ_1$)** of the questionnaire (p.139):

**$QH_1$.** - Since the questionnaire addresses participants who have interest in the offered product, and since the 3D printers are theoretically offered with no required cost, most of the participants will select to own 3DP.

With reference to the second general hypothesis **($H_2$)** of the general research (p.40), with correlation to **'Issue no.2'** (p.139):

**$QH_2$. –** Participants that will select the option to own 3DP, will prefer to customize the bicycle, according their need.

Conclusions from the questionnaire's theoretical basis suggest that people prefer customizable products and are willing to pay more for such products (Kamali & Loker, 2002; Randall et al., 2003; Franke & Piller, 2004; Franke & Schreier, 2010, Moreau & Herd, 2010). Thus, I would add 2 more sub-hypotheses to **$QH_2$:**

**$QH_{2.1}$.** – Since most of the people prefer customizable products, even participants that will select not to own 3DP, will prefer to customize the bicycle, according to their needs.

**QH$_{2.2}$.** – The common consumer is not used to purchase 'open-architecture products'. Standard products enable, at the most, color differentiation and in some cases adjustments according to the physical constrains of the user. Therefore, participants that will choose to customize the bicycle, will tend to focus on the **'Physical customization'** and the **'Personalization'** factors, out of the MCP factors.

With reference to the factors that compile the 'General Perception', participants that will choose to own 'Maker' 3DP, are most likely familiar with the technology, and/or enthusiastic by the idea of being an owner of such a machine. Therefore, it stands to reason that this kind of participants will perceive 3DP as a hobby tool (digital camera), and they will be willing to pay for it the highest amount, relative to other participants. Participants that will choose to own 'Common' 3DP, are most likely familiar with the technology, and/or enthusiastic by the idea of being an owner of such a machine. Differently from the 'Makers', they want to be less involved in the manufacturing process, and therefore they might be willing to pay less, relative to the average amount of the 'Maker' participants and will refer to 3DPs as a product that will become an essential part in their life, but they do not really understand how it works (smartphone). Participants that will choose not to own 3DP, are most likely not familiar with the technology and/or do not find any interest in self-manufacturing. Therefore, it implies that this kind of participants will not invest any amount in order to own 3DP, and most likely, they will refer to 3DPs as manufacturing mean that they do not need / want (inkjet printer). To summarize:

**QH$_{3}$.** – 'Maker' option participants will perceive 3DPs as a digital camera, and will be willing to pay the highest amount, compared to the other participants. 'Common' option participants will perceive 3DPs as a smartphone and will be willing to pay less than the average amount of the 'Maker' participants. 'None' option participants will perceive 3DPs as inkjet printer and will not invest any amount in order to own one.

One of the goals of the research is to understand the gap that exists between the 3D printing market and the common people. In light of this goal, the questionnaire might provide few explanations. Market research points to the ignoring of the women market as one of the reasons for market failure in different levels. "…women represent a growth market bigger than China and India combined – more than twice as big, in fact"

(Silverstein & Sayre, 2009). Therefore, one of the reasons that might explain this gap is that 3DPs producers have not as yet capture the women market. Hence:

**$QH_4$.** – Female participants will select the 'None' option more than male participants.

## 3.5. Questionnaire Analysis

The designed questionnaire was distributed by printed copies and was adjusted also for online distribution by Google Forms online application. The online form was distributed through social networks (Facebook, LinkedIn and Research-Gate), and until the 03/01/17, 129 participants responded. Two participants were less than 15-year-old, and thus, the total number of the examined responds reduced to **127**. As can be seen in Figure 3.5A, **95 males (≈75%) and 32 females (≈25%)** have responded.

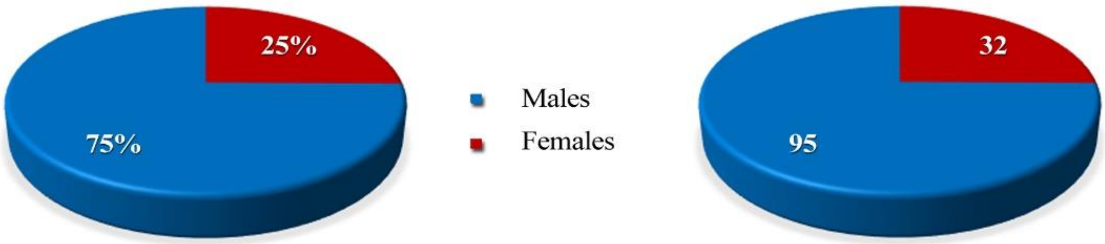



**Figure 3.5A - Division of the participants by gender (numbers and percent).**

Up to 01/05/16 94 males and 16 females have responded. The disproportion between the male respondents and the female respondents, had led to women-centered call-for-participation move, which emphasized the bicycle rather than the 3D printing issue. This attempt has managed to double the number of the female respondents, but still did not manage to balance the proportion between the females and the males. This low participation rate of women (relatively to men), indicates that women associate less with the 3D printing field, and with reference to **$QH_4$.**, prior to the examination of the question that refer to the preference of the type of the 3DP, the low rate of participation might partially support **$QH_4$.**

Examination of the division of the participants by gender and age (Figure 3.5B), shows that the clear majority of the participants was between 20-40 years-old (total: 90, 71%; males: 66, 69%; females: 24, 75%), a data that clearly represent the most relevant range of ages that finds interest in 3DPs. Additionally, the distribution of the participants (according to age-gender) turned to be relatively similar (general: $\bar{X}$=28.43, σ=9.36; males: $\bar{X}$=28.61, σ=9.74; females: $\bar{X}$=27.88, σ=8.23), and therefore the examination will refer to males and females separately, and by comparison to the general results, and to each other.

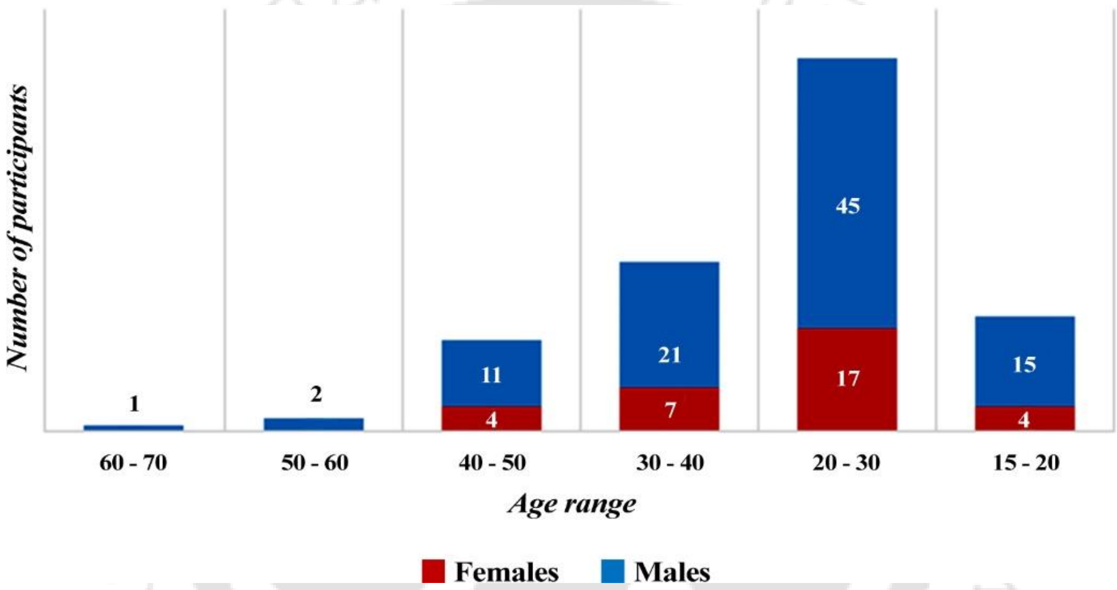



**Figure 3.5B - Division of all the participants by gender and age.**

*3.5.1. Analysis of the results of' the 'Second page'*

Regarding **GQ₁.** (type of 3DP) the general division of the participants (Figure 3.5.1A), shows that each option got approximately ⅓ of the vote of the participants. More accurately, according to the collected data, 65% see themselves as owners of a small size (31%), or a big size (34%) 3DP. This interesting data indicates that once the common people find rationale to own 3DP, the major part are willing to adopt the technology. A food for thought for the producers, whether the gap that exist between the personal 3D printing market to the potential users drives from marketing / design failure, or both.

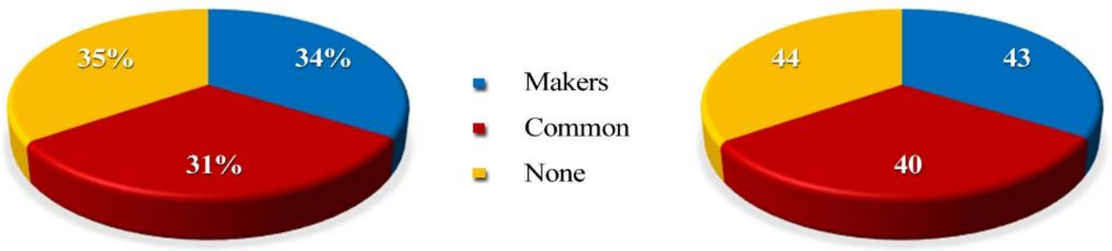



**Figure 3.5.1A - Division of the preference of the type of 3DPs (numbers and percent).**

Examination of the selections per gender (Figure 3.5.1B) presents interesting difference between the male and the female participants. While 70% of the males chose to own one of the types of the offered 3DPs, almost 60% of the females chose the option 'None'. Despite the disproportion between the males and the females, this result clearly indicates that women do not find the need, or interest in the 3D printing field. Moreover, while the distribution of the men is more or less equal, the women represent more of an all-or-nothing attitude (with clear tendency toward the nothing).

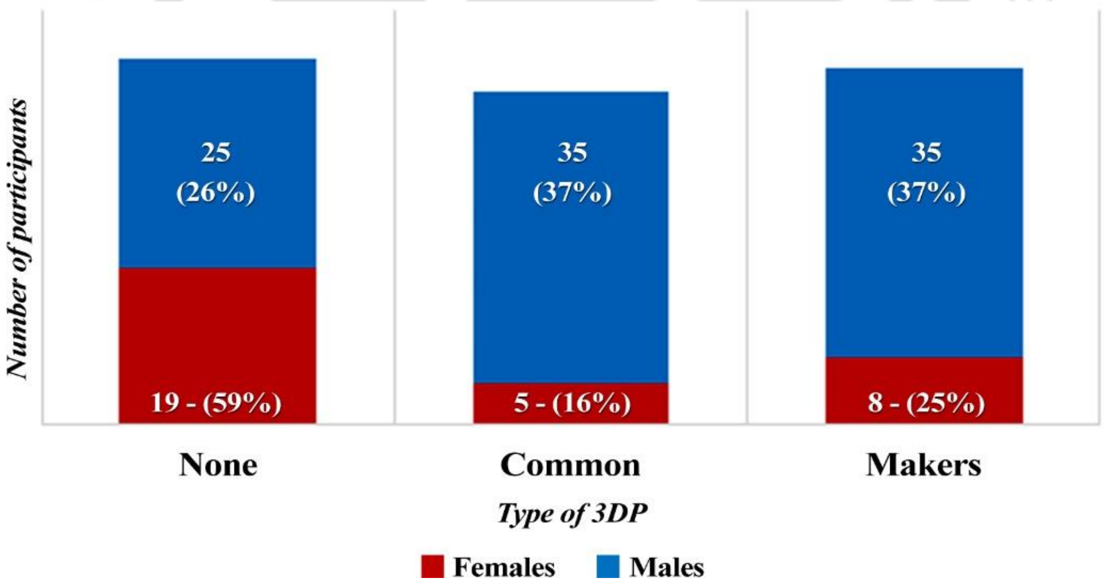



**Figure 3.5.1B - Division of the preference of the type of 3DPs by gender.**

Deeper examination of the trend of how each gender has made his choice regarding to the type of 3DP and according to age range (Figure 3.5.1C – for males, and Figure

3.5.1D – for females), shows that in both cases, the 20-30 age range is the most prominent range in which the participants showed interest in participation in the research. Relatively to this age range, there is a trend of gradual decay in the interest of the people.

The case of the male participants presents slight advantage to the ‘Common’ option over the ''Makers' option at the 20-30 age range, and slight advantage to the ‘Makers’ option over the 'Common' option at the 15-20, 30-40, and 50-60 age range. Only at the left edge the ‘None’ option gains leadership (one participant at the 60-70 age range).

The case of the female participants presents clear advantage to the ‘None’ option over the other options at the 30-40 and 40-50 age range age. Interestingly, the 'Makers' and the 'Common' options are significantly tightly on top at the 15-20 and 20-30 age range.

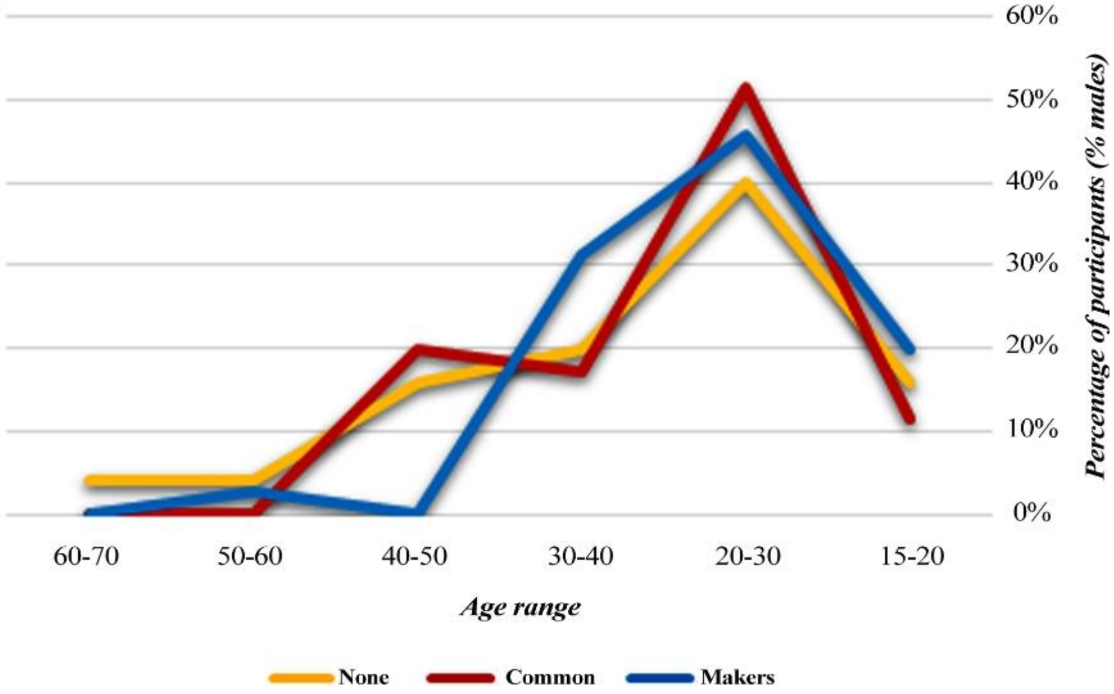



**Figure 3.5.1C – The trend of the preferences of type of 3DP by gender (males) – age range.**

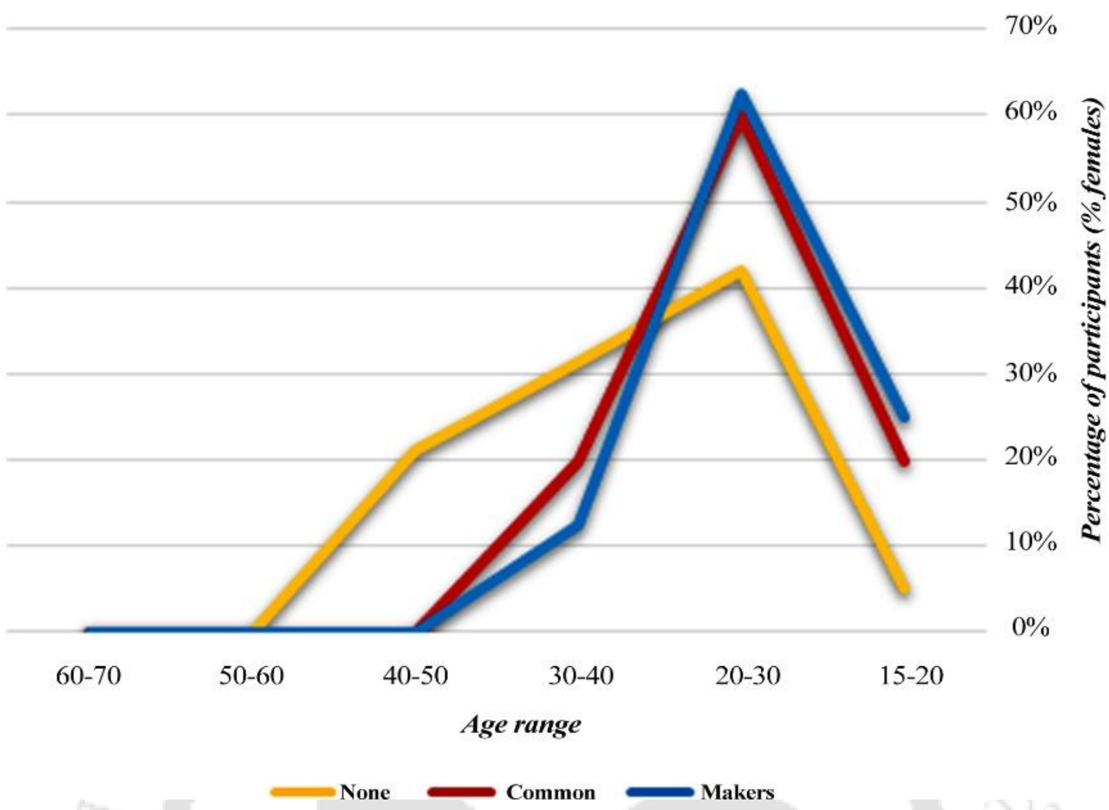



**Figure 3.5.1D – The trend of the preferences of type of 3DP by gender (females) – age range.**

With reference to the first questionnaire hypothesis **($QH_1$.)**, in general perspective, indeed most of the participants (65%) had selected one of the offered 3DP, but close examination of the results per gender, as mentioned, indicates that only the male participants' results validated the hypothesis. Despite that, both genders have shown more theoretical willingness to adopt the technology, opposed to the real-life situation. It clearly passes the responsibility onto producers, who must improve the design of the 3DPs, and find rationales so that potential users might find interest and need in it.

With regard to the participants that selected the 'None' option (Figure 3.5.1E), 10 participants (23%) have chosen to customize and assemble the bicycle by themselves (high level of involvement in the production of the product), 17 participants (39%), have chosen to customize only (moderate level of involvement in the production of the products), and 17 participants (39%) have chosen to follow the most common standard approach, and preferred to choose readymade design from a catalogue. Interestingly, 62% out of these participants have chosen to customize the bicycle, despite that they did not show any interest in the manufacturing process. This data is strongly aligned with all the conclusions that arose from prior researches and studies that were mentioned in the literature review.


**Figure 3.5.1E – The ‘None’ option - general division of the preferences (numbers and percent).**

By taking in consideration all the participants (Figure 3.5.1F), ≈87% of the participants have chosen to customize the bicycle (regardless to the 3DPs). As mentioned, this data is not unexpected, and it is strongly emphasizing claims from prior studies and researches that relate to the MC field, and which highlight the competitive advantage of customized products in a competitive market.


**Figure 3.5.1F – General division of the customization preferences (numbers and percent).**

Examination per gender of the sub-results of those who have selected the ‘None’ option, present similarity among the preferences, in both genders (Figure 3.5.1G). Approximately 60% have chosen to be involved in the production of the product, while approximately 40% have followed the most common approach, and chose the readymade design from the imaginary catalogue. This similarity reflects distribution basis that do not have any gender relevancy. Hence, the general division represents people who do not find interest / need in 3D printing (or even maybe any manufacturing mean, regardless to their gender.

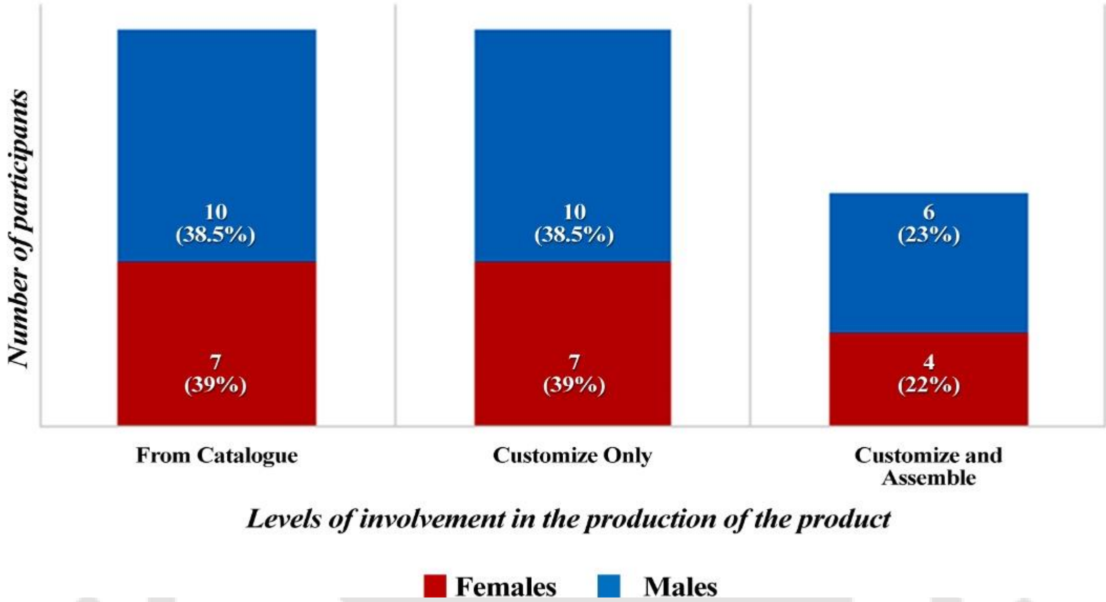



**Figure 3.5.1G – The 'None' option – division of the preferences by gender.**

Examination of the trend of how each gender voted according to age range (Figure 3.5.1H – for males, and Figure 3.5.1I – for females), shows that in the male participants' case, the 15-40 age range is the most prominent range where the participants showed interest in being involved in production of the product. Differently, at the 40-70 age range, there is a clear preference for the ready-made design. In the female participants' case, the trend is similar, even though that relative to the male participants' results (by percent) they have chosen more from the ready-made design option (from catalogue).

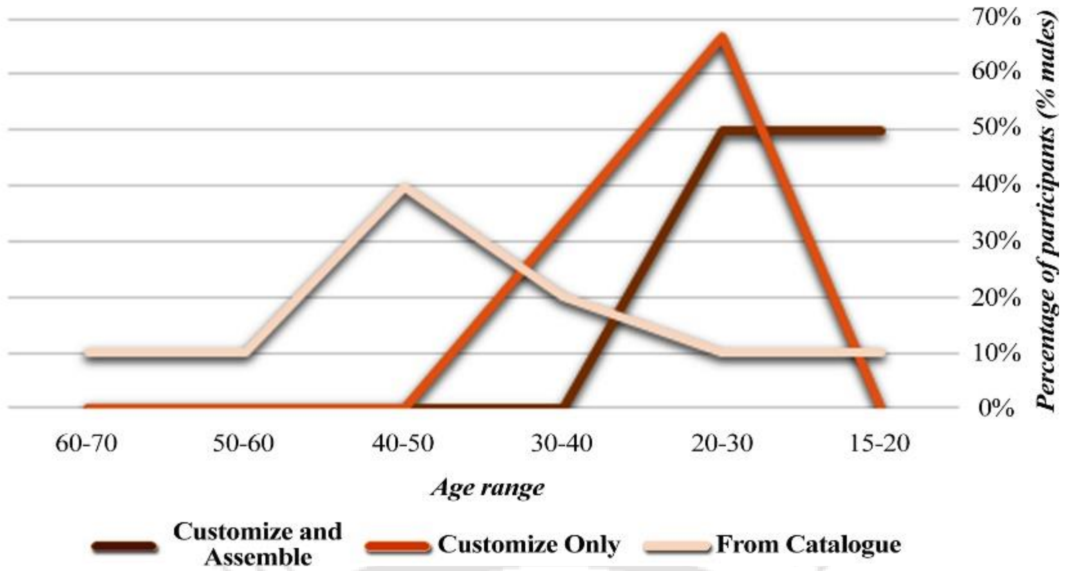



**Figure 3.5.1H – The trend of the sub-preference of those who have selected the 'None' option by gender (males) – age range.**

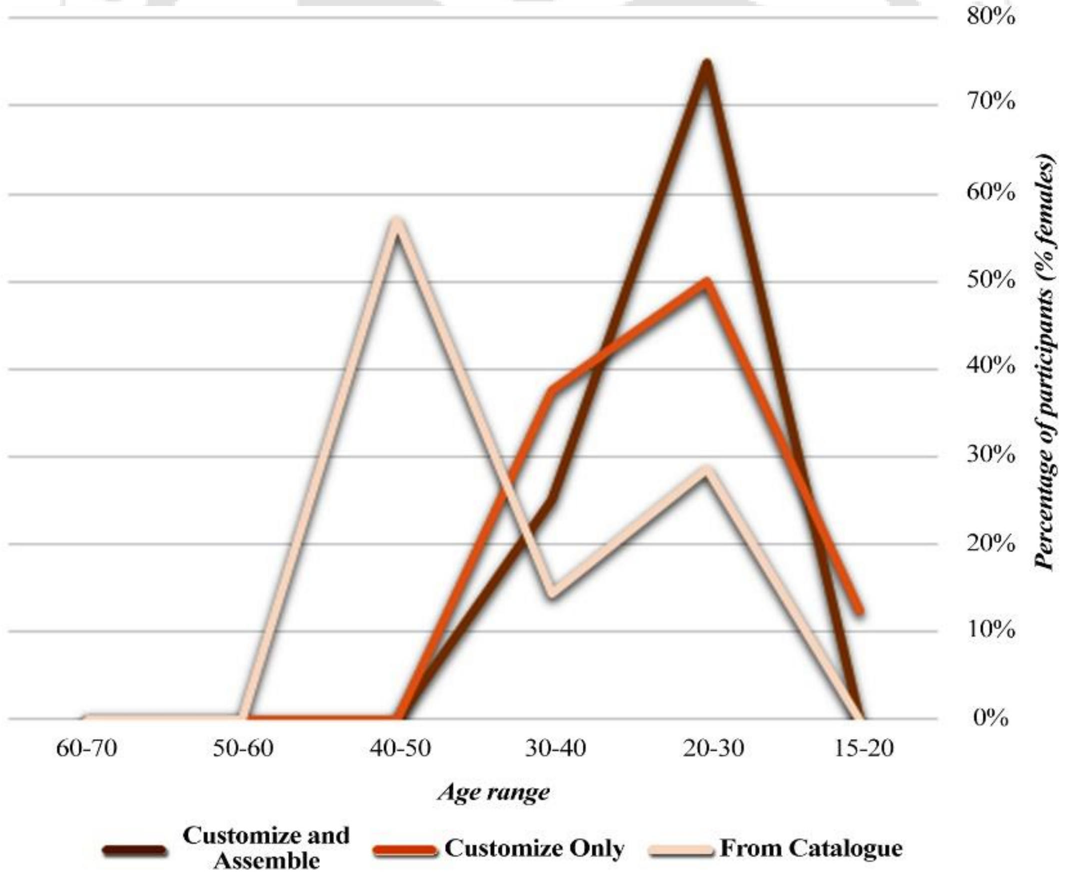



**Figure 3.5.1I – The trend of the sub-preference of those who have selected the 'None' option by gender (females) – age range.**

With reference to the first sub-hypothesis of the second hypothesis of the questionnaire **($QH_{2.1.}$)**, and based on the literature review, its clearly seen that the results of those who have chosen the 'None' option (regardless to gender issues), are aligned with the hypothesis, i.e. most of them want to be involved in the production process, in different levels of influence.

### *3.5.2. Analysis of the results of the 'Third page'*

With reference to the results' analysis of the third page of the questionnaire, which was designed to examine the correlation between the preference of the type of the 3DP to the level of the involvement in the design (according the MCP factors), I had to take into consideration, only participants that chose 3DP, and participants that chose the 'Customize and Assemble' (C&A), and the 'Customize Only' (C/O) sub-options, out of the 'None' option. Accordingly, the number of the participants that were taken in consideration, was reduced to **110 (86 males and 24 females)**. This reduction had led to prevention of the ability to do extra-fine analysis, due to convergence of too few participants (especially in the female participants' case). [8]Examinations of the correlation between the type of the 3DP to the gender of the participant, and the correlation among the type of the 3DP, the gender of the participants and the age range, turned out to be irrelevant, due to the mentioned reduction. Therefore, the analysis of the results of the third page refers to all the participants, without gender segmentation.

First general review of the results shows that ≈98% out of the relevant participants chose to customize the bicycle, and ≈2% (2 participants that selected 'Makers' 3DP) did not customize any of the components, even though they could do so. On one hand, it can be explained as lack of seriousness, or on the other hand, as willingness to be involved in the manufacturing process only.

Examination of results of which component the participants wanted to customize according to their level of involvement, and according to the MCP factors including the material factor in few cases (Figures 3.5.2.A, 3.5.2B, 3.5.2C), presents 3 major interesting insights:

[8] All the analyses (including the extra-fine analyses) are presented in appendix 3.5.

1. Paradoxically allegedly, participants that chose to be involved in moderate / low level in the production of the bicycle ('Common' and C/O) were the most prominent customizers. In ≈90% of the customization options ('Common' ≈53%, C/O ≈37%) they showed the greatest interest in being involved in the design of the bicycle. The participants that had the option to be involved in all the stages ('Makers'), and the participants that had the option to be involved in high level in the production process, except in the manufacturing process (C&A), showed much less interest in customizing the design. Only in ≈10% of the customization's options ('Makers' ≈7%, C&A = 3%) these participants were leading as customizers. This interesting paradox indicates that people that have interest in the manufacturing process, and / or in the assembly process, prefer to be involved in these stages significantly more than in the design process, and people that show less interest in the manufacturing / assembly processes, or that show no interest at all, are significantly more customized design oriented people.

2. Generally, in 80% of the components (except in the frame and the fork cases), the option to choose the color and the graphics option was the less marked option, while the shape's option and the dimensions' option (in relevant components), were the most marked options. These results indicate that the common people perceive the aspects of the function and the adjustment to their physical dimensions as more significant / influential than the aesthetic issues. This statistic embodies great potential of competitive advantage in competitive market, since the mass-production systems finds difficulties to flex the manufacturing process in order to enable each user to customize the products according to his / her needs, and they mostly offer standard physical customization, and / or variety of colors and graphics. The 3DPs could overcome the challenges of the mass-production systems' manufacturing limitations, and tilt the weight to the 'modulation' and the 'customization' factors over the 'personalization' factor, hence be more aligned with the things that are considered as more important by the potential users.

3. Unexpectedly, the most marked option was the shape of the levers of the breaks. Slightly less were the shape of the levers of the gear, the shape of the handlebars, and the shape of wheels. Even though I could not find a logical explanation why the participants have found so much interest in customizing the shape of the wheel, the

common factor of the other mentioned components is that they come in touch with the users' hands. The dimensions and the shape of the saddle got also much attention from the participants, and the pedals got much less attention relatively to the levers, the saddle, and the handlebars. Generally, the fork was the component that got the lowest attention, and I assume that it happened because the common people perceive the fork as integral part of the frame, and they did not know how to refer to it as separate component.

Based on these results, the second sub-hypothesis of the second hypothesis of the questionnaire **($QH_{2.2.}$)**, turned out to be inaccurate. Even though that the common people are not used to engage with open-architecture products, the participants, as representative of the common people, have shown great interest in being involved in all the production processes of the product, in various levels, and they are naturally willing to adopt open-architecture products. As reflected from the results, there is a noticeable section in the population who prefer to consume mass-produced standard products without being involved in any of the production processes, but in context of the essence of the preface chapter (pp.5-14), basically our ancient ancestors started their first step as DIYers, and maybe, this genetic tendency, is the fossil fuel that needs to be cut off so that the personal 3D printing market will start to move toward the potential users.

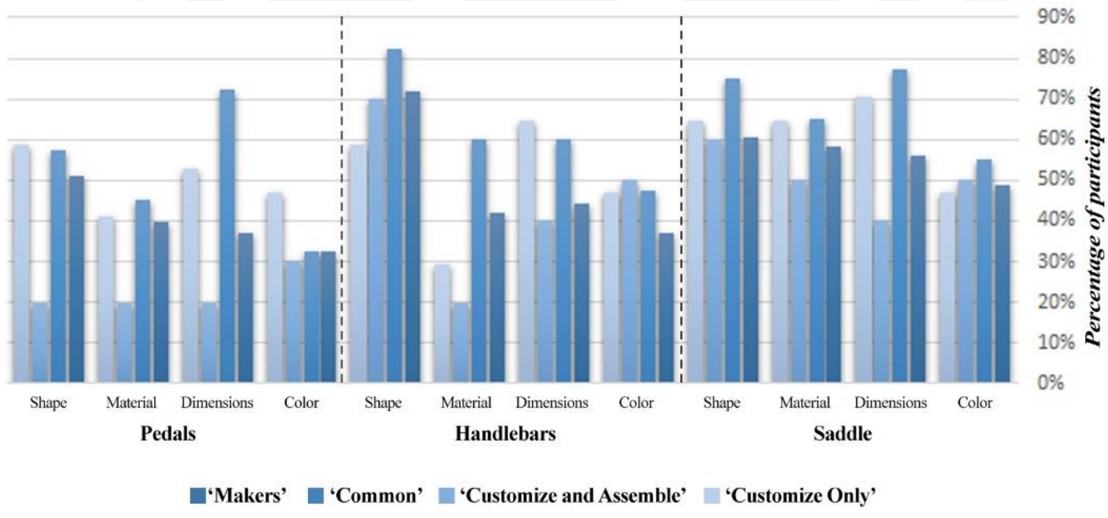



**Figure 3.5.2A – User Adjustment Components – Type of 3DP**

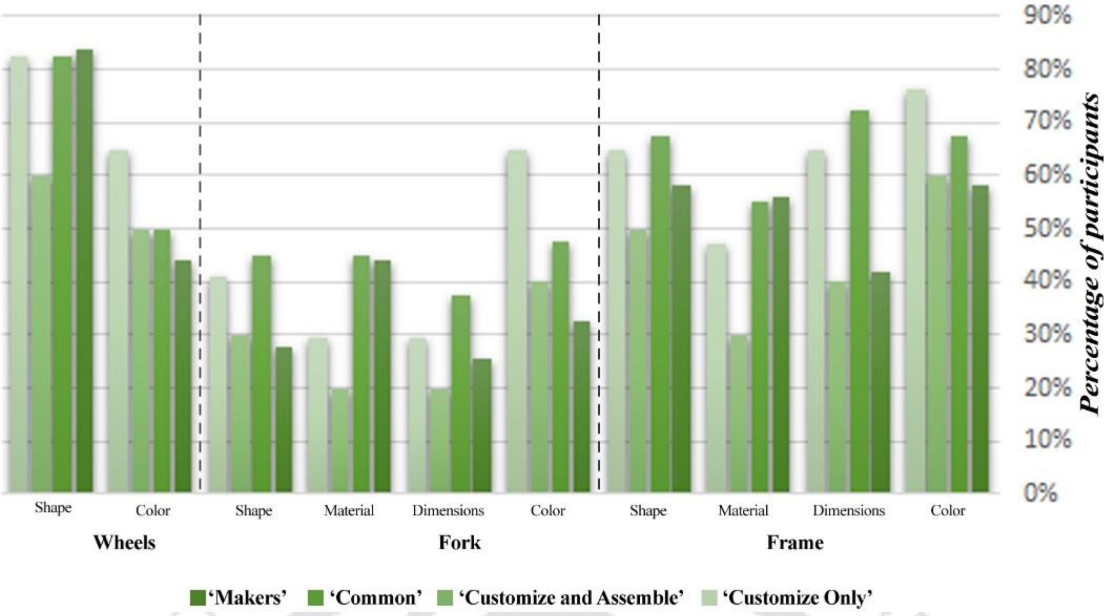



**Figure 3.5.2B – Basic Functional Components – Type of 3DP**

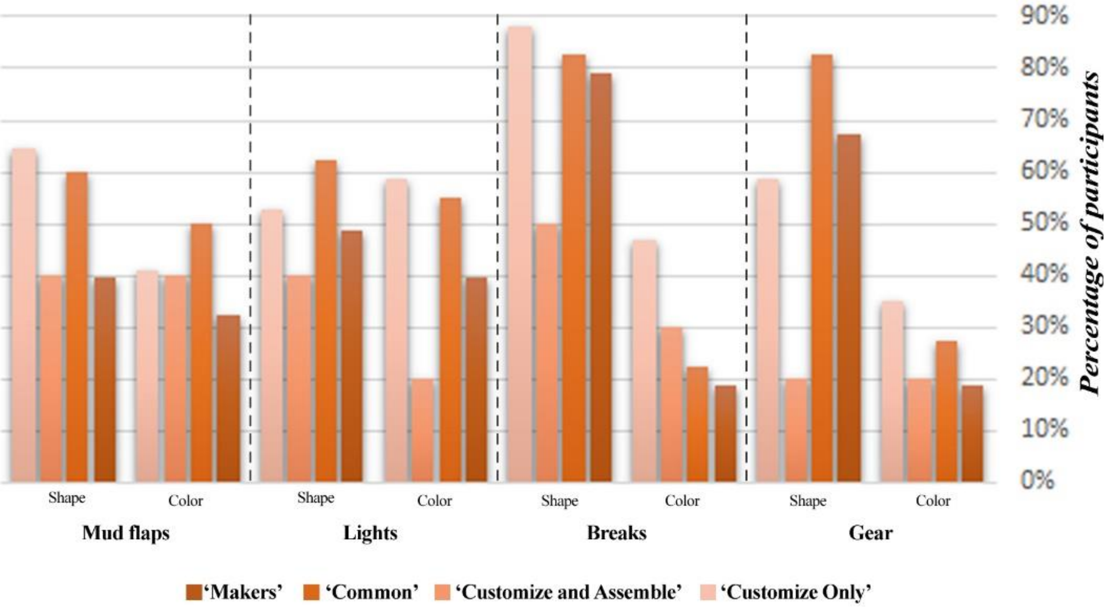



**Figure 3.5.2C – Mechanisms & Enhancers – Type of 3DP**

Examination of which MCP factors the relevant participants chose to customize according to their age range (Figures 3.5.2D, 3.5.2E, 3.5.2F), shows that in **84%** the age range 30-50 was the most prominent age range which showed willingness to customize the bicycle **(40-50 ≈57%, 30-40 ≈27%)**. This statistic is consistent with the first insight of the conclusions from the analysis of the previous examination (at which level the participants chose to customize the bicycle, according to the desired level of involvement in the production of it), i.e., since that relatively, there is higher incidence of 'Makers' and 'C&A' participants at the 15-30 age range with comparison to the 30-50 age range, the willingness to customize the bicycle at the 15-30 age range decreases.

In both examinations, the participants paid a lot of attention to the dimension factor, which relates to the 'Customization' factor, and which enable them to customize the relevant component according to their physical dimensions. This attention indicated that along with the functional shape, the physical customization comes first, and then the material and then the color. This order presents discrepancy to the second sub-hypothesis of the second hypothesis of the questionnaire **(QH2.2.)**, which assumed that the participants will tend to act on the basis of the conditions of the interaction with mass-produced products, i.e. will tend to focus on the 'Customization' and the 'Personalization' factors.

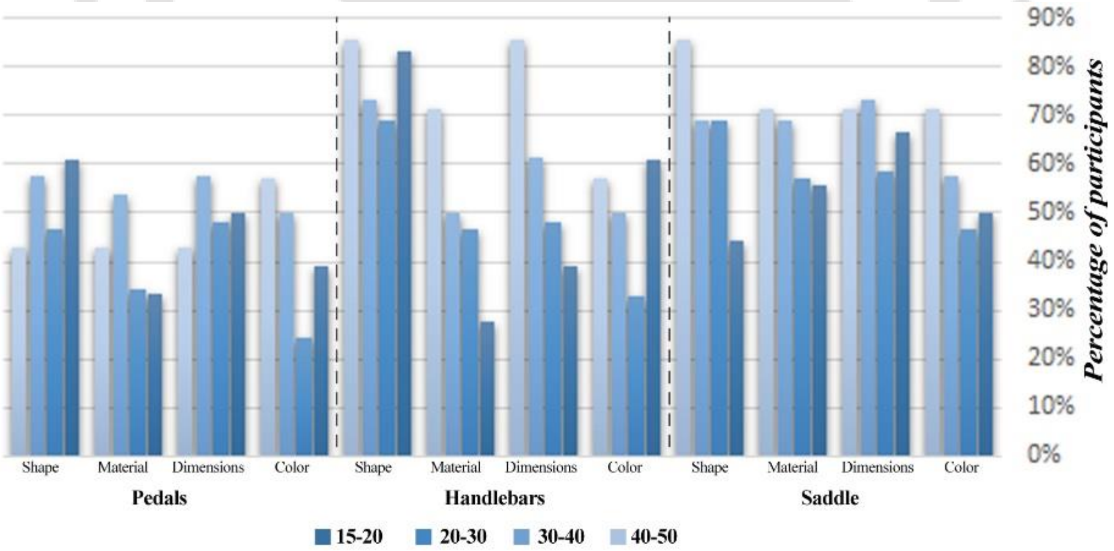



**Figure 3.5.2D - User Adjustment Components – Age range**

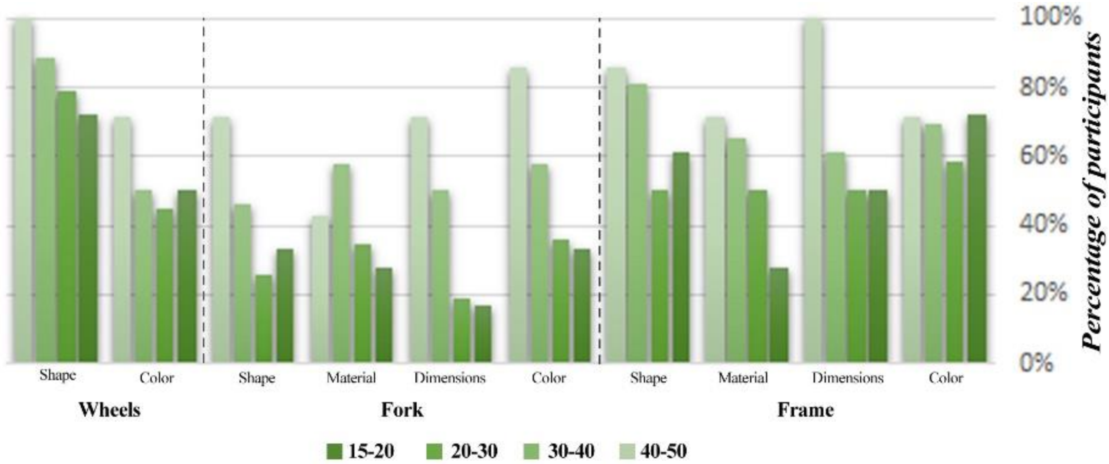



**Figure 3.5.2E - Basic Functional Components – Age range**

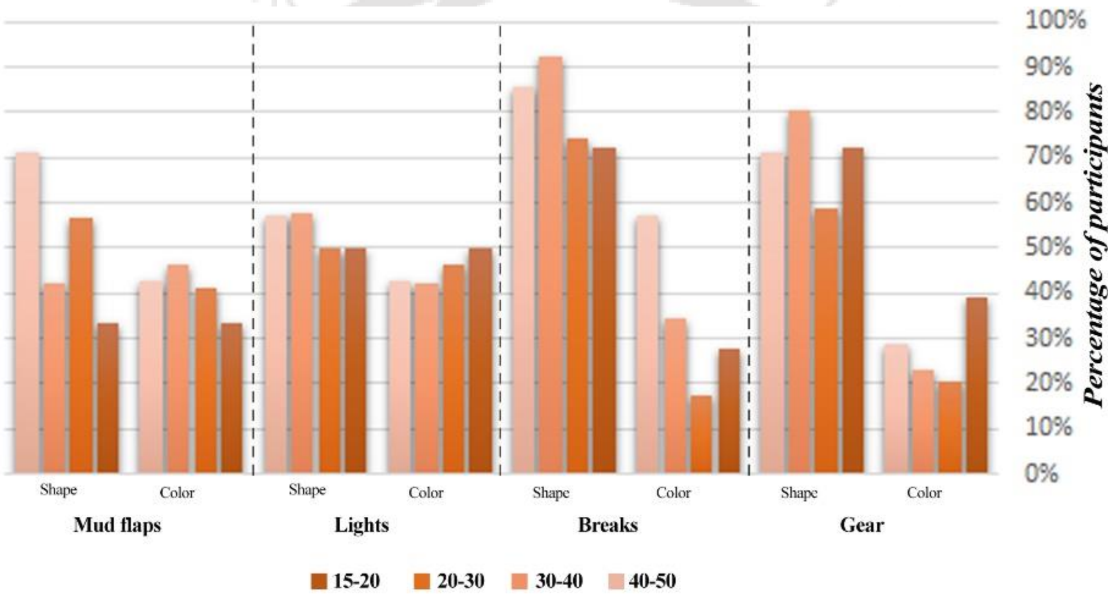



**Figure 3.5.2F - Mechanisms & Enhancers – Age range**

### *3.5.3. Analysis of the results of the 'Forth page'*

Initial general examination of the results according to the type of the 3DP that the participants have chosen (Figure 3.5.3A) shows that most of the 'Makers' (≈38%) perceive 3DPs as inkjet printer, i.e. simply as an automatic mean of manufacturing that the only expectation from it, is to deliver a required output. Most of the 'None' participants (≈48%) perceive 3DPs as inkjet as well, purely as an automatic mean of manufacturing, similarly as 'Makers' perceive 3DPs, with one big difference: at this point, they do not see themselves as owners of a 3DP, due to unexamined reasons. Regarding to the rest of the results of the 'Makers', 33% perceive 3DPs as a smartphone, i.e. as something that they do not really know how it works, but they are willing to adopt, and to integrate it in their lives, and 29% of them perceive 3DPs as a digital camera, i.e. as a hobby tool that you voluntarily spend time and money on it, and you really feel dedicated to it, out of your own free will. In general, I should note that there is no unequivocal statistical significance on how 'Makers' participants perceive 3DPs, and unfortunately, it is not possible to rely on the high resolutions analyses in order to try to find characterizations' criteria to each perception, due to convergence of too less participants at the high resolution sub-categories.

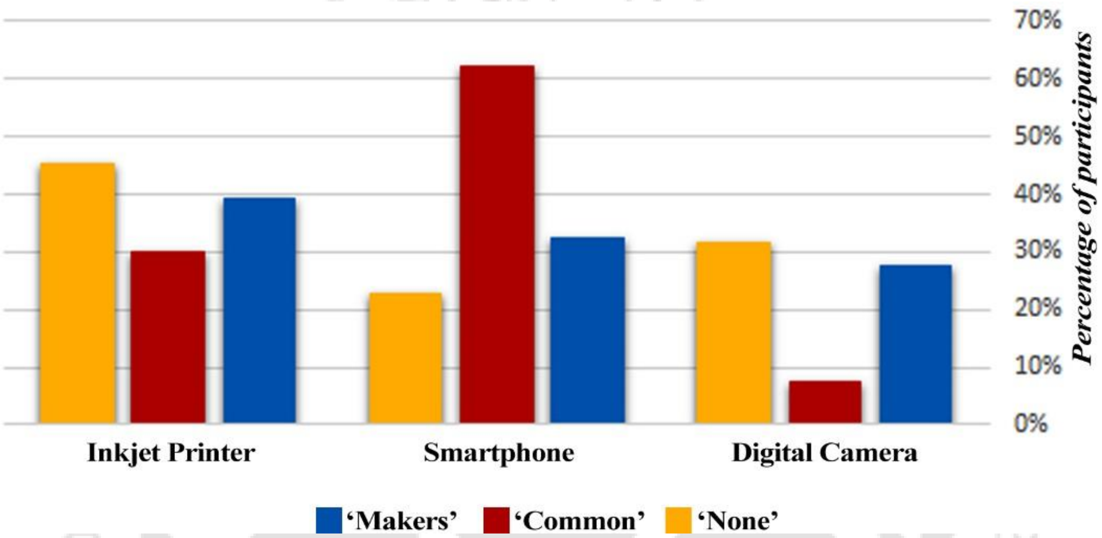



**Figure 3.5.3A – How the participants perceive 3DP per the type of 3DP.**

Regarding the rest of the results of the 'None' participants, there is more statistical significance relatively to the 'Makers', and as can be seen, 31% perceive 3DPs as a digital camera, and 21% perceive 3DPs as a smartphone. The fact that 31% perceive 3DPs as digital camera, can suggest that some of the participants perceive 3DPs as money and time consumer, hence the affordability aspect, is the factor which could positively divert their thoughts regarding to the possibility to own 3DP.

Regarding the way of how the 'Common' participants perceive 3DPs, as can be seen, ≈63% perceive 3DPs as a smartphone, 30% as an inkjet printer, and ≈7% as a digital camera. This statistical significance points that the 'Common' participants, who are the most relevant potential customers, as for their selection is the most aligned with the type of 3DPs that the 3D printing industry is trying to market for home environment, are more than willing to adopt the technology, and integrate it in their lives. Thus, as suggested and deduced out from the previous analyses, the gap that exists in the market, most likely, is not derived from fundamental reluctance of the potential users, but rather from design problems, and / or marketing failures (accessibility, affordability and persuading aspects).

Examination of how the participants perceive 3DPs per age range (Figure 3.5.3B), without taking in consideration the 50-70 age range (3 participants), shows similar perceptional trend at the 15-40 age range, regarding to the percentage of the participants that perceive 3DPs as a digital camera, or as an inkjet printer. As can be seen, as the age range increases, the perception of the 3DPs as a digital camera simultaneously moderately increases, similarly as the perception as an inkjet printer, but with more significance. With reference to the same age range, the perception of the 3DPs as a smartphone presents opposite trend. As the age range increases, the percentage of participants that perceive 3DPs as a smartphone decreases. These opposite trends could be interpreted as differentiations in life's priorities. Since as we grow up, our attention diverts gradually from purely inner-self issues, to family and career issues, the interpretation could be accordingly, i.e. as the age range increases, the participants change their technological perception, and tend to perceive 3DPs simply as automatic means of manufacturing that should do what it is meant to do, and less as intensively integrated in-life product, such as the smartphone.

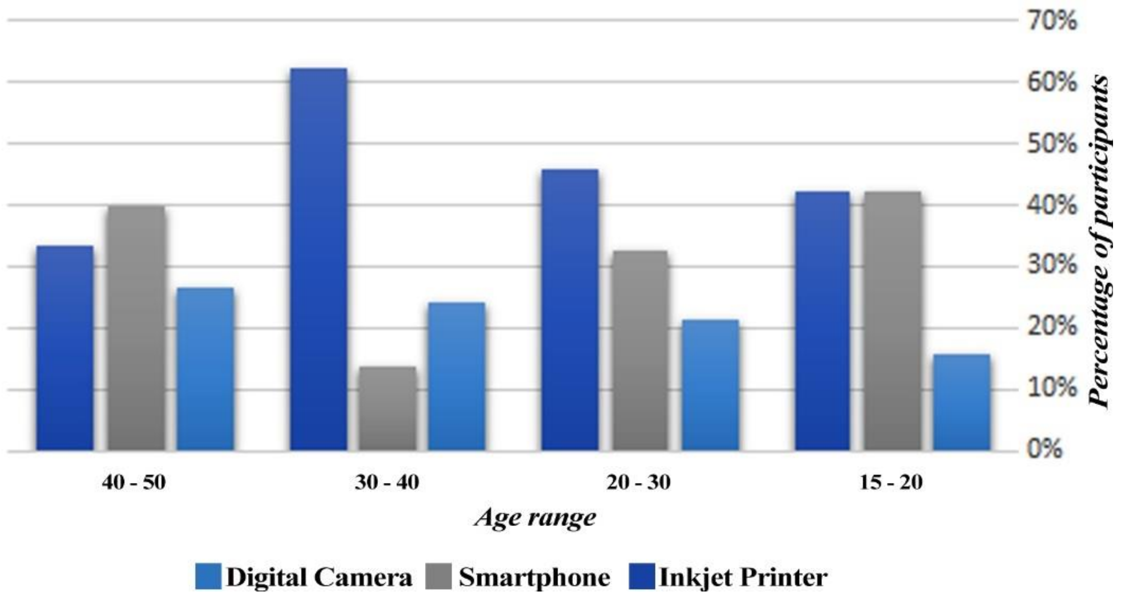



**Figure 3.5.3B – How the participants perceive 3DP per age range.**

With reference to the 40-50 age range, there is no unequivocal statistical significance regarding to how this group perceive 3DPs, but in wider context, the consistency of the perceptional trend of the 3DPs as a digital camera, continues, while there is a trend change regarding to the perception of the 3DPs as an inkjet printer, and as a smartphone. This trend change could be interpreted out of the same mentioned life's circumstances, and it could suggest that at this age range, as representative of a period when the chicks leave the nest, tend to expect more from the technology (same as 15-20 age range participants, with less significance).

Secondary general examination of how much the participants are willing to pay for 3DP, per the type of the 3DP that they have chosen (Figure 3.5.3C), shows that the clear majority of the participants, of all types, are willing to pay up to 400 USD, or thinks that it should not cost more than this amount. Comparison of this statistic with the price tags of common desktop personal 3DPs, which are being offered for sale on the web, indicates that there is clear gap between the amount that the common people are willing to pay, to the price of the common desktop personal 3DPs. [9]While few Mini 3DPs and DIY kits of small size desktop 3DPs were found for sale on the web with price tags of ≈200 USD, most of the branded familiar 3DPs were offered for sale with price tags of ≈500 USD and more, and the few who considered as the best 3DPs, with much higher price tags.

Examination of the results of each sub-group, shows that the willingness to pay of the 'Common' participants is aligned with the price tags of few of the cheapest offered for sale 3DPs, and there is a big question mark, why this potential is not being fulfilled. In the case of the 'Makers' sub-group, there is a wide chasm between their willingness to pay and the price tags of the large size 3DPs (without taking in consideration industrial 3DPs). Since relatively large size desktop personal 3DPs are being offered for sale with price tags of 2,500 USD and much more, marketers and producers should find creative ways to solve this dissonance, which is much more challenging, in comparison to the 'Common' participants'' case. Similarly, to the 'Common' participants' case, the 'None' participants were found as aligned with few of the price tags of the cheapest 3DPs as well, and therefore there could be a need to examine hidden potential users' sub-groups

[9] Quick search of 3D printers on Amazon, eBay, and Aliexpress.

that selected the 'None' option maybe because they thought that a 3DP is beyond their affordability.

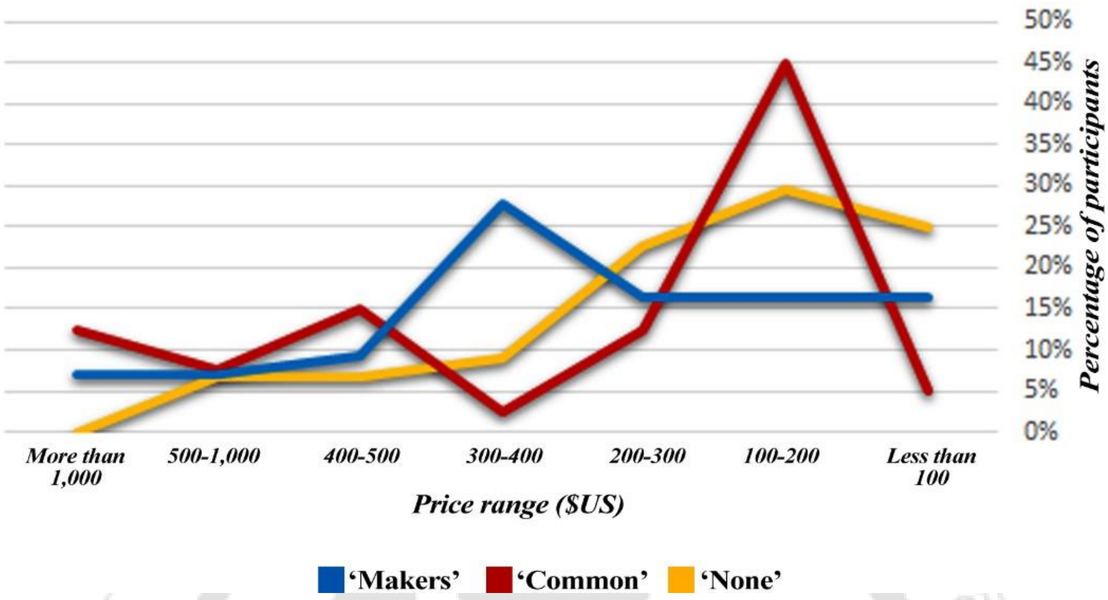



**Figure 3.5.3C – How much the participants are willing to pay per type of 3DP.**

Examination of how much the participants are willing to pay / thinks 3DP should cost per age range (Figure 3.5.3D), shows similar trend like the previous examination. While most of the participants are willing to pay an amount at the less than a 100 USD to 400 USD price range, each age range's sub-group, presents different distribution. Most of the 15-20 age range sub-group presents willingness to pay somewhere between 100-200 USD (47%). 21% are willing to pay 300-400 USD and as for the rest of the price ranges, there is an average of 6% of the participants who are willing to pay the remaining face values. This way of distribution represents two interesting primary and secondary peaks. The primary 100-200 USD price range which represents a first point of willingness, in which they perceive as an amount that they are willing to pay for a reasonable 3DP, and the secondary 300-400 USD price range, which could be interpreted as the price of the best 3DP that they can afford themselves (or this is the maximum price that they think that their parents would invest). The 20-30 age range participants present a slightly different trend. 77% (less than a 100=21%, 100-200=34%, and 200-300=21%) of the participants from that sub-group are willing to pay somewhere between under 100 to the 200-300 price ranges, while there is an average of 6% of the participants who are willing to pay the remaining face values. In this case, there is one primary peak (100-200), and two equal secondary peaks (less than a 100, and 200-300). This way of distribution could suggest that since this age range, most likely pays himself for his purchasing, so the first secondary peak could represent a wishful thinking price tag, the first primary peak could represent the realistic price, and the second secondary peak could represent the maximum price. Interesting to see how financial independency in its early steps, narrows the price range of the willingness to pay.

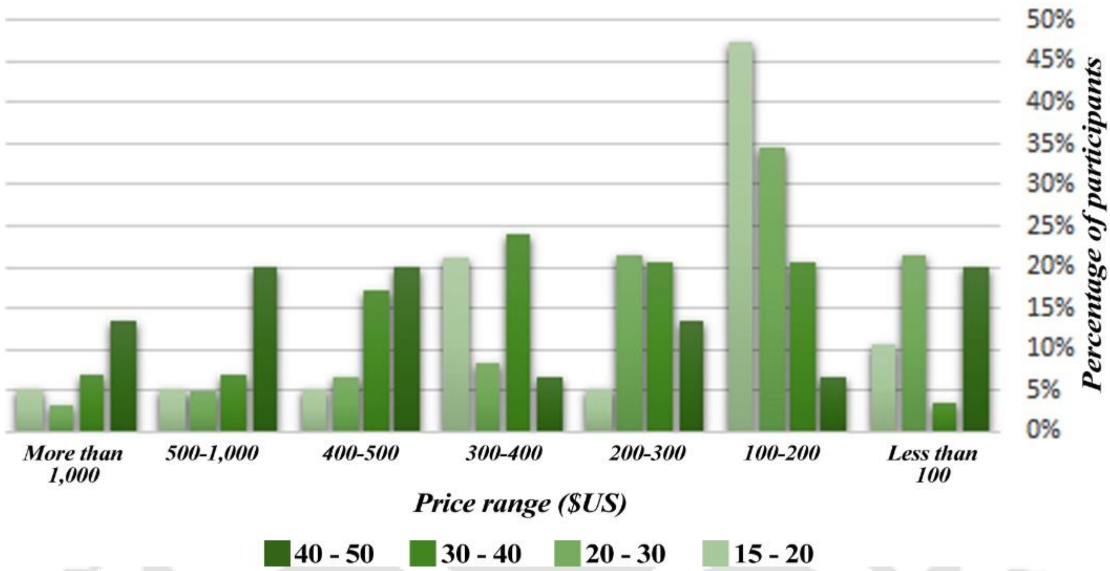



**Figure 3.5.3D – How much the participants are willing to pay per age range.**

The 30-40 and the 40-50 age ranges participants present a different trend of willingness to pay, relatively to the other participants, and to each other. Out of the 30-40 age range participants 84% presented willingness to pay an amount of somewhere between the 100-500 USD price ranges (100-200=21%, 200-300=21%, 300-400=24%, and 400-500=17%), with no statistical significance of any of the sub-price ranges. With more financial stability and availability of money, the 30-40 age range participants present wider and higher spectrum, in comparison to the younger age ranges, and it seems like that these age range participants, are the most aligned with the market participants, in context of the willingness to pay and the price tags of the commonly offered for sale 3DPs. The 40-50 age range participants present completely different trend of willingness to pay, in comparison to the other participants. While the results of the other participants converge into mid-price range (wider or narrower), the results of the 40-50 age range participants converge primarily at the edges. 20% are willing to pay less than a 100, 53% over 400 USD, and an average of 9% for each one of the remaining price ranges. According to these results, the suggested interpretation is that the lowest price range represents a bargain price (according to their perception), the mid-price ranges (100-200, 200-300, and 300-400) represent price range of inferior 3DPs, and the highest price range represents the expectation to get the best value for money 3DP.

General conclusion that derives from this analysis, is that the younger the age range, the price range of the willingness to pay becomes narrower and lower, probably as reflection of the socio-economic status in life. No doubt that the affordability aspect is being perceived differently among different age ranges, and marketers should notice it and act accordingly. As mentioned at the introduction chapter (p.19), affordability and accessibility are the factors that enable democratization in any field, and in context of this axiom, the accessibility factor was not examined, but the affordability factor got a complicated but clear representation, from the participants' perspective.

Examination of the general perception, according to the general perception diagram as constructed and presented at the theoretical basis sub-chapter of the questionnaire (p.116), presents in general the perception differences among the types of the participants (Figure 3.5.3E). Few adjustments and details were inserted into each diagram, according to the details that were presented at the questionnaire. The left edge was divided into 3 sub-levels: 'Amateur' (represents participants that chose the 'Inkjet Printer' option), 'Semi-Pro' (represents participants that chose the 'Smartphone' option'), and 'Pro' (represents participants that chose the 'Digital Camera' option). The right edge was divided into 7 sub-price ranges, so that each sub-level represents the average amount of the relevant price range, while for the 'Less than 100' option the value 50 was inserted, and for the 'More than 1,000' option the value 1,500 was inserted (as an average amount of relatively expensive desktop personal 3DPs).

Editing these diagrams revealed a problem in the sub-group of those who checked the 'Common' type of 3DP option along with the 'Digital Camera' option ('Pro'-'Common'). Due to convergence of too fewer participants in this sub-group (3), even though it is present, it was not taken in consideration in the analysis.

By examining each row in the presented diagrams matrix, an indication of how each sub-group (type of 3DP) perceive 3DPs is given. Interesting minor differences that can be observed, lawfully reflects the gap that exists between the market to the potential users, as a whole. The 'Makers' participants present steady trend of willingness to pay (average of 375 USD), which is significantly far-off the price tags of the relatively big size 3DPs. As certain potential users (since they checked the 'Makers' option), they clearly represent the fact that the affordability factor, is the factor that mostly cause this gap. Their expectation to own a big size 3DP, in face of the price tag that they are willing to pay, is detached from reality at the moment. The 'Common' participants (without taking in consideration the 'Pro'-'Common' participants) present much more realistic perception. According to their results, they represent a segment in the population, which is ready to adopt the technology, as there are no gaps between their expectations from their 3DP to the real-life price tags. Hence, there is a big question mark, as mentioned previously in few of the interim conclusions, why this gap, between the market and this segment, exists.

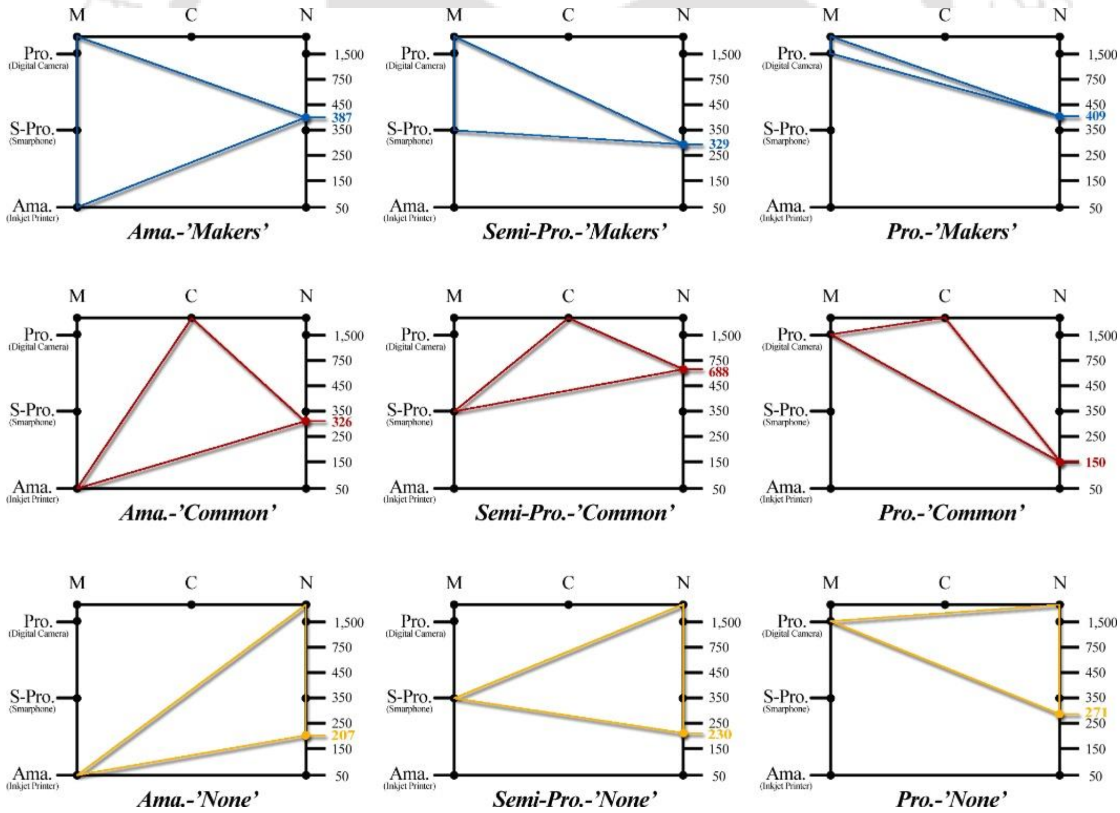



**Figure 3.5.3E – Diagrams matrix of how the participants generally perceive 3DPs.**

The 'None' option participants, as observers, present logical perception trend. As the perception of the level of the professionalism of the users rises higher, the willingness to pay rises accordingly. Similarly to the 'Makers' participants, there are no significant differences among the willingness to pay, and the trend remains steady (with average of 236 USD). These results reflect matching to cheap mini-3DPs price tags, and even though that this segment of participants chose not to own 3DP, there is a probability that the customizers (those who checked the 'C&A', and the C/O options) could find interest in 3DPs, since the affordability factor is not the factor that prevents them from owning a 3DP.

### *3.5.4. Conclusions*

Initially I would note that the questionnaire strongly reflected the 'voice' of the common people, in context of the questions that were asked, and of the segment that the participants have represented. Yet, in light of the research's objectives (p. 24), and in order to obtain a comprehensive understanding of the 3D printed products market, I have noticed that additional examination, from the market perceptive as an abstract holistic factor with all its involved variables, was needed.

As for the conclusions from the questionnaire, first technical conclusion that arose, is that due to convergence of too few participants in the high-resolution analyses cases, the number of the participants should be doubled, in favor of the reliance on the results in these cases, under scientific connotation.

Secondly, non-technical conclusion that was reflected from the distribution of the gender of the participants, is that the female participants feel much less associated with the 3D printing field (as for the number of the female participants was significantly low, relatively to the male participants, and it was really hard to recruit them), and the marketers should find creative ways to engage this technology to this segment of the population. 41% of the females' segment showed willingness to adopt the technology, a statistic that should not be ignored. Even though that this issue is not carrying the responsibility for the gap, solely, it is certainly part of it.

Thirdly, a wide range conclusion that refers to the potential users, shows that according the $\mathbf{GQ_1}$. (type of 3DP), 65% of the participants showed willingness to own a 3DP. A remarkable statistic that should be taken into consideration in the context of the questionnaire. Meaning that, since the questionnaire referred to non-professional cyclists, and offered them bicycle, the participants could have found more easily, initial interest and rationale to own 3DP (unlike the way personal desktop 3DPs are being marketed nowadays, i.e. marketers do not link any specific rationale that could encourage people to own 3DPs). Deeper examination, as presented in the analyses of the forth page, shows that realistically only the 'Common' participants present readiness to adopt the technology, hence the more realistic percentage of potential users reduces to ≈30%, which is a significant statistic. In an interview that was conducted with [10]Mr. Boris Belocon, Boris mentioned that the 3D printing companies are finding difficulties to expand the personal desktop 3DPs market, and they are relying on Wohlers' forecasts that predict enormous growth in this market, in the years to come. This statement, which reflects reliance on the potential users so that they will find the reason to own desktop personal 3DP, generally clashes with the results of the questionnaire, and passes the ball back to the field of the industry.

Last Additional conclusion, shows that ≈87% of the participants (regardless to the type of 3DP), have presented willingness to customize the bicycle, in different levels. Since 3DPTs are the most suitable and sophisticated technologies that enable to produce on-demand open architecture products, this statistic should encourage industrialists to accelerate the development of 3DPs as an AMT, in parallel to the development of the personal desktop 3DPs.

[10] Innovative Solutions Manager at 'Stratasys', Israel.

## CHAPTER 4

# THE NEW 3D PRINTED PRODUCTS MARKET

## 4.1. General Introduction

In order to accomplish the second, the third, and the fourth research objectives, i.e. to identify the key factors in the value chain of the personal 3DP (P3DP) market, and to define types of products and users in this market, I have conducted a deep examination and comprehensive review of the current situation. As general background, almost 30 years after the invention of the first 3DP (1984), at around 2010 startup companies e.g. 'MakerBot', and 'formlabs' have started to market desktop FFF and SLA personal 3DPs. Intentionally, or unintentionally their developments turned to be the starting point of the new P3DP market, same as Apple's first Macintosh that was presented by Steve Jobs at 1984, represents the starting point of the creation of the personal computers (PC) market.

Computers, in general, considered to be as the initiators of the digital revolution, and the invention of the PC along with the Internet, have intensified this revolution and changed dramatically many of the society's ways of life. It is almost obvious nowadays that people can do banking transactions from their home, or listen to endless variety of musical pieces, order vacation, virtually socialize, etc. in the same manner. Aside from the changes that occurred at the consumers-businesses interaction, and from the impact of the PCs and the Internet on industries, and markets, the accessibility of such a sophisticated mean to the common people, have led also to an intensification of the DIY spirit, in what became to be known as the 'Independent' (Indie) industry. As mentioned at the 'Research Rationale' chapter (p.19), musicians for instance, can record, edit, finalize, and distribute their musical creations by using their PC, relevant supplementary means (e.g. microphones, mixers, etc.), and the Internet, without any dependency on intermediaries. In this way, they gain genuine popularity (or not), and unlike times before the invention of the PC and the Internet, record labels are tracing after successful artist through the web in order to sign them, instead of reality in which musicians were knocking on the record labels doors, bagging just to be listened. Worth mentioning that the flourishing of the Indie industry has changed the rules in some ways, but did not eliminate the traditional industry, which changed the focus from selling albums, to other profitable roots, e.g. live shows productions, professional albums recording, etc.

One of the first accompanying products that was integrated and instructed by the desktop computer was the desktop printer, and just like in the music industry, the presence of digital printer in home environment, did not eliminate the printing industry, but rather opened new options for the home users. In an experts' panel that was conducted at Rochester Institute of Technology and was discussing about trends in the printing industry, two major changes that happened in the printing industry were mentioned (Romani, 2004):

1. Desktop publishing: the move from typewritten (monospaced) printout to typographic (proportional) printout
2. Personalization: the use of specific information to generate printed products, as well as the personal empowerment provided by personal computers and personal printers.

Both changes were a consequence of the invention of the PC and the desktop printer, and they deeply influenced the design and the manufacturing process, and the workflow in between. They shortened the time and expanded the options from the industry perspective, and as initial step from the common people perspective, text and documents printing became accessible.

A table that was presented in the mentioned colloquium that was discussing the printing industry (Romani, 2004) shows that the distribution of the printers' uses, (holds relevancy for 2004 - 20 years after the launching of the personal desktop printer) was as such: 76.0% of the printers (not only desktop types) were held by factories and designated shops; 19.0% were held by offices; 3.5% by home users; 1.5% described as "Other". The table was divided to three sub-categories that represent the main purpose of the printers: copier, printer, and press. The press category holds 71.0% of printers in the market, and the copier and the printer categories hold the remaining 29.0%. Out of the remaining 29.0%, 13.5% of the usage was made by small size printers, which means that the use in desktop size printers holds 46.5% of all non-press jobs. By normalizing the 3.5% of the usage by home users, relative to the 13.5% of the usage by desktop printers shows that the home users hold almost 26.0% of the usage. This distribution analysis cannot predict whether the 3DP market will act the same, but because both the digital printer and the 3DP function as a mean of manufacturing, and because the digital printer launched significantly earlier, it is possible to follow the steps that need to be taken in order to successfully integrate similar manufacturing mean in home environment.

## 4.2. The New Independent (Indie) Market

In context of the products market, one of the consequences of the industrial revolution was the shift of the dominancy from the craftsmen to the factories. The motor as the invention that initiated the industrial revolution, and the motorized machines, enabled production of parts in high volumes and in lower costs per unit, which lead to the birth of the mass production system. The necessity to sell many products to many consumers increased the level of democracy in the products market, i.e. the development of the marketing and distribution industries increased the accessibility aspect, and the supply of a variety of cheap products increased the level of the affordability factor.

Engines (like computers) were minimized over the years, and have begun to be embedded in various devices, including designed for home environments devices. Machining devices could be included as part of these devices (such as drills, saws, etc.), tools which have contributed significantly to the flourishing of the DIY movement. Now, for the first time, a manufacturing mean of 3D products, which is the home use 3DP, will enable the expansion of the manufacturing process in the user's home environment. This expansion will not eliminate the factories, same as factories did not eliminate craftsmen, but it will increase the level of democracy in the products market by increasing the accessibility aspect and by reducing the costs of certain types of products, hence increasing the affordability aspect. "In an industrial economy, goods are produced in the physical space of the manufacturer. From there they are distributed, often through intermediaries, into the hands of the consumers. In the new economy, the end of the manufacturing chain of goods and services increasingly will be produced by customers, in their own physical space" (Davis, 1987). Even though Davis's statement predicted the partial shift of the market from the public physical space to the user's private physical space, it did not predict the possibility of such a manufacturing mean as the 3DP to be in the hands of the users. From the industry perspective, levels of MC, like "Tailored Customization" and "Pure Customization" (Lampel & Mintzberg, 1996) will become more feasible for every user in a personal 3DP reality, and thus the level of competitive advantage factor will expand. From the perspective of both the users and the designers, the level of the user's involvement in the final design can be more significant, and thus it will increase the value of the product for each user.

### *4.2.1. The General Indie Process*

Back to the music field, the essence of the Indie phenomena is the ability to enable musicians to compose and produce independently musical pieces, distribute them through designated websites, or social networks, and then wait for feedbacks in order to calculate their next steps. From the other side, the consumers are getting exposed to the musical pieces through the same websites, and then giving positive, or negative feedbacks, or remains indifferent. Positive feedbacks, usually means ranking, doing "like", or sharing the musical pieces, actions that create additional distribution by satisfied customers. Not many years ago, the only effective process that ruled was the production process under record labels responsibility. At the beginning of the process, record labels were intervening in artistic considerations, for the compositions to be more "commercial", then they were mass-producing the products that included the CD and the package, distributing it through intermediaries to music shops, and then were hoping that the stock will be sold, while spending money on promotions and marketing. A graphic simplification of the levels of the value chain that links any virtual Indie product to a customer that consumes products by using PC and Internet (Figure 4.2.1A), according to the described processes, presents a dramatic elimination and / or reduction of the significance of certain levels, with comparison to the conventional processes, e.g. packaging, marketing, physical distribution, ordering, and other additional services (partially adopted from Da Silveira et.al., 2001).

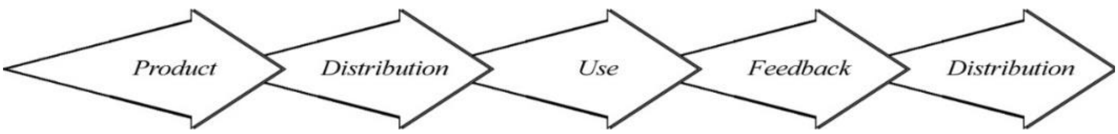



**Figure 4.2.1A - A simplification of the value chain that links a product to a customer in an "Indie" market.**

An Examination, and a comparison among 3 "Indie" industries: music, graphic design and the newborn 3D printed products Indie industry (Table 4.2.1.1), shows a real similarity in the process that makes products more accessible to customers. As can be seen, the obvious differences are in the tools that are being used by the designer / artist as complementary means for the final production of the product, and by the complementary means that enable the product to be tangible for the user. There are other "Indie" industries that are surfing on the digital revolution waves such as the creative writing, cinematography, teaching, and more, and each one behaves generally the same, i.e. according to the process that was presented in Figure 4.2.1A.

**Table 4.2.1.1 – Comparison among 'Indie' music, graphics and 3D printed products production processes.**

| | | ***Music*** | ***Graphics*** | ***Products*** |
|---|---|---|---|---|
| ***Designer / Artist*** | ***Production means*** | Software | Software | Software |
| | ***Complementary means*** | Microphone, Speakers, Headphones, Mixers, etc. | 2D Digital Printer | 3D Printer |
| | ***Marketer / Distributor*** | Designated websites, Social networks | Designated websites, Social networks | Designated websites, Social networks |
| ***User*** | ***Consumption means*** | Computer + Internet | Computer + Internet | Computer + Internet |
| | ***Complementary means*** | Speakers, Earphones, etc. | 2D Digital Printer | 3D Printer |
| | ***Marketer / Distributor*** | Play, Cyberspace: Share, Like, Rate, Comment, etc. | 2D Printing, Cyberspace: Share, Like, Rate, Comment, etc. | 3D Printing, Cyberspace: Share, Like, Rate, Comment, etc. |

Regarding the 3D printed products Indie market, close examination of the process (Figure 4.2.1B), shows that there are two related critical points, and one important endpoint that represents the end of the controllable process. The first critical point refers to the design process, which is the unmentioned basis of the process, and the second critical point is the period when the user manufactures the product by using a 3DP, and assemble it. The next secondary sub-chapter will present examinations of the design process, and the methodology that will be presented in the final chapter should provide tools for success creation at the second critical point.

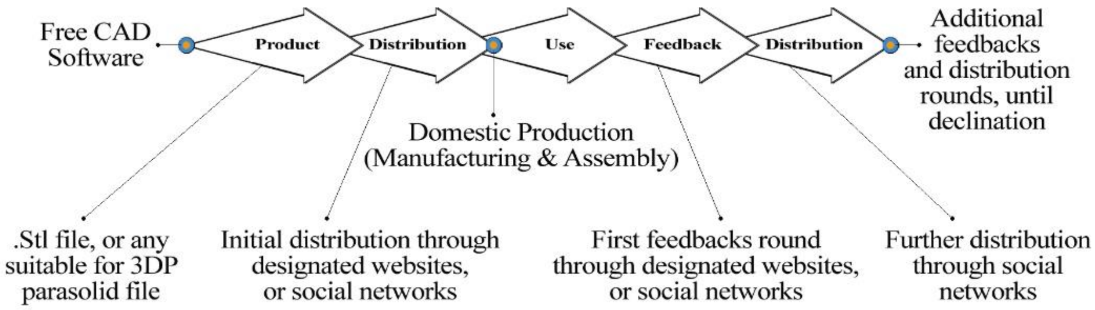



**Figure 4.2.1B - A simplification of the value chain that links a 3D printed product to a customer in an "Indie" market.**

*4.2.2. The Indie Product Design Process*

Nowadays, there are varied ready to use software for non-professional users, such as typography, illustration, packaging, architecture, graphics, editing, animation, and so on. CAD software for product design can be classified to two main categories: Professional and non-professional CAD software. Most of the non-professional software are share-ware (free of charge) and can be found widely on the Internet. The fields of graphic design and word processing offer enormous amount of free software for different purposes, e.g. free writing, documenting, presentation, free graphic design, data analysis, questionnaires, etc. Each software provides the relevant tools and **enables to accomplish the design and the manufacturing workflow in a unified stream.** A simplification of the product design process as presented by Pahl et.al. is representing the steps that need to be made in order to get from the ideation phase to the actual design phase (Figure 4.2.2A). Despite the fact that this process is conceptually similar for professional and non-professional designers, there are lots of differences in the way it is being implemented. While in the first 2 links (the definition of the task and the specifications) the professional designer is relying on knowledge and experience, the non-professional designer is crossing those stages intuitively without awareness to any design methodologies.

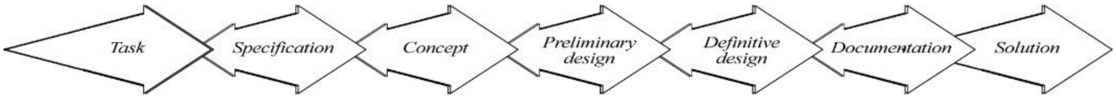



**Figure 4.2.2A - A simplification of the product design process.**

The process that leads to the formulation of the concept and the preliminary design, is usually where the CAD software is required for the first time. In the popular text processing and graphic design software, the developers succeeded to generate fluent workflow by enabling the following parameters: creation tools, editing tools of a new creation, or of a readymade creation, failure prevention and evaluation features, technical support and tutorials, generation of a suitable file for digital printer and direct connection to the printer. Those parameters were conceptually converted to 3D CAD software, and 5 product design oriented free software for non-professional users were compared **(3D Builder – Microsoft, Tinkercad and 123D Design along with Meshmixer – Autodesk, 3D SLASH, FreeCAD)** according the converted parameters. A comparison table (Table 4.2.2.1) compares between the mentioned software according to the parameters that were converted as follow:

1. **Creation tools:** This parameter was split into two sub parameters: basic bosses and complicated bosses. The comparison examined whether each software provides basic tools only (primitive shapes and extruded bosses) and / or provides complicated tools (revolved, swept, lofted bosses and Boolean actions). This parameter is the initial step, and thus not influencing the workflow, but can give an impression of how the developers perceive the users.

2. **Editing tools:** This parameter was examined under two sub parameters as presented above: editing a new and/or readymade design. Both of the sub parameters classified under two sub categories: basics and advanced features. The basics features include scale, move and rotate options, and the advanced features include features like mirror, patterns, fillet, chamfer, shell, split and the basics.

3. **Failure prevention and evaluation features:** In order to get a qualitatively definite design, the professional designer / engineer is doing 3 important actions: 1. Applying fit tolerances between holes and shafts in a case of an assembled product; 2. Adjusting the design to the manufacturing technology; 3. Evaluating the design in order to prevent engineering failures by using finite elements analysis add-ons or designated software, and by producing and testing prototypes. Since applying fit tolerances in a design requires professional knowledge, it was not taken into consideration while examining and comparing the software. The adjustment of the design action was not taken into consideration as well because it requires professional understanding and there is only one manufacturing technology involved in this case (3DP). The third action was the only one to be compared, and the parameter of the prevention of engineering failures relates to it.

4. **Technical support and Tutorials:** This parameter was examining whether there is an integrated feature that provides technical support and tutorials.

5. **Generate suitable file for 3DP:** This parameter was examining the possibility to generate a standard suitable file (. stl) for 3DP.

6. **Connection to the 3DP:** Like the Ctrl+P keyboard shortcut, this parameter was examining the directness of the shift from the CAD software to the 3DP.

**Table 4.2.2.1 -** Comparison between 5 free 3D CAD software.

| | **Basic bosses** | **Complicated bosses** | **Editing Features** | **Modify readymade design** | **Preventing engineering failure feature** | **Tutorials** | **Generate suitable file for 3DP** | **Connection to 3DP** |
|---|---|---|---|---|---|---|---|---|
| **3D Builder** | + | - | Basics | + | - | - | + | Indirect |
| **Tinkercad** | + | + | Basics | + | - | + | + | Indirect |
| **123D Design** | + | + | Advanced | + | + (Mesh-mixer) | + | + | Indirect |
| **3D SLASH** | + | - | Basics | + | - | + | + | Indirect |
| **FreeCAD** | + | + | Advanced | + | - | + | + | Indirect |

The comparative analysis that was done shows that there is a lack of uniformity in the approach toward the users. While all the software provide basic tools for designing and editing a virtual model, part of the lack of uniformity is reflected in the possibility to generate complicated shapes and by editing the virtual model by using advanced tools. Even though this lack of uniformity can be explained by directing the software for different levels of users. Unlike word processing software, there are differences in the most basics actions that are being operated by using the mouse, like moving, zooming and rotating the virtual model. The option to import a readymade design is available in all the software, but modifying them is possible only according to the software's tools. Beside 3D Builder all the software have a built-in support feature including tutorials, but a highly critical feature that prevents engineering failures are missing in all the software.

A testing virtual model of a 50X50X50mm shelled cube with 0.01mm wall thickness was built, and all software did not alert that there might be a failure in the design. 123D Design directs to an external software (Meshmixer) which enables to analyze the design, but it is not done automatically. It should be noted that Meshmixer enables to design virtual models but it more of a free design oriented software such as for jewelry design, sculpted elements, etc. and less for product design. Therefore, it was not compared with the other software. The analyze tool was examined and it can be considered as very basic and semi reliable comparison to a professional finite analysis software.

As can be seen, all the software enable to produce a suitable file for 3DP. Despite that, the connection to the 3DP is indirect, and it creates a break in the design to manufacturing workflow. The main reason for the indirectness of the connection to the 3DP is the way in how desktop FFF 3DP are being operated. The vast majority of the desktop FFF 3DP are designed as an independent machine i.e. each machine has a suitable software (there are few generic ones) that converts the meshed geometry file to a G-code that instruct the 3DP how to operate. All the settings before the manufacturing processes are being made through the controller of the 3DP. In the vast majority of the FFF desktop 3DP a flash memory portable device is required in order to upload the G-code file that was copied from the PC, to the 3DP. Another reason is because the raw material in the vast majority of the desktop FFF 3DP is hanged freely aside (usually behind) the 3DP and the 3DP is not detecting it automatically, similarly like a desktop digital printer detects the ink cartridge and the paper. Based on the design to manufacturing fluent process of the desktop digital printers and the preproduction software that feed them, the indirectness of the connection to the 3DP can be pointed as the disruption point in the workflow.

The comparison that was made was testing the ability to design a single part. Since many products are assembled from more than one part, an assembly module could significantly contribute to understanding the design of an assembled product. Such a module is not a disruptive factor in the design to manufacturing workflow, and thus it was not examined as an influencing one (FreeCAD offers such a module).

In the interview that I was conducting at 'Stratasys', I mentioned the workflow issue and surprisingly, their representative showed no awareness to that. In few points at the analysis of the questionnaire, I mentioned the option that the gap that exists between the 3D printing market to the potential users, derives from design problem, and the examination that was presented, clearly reflects few of these problems, i.e. the current interaction is too complicated for the common people.

## 4.3. The General Market

Despite the flourishing of the "Indie" industries, it is still a green branch in the products market, where the mass production system is the main trunk. The main purpose of the 3DPT is mostly to produce prototypes during the product development process, but in recent years it was starting to be used as an additive manufacturing tool in the mass production system, or as a leading technology in tailor made industries e.g. the medical implants field. There are two main reasons why companies are using 3DPT as an additive manufacturing tool. First, to produce parts with geometry that cannot be reached by using traditional technologies, or relatively expensive to produce e.g. "Boeing" company that integrated housing for a compressor inlet temperature sensor that was manufactured by Direct Laser Metal Sintering (DLMS) printer in its jet engines. Second, more consumers oriented, and more aligned with the MC approaches.

As mentioned in the literature review chapter, the term MC that was coined by Davis in 1987 was defined as an ideal in which "the same number of customers can be reached as in mass markets of the industrial economy, and simultaneously treated individually as in the customized market of pre-industrial economies". Since that definition was stated, many scholars were trying to interpret and categorize this term, relying on the mass production system (Pine, 1993; Ross, 1996; Lampel & Mintzberg, 1996; Pine & Gilmore, 1999; Duray et al., 2000; Piller, 2000; Da Silveira et al., 2001; MacCarthy et al., 2003; Hu, 2013; Kull, 2015). Pine refers to the term MC, as an operation that gives advantage in a competitive market. "While the practitioners of Mass Production share the common goal of developing, producing, marketing, and delivering goods and services at price low enough that nearly everyone can afford them, practitioners of Mass Customization share the goal of developing, producing, marketing, and delivering affordable goods and services with enough variety and customization that nearly everyone find exactly what they want" (pine II, 1993). Because of the reason that mass production systems are relying mostly on molds, the most challenging thing is to flex the manufacturing system. Therefore, the most common customization act that is offered to customers is an offering of a variety of the same solution in different scales, colors and cosmetic graphics. A reality in which 3DP will be integrated in home environment and will be more significantly integrated in factories as an additive manufacturing tool, might overcome this challenge, and will enable to fulfill Davis's and Pine's ideals.

### *4.3.1. Market review*

In order to analyze the characterization of the 3D printed products market, a review of companies and businesses that integrate 3DPs in the manufacturing process, was conducted. The first company that was examined was the American jewelry studio: [11]**'Nervous System'** (n-e-r-v-o-u-s.com), which runs a website that offers a variety of on-demand jewelry designs. The studio presents few flexible / open architecture jewelries that enable the user / customer to be involved in the determination of the final design. A dynamic interactive platform enables customization according to the MCP

[11] Reviewed also as part of the 'Literature Review' chapter, 'Mass Customization' sub-chapter, Unstudied cases secondary sub-chapter, p.85).

factors, i.e.: 1. The design of the shape (under considered conditions); 2. Physical customization, according to the physical dimensions of the user; 3. Personal customization, according to the personal taste of the user (color and type of material). Once the customer places the order, the studio is 3D printing the required design and delivering it to the customer. This kind of website can clearly demonstrate the advantage of the computer-internet-3D printer potential, and its ability to deliver a pure customized product. A simplification of the described interactive process (Figure 4.3.1A) demonstrates a mass personalized production system that combined from "Open Architecture Products, Personalization Design, On-demand Manufacturing System and a Cyber-Physical System" (Hu, 2013). The "Open Architecture Products" is represented by the "Meta Design" link which presents a general design, ready to be customized by the customer. The "Personalization Design" is represented by the "User Involvement" and the "Definitive Design" links, by the ability of the system to enable adjustments and customization according to the customer personal taste. The "On-demand Manufacturing System" is represented by the "Manufacturing" link (based on 3DPT) which enables production of the required design without any special preparations, beside the need to generate a suitable file for 3DP. The "Cyber-physical System" is represented by the "Dynamic Platform" and the "Order" links which enable implementation of the whole process.


**Figure 4.3.1A - A simplification of a fully 3D printable "Industrial Personalized Design and Manufacturing System" process.**

Based on Hu's model, the only link that remained unassociated is the "Delivery" link, since that in a situation in which products are offered to customers through a similar interactive system, but the manufacturing process will be held by the customer (using a personal 3DP) can eliminate the necessity of the delivery stage (Figure 4.3.1B). The process's inner changes will occur in the "Order" and the "Manufacturing" processes, by the need to get a suitable 3DP file from the "Design Source", and by the fact the customer is manufacturing the products by himself. In such a case, the value chain can be implemented as a whole in the customers' home environment, and thus implement Davis's and Pine's ideals. Such a process can truly represent a fully democratic product.

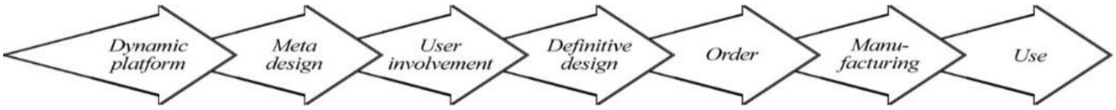



**Figure 4.3.1B. A simplification of a fully 3D printable "Personalized Design and Manufacturing System" process.**

Another American company called [12]**normal** (newnrml.com) used to offer through an interactive app customized earphone. The company decoded the shape of the external space of each user, and 3D printed the intermediary part, so the earphones will fit exactly to each user's ear shape. The rest of the product was assembled mostly from standard parts, and there was a fusion between 3D printed and mass-produced parts. Unlike a standalone jewelry that can be 3D printed as whole, without any need of a complementary part to complete the assembly of the product, the earphones depend on complementary unprintable electronic components, and other parts. A simplification of the described process (Figure 4.3.1C) shows that the dependency on complementary parts and components prevents from the product to be 3D printed by a personal 3DP in a case when the user owns one. Another difference is in the level of the involvement of the user. While in the previous case, the user was involved in the design and thus become kind of a designer, in this case, the user is only supplying required information (imaging of the shape of the ear) while the rest of the process is being managed and done by the company.

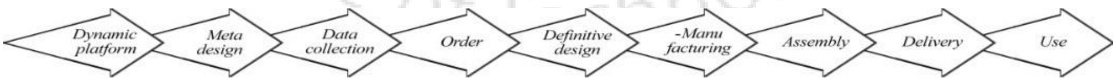



**Figure 4.3.1C. A simplification of a partially 3D printable "Industrial Personalized Design and Manufacturing" process.**

[12] Reviewed also as part of the 'Literature Review' chapter, 'Mass Customization' sub-chapter, Unstudied cases secondary sub-chapter, p.104).

In such a case, when a product depends on unprintable parts or components, even an existence of a personal 3DP will not create a fully democratic move. As can be seen in Figure 4.3.1D, in case of an existence of a personal 3DP and a suitable interactive cyber system for such a product, the changes in the process occur in the replacement of the "Definitive Design" and the "Order" stages. The "Order" stage, with relevancy to this discussion, represents the need to get a 3DP suitable file. The "Delivery" stage becomes more fluid and it represent the need to get complementary parts / components in order to assemble the final product and then use it.

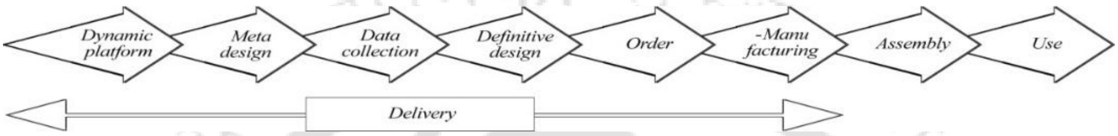



**Figure 4.3.1D - A simplification of a partially 3D printable "Personalized Design and Manufacturing" process.**

This type of model was found during a comprehensive review of [13]15 websites which offer 3D printed products (non-oriented to single type of product). The review has revealed much wider picture of two types of business models:

1. Traditional model
2. Democratic model.

The traditional model represents perception in which the responsibility to manufacture the product is in the hands of the seller, and therefore its being sell through the Internet like any other sustainable product. The democratic model takes in consideration personal 3DP and offers 3DP files so the customer can download a file and manufacture the product in his home environment. Both of the models, stance two different approaches relating to the products:

1. The standard approach
2. The customization and the user involvement approach.

[13] Thingiverse, pinshape, YouMagine, My Mini Factory, Cults, REPABLES, cg-trader, 3DShook, MakerBot Digital Store, Sculpteo, Digital Forming, e-bay, Amazon, Etsy, and Kraftwurx.

The standard approach offers readymade non-customizable designs and the customization approach offers open architecture designs that can be modified and customized in different levels by the customer, according to his needs.

The taxonomy matrix (Figure 4.3.1E) describes the sub-types of the mentioned business models in the 3DP cyber space market, according to the types of condition of the architecture of the products.

| | | **3D Printer** | |
|---|---|---|---|
| | | ***Personal*** | ***Industrial*** |
| **Design Architecture** | **Open** | *Customized Democratic Model* | *Customized Traditional Model* |
| | **Close** | *Standard Democratic Model* | *Standard Traditional Model* |

**Figure 4.3.1E - A taxonomy matrix of business models in the 3D printed products cyber market place.**

**Customized Democratic Model.** A unique example for that model can be seen in **Thingiverse**. As this website offers readymade designs available to download for personal 3DP, it also offers with some designs the option to customize them under pre-decided conditions. There are also few models that integrate 3D printed parts with standard parts, same as the partially 3D printable "Personalized Design and Manufacturing" process that was presented (Figure 4.3.1D).

**Standard Democratic Model.** This model is the most popular one. Examples for that model can be seen in the following websites: **pinshape, YouMagine, My Mini Factory, Cults, REPABLES, cg-trader, 3DShook, and MakerBot Digital Store.** Free of charge or not, those websites provide a bank of readymade designs and enable to download a suitable file for 3DP.

**Customized Traditional Model.** This model which follows MC approaches for mass production system, exploit the advantages of the 3DP together with the PC and the Internet, and enable to produce customized and tailored-made products. Examples for that model can be seen in the following websites: **Nervous System, Sculpteo and Digital Forming.** The manufacturing process is exclusive to the firm, and there is no option to download a suitable file for personal 3DP.

**Standard Traditional Model.** Websites like **e-bay, Amazon and Etsy,** that offer all kind of good, and **Kraftwurx** that offers 3D printed products follow the standard model in which the customer selects a non-customizable readymade design and the manufacturing process is exclusively in the hand of the seller. This model is considering the 3DP more as AMT and thus, the existence of a personal 3DP is irrelevant.

### *4.3.2. Interim Discussion*

The reviewed cases reflect the current possibilities that were mostly influenced by the abilities and the limitations of the existing 3DPT. Even if most of the limitations which were described in previous researches (Berman, 2012; Weller et.al, 2015) will be solved, designers should take in consideration one external aspect that determines whether the product is 3D printable or not. This aspect is the size of the personal 3DP which influences directly on the size of the parts, and thus the designer should set a decision for which minimum size of a 3DP the product fits (relates to the volume). For a one-part product this decision can be easily made, but in a case of a multi parts product that need to be assembled, an understanding of fact that the biggest part will determine the minimal 3DP size that is required for the ability to fully produce the part by the user. In a case when a product is fully, or partially 3D printable, a generic dynamic physical-cyber platform such as Nervous System's platform will be needed, if the offered design is flexible architecturally for customization by the user. Such a platform will also have to include a feature that prevents engineering failures in the product while the customer is doing manipulations on the design. In a case of a rigid architecture design, such a platform will not be required. Once the customer will find, or design exactly what he / she wants, the following steps will include an order (downloading a suitable file), manufacture (using the personal 3DP), assembly (in a case of a multi parts product) and use. Dependency on non-3D-printable components e.g. batteries, processors etc. will require the user to get / purchase those complementary parts in order to complete the assembly of the product.

As can be studied from the 2D digital printing market, there is a certain maximum size of printers that fit to home environment. The research questionnaire examined two general types of 3DPs that suit for home environment (based on the literature review and the theoretical basis), and it is not likely that people will own a size of a 3DP that will enable them to print a car. Though, more likely that people will own types of 3DPs (as presented in the questionnaire) that will enable them to print certain assembled big size products, and/or integrate complementary personalized and customized parts in readymade standard product, e.g. the steering wheel, buttons, handles, etc. (in case of a car).

## 4.4. Types of products

Out of understanding of the current situation, and the potential possibilities in an era in which personal 3D printers will be widely integrated in home environment, [14]two main factors will define the products' characteristic:

1. Whether the architecture of the design is open or closed for customization by the user.
2. Whether the product is fully or partially 3D printable.

A taxonomy matrix (Figure 4.4A) shows that by combining those factors, four characteristics of products may exist:

I. **Flexible Democratic Product (FDP):** like 'Nervous System's' case, i.e. the user gets the opportunity to be involved in the design stage, and in all the manufacturing, and the assembly processes.

II. **Flexible Semi Democratic Product (FSDP):** like Normal's case, i.e. the user gets the opportunity to be involved in the design stage, and partially in the manufacturing process, due to unsuitability of certain parts to be 3D

[14] Both factors refer to a situation in which the user own a P3DP.

printed, or due to unavailability of required raw material, or insufficient build volume of the 3DP.

III. **Rigid Democratic Product (RDP):** close architecture 3D printable product, like widely offered today by companies and "Indie" designers in designated websites and cyberspace social networks. The user gets no option to change the design, but the product is fully 3D printable.

IV. **Rigid Semi Democratic Product (RSDP):** can be less found today relates to products, but widely in use by product designers and mechanical engineers for prototypes. In this case, the user gets no option to change the design, and the product itself is not fully 3D printable, due to the reasons that were mentioned above.

In sum, the flexibility and the rigidity of the product relates to the type of the architecture of the product, and its ability to enable customization by the user. The democratic aspect relates to the dependency of the user on intermediaries which comes down to the dependency on a complementary part / component.

| | | **Product dependency On complementary parts / components** | |
|---|---|---|---|
| | | **Dependent** | **Independent** |
| **User involvement in the product design** | **Involved** | *Flexible Semi Democratic Product* | *Flexible Democratic Product* |
| | **Uninvolved** | *Rigid Semi Democratic Product* | *Rigid Democratic Product* |

**Figure 4.4A – Types of products taxonomy matrix.**

By taking in consideration the involved factors that assemble the continuous interactive process between to the product designer and the user, and the four characterized products that were classified and presented in Figure 4.4A, it became possible to formulates a matrix map (Figure 4.4B) that represent the similarities and the differences among the types of the characterized products. The map relates to a situation in which the user owns a 3DP and can fully or partially 3D prints the desired product. In a case when a product is 3D printable, but the user owns a kind of a 3DP that cannot produce the parts because of not having the proper raw material, or the volume of the 3DP is too small, then this kind of case will be classified under the semi-democratic products columns, depending on the type of the customization factor. A flexible design that enables customization through an interactive physical-cyber platform, but the user cannot 3D print it using his/hers 3DP will be characterize as a FSDP, while a rigid one that cannot be manipulated will be characterize as a RSDP. The factors that assemble the value chain relate to the flexibility / rigidity of the design architecture and thus to the ability to do manipulations in the design in favor of the customization act, the type of the intermediary platform, the ownership transfer phase (order & delivery), and the common independent phases that supposed to be made by the user only.

With reference to the factors that assemble the value chain, the design architecture that can be open or closed should be implemented under many considerations. In a case of a closed architecture, then following design methodologies of MC for mass production systems can be much useful. In a case of an open architecture product, those methodologies can assist to form the Meta design, but there are missing methodologies that direct designers how to design such a product, and therefore, the main objective of the research is to formulate a methodology for such cases.

The intermediary platform of the flexible products, which can be Nervous System alike, with more consideration regarding to the types of personal 3DP, should support the design by preventing conflicts between factors and by preventing engineering failure in the product. The ownership transfer phase should embody in it a business plan which needs to be competitive relatively to mass produced products, and should embody profit for the designer / studio / company etc. Completion of the ownership transfer phase, transfer the process to the independent phase where the user should complete the manufacturing and the assembly (if necessary) by him / her self. In some cases, additional services from the designer might be needed, e.g. supplying manuals for an assembly of complicated products, enabling access to spare parts files, user manual etc. The feedback phase which obviously can enable the users to comment and rate the process and the product can also be useful for data collection, in favor improvements making in the process and / or in the product. It can act also as a platform that enables further distribution of the product, by the users.

| | *Flexible Democratic Product* | *Flexible Semi-Democratic Product* | *Rigid Democratic Product* | *Rigid Semi-Democratic Product* |
|---|---|---|---|---|
| **Design architecture** | *Open* | *Open* | *Close* | *Close* |
| **Platform** | *Interactive Physical-Cyber System* | *Interactive Physical-Cyber System* | *Website* | *Website* |
| **Type of customization** | *Pure* | *Pure* | *Standard* | *Standard* |
| **Definitive design** | *Determined by the user* | *Determined by the user* | *Choosing from a variety of options* | *Choosing from a variety of options* |
| **Order** | *3DP file* | *3DP file + Coplementary Part / component* | *3DP file* | *3DP file + Coplementary Part / component* |
| **Delivery** | —— | *Coplementary Part / component* | —— | *Coplementary Part / component* |
| | *3D Printing* | | | |
| | *Assembly* | | | |
| | *Use* | | | |
| | *Feedback* | | | |

**Figure 4.4B - A mapping of relevant factors according to the characterized products.**

## 4.5. Types of Users

MC methods characterize types of users based on the fact that the manufacturing means are in the hands of the powered-central source. The democratic model represents a new MC approach in which the manufacturing mean is in the hand of the user, and there is no necessity to flex standard manufacturing processes. Even if the user does not own a personal 3DP, the type of the products is such that the option to manufacture them by using personal 3DP is there. A taxonomy matrix (Figure 4.5A) defines types of users according to the new MC approach that includes the two factors that represent the essence of the democratization move:

1. The option for the user to be involved in the design stage, so that the final design will be according to his / her needs.

2. The option for the user to fully manufacture and assemble the product in his / her home environment.

| | | Personal 3D Printer | |
|---|---|---|---|
| | | ***Own*** | ***Doesn't own*** |
| **Involvement in the product design** | ***Involved*** | Producer | Customizer |
| | ***Un-involved*** | Manufacturer | User |

**Figure 4.5A - A taxonomy matrix of types of users in a democratic model.**

**Producer:** This type of user represents users in a scenario of full exploitation of the advantages that the democratic model offers (FDP). The user holds the possibilities to be involved in the design stage, and to fully manufacture the product. Out of the market review, 'Nervous System's' business model (despite that they do not deliver suitable files for 3D printing) is the only model that represent perception of users as producers. By referring to the research questionnaire, the 'Makers' participants, are the type of users that represent the aspiration to be producers, but as deduced from the results, their expectation from the 3DPs are unrealistic at this point of time.

**Manufacturer:** This type of user represents users that have interest in the domestic manufacturing process only (very few of the 'Makers' participants presented an attitude as such), and / or users that engage with RDP. Most of the reviewed 3D printing oriented websites perceive their users as manufacturers only, i.e. they offer delivery of suitable for 3D printing files, without the option to do manipulations on the design.

**Customizer.** This type of user represents users that get the opportunity to be involved in the design stage, but without the option to be involved in the manufacturing process (willingly or unwillingly). Additionally, users that cannot fully manufacture the product, can be considered as customizers as well, since they depend on external sources (FSDP). By referring to the questionnaire, the 'Common' participants, and the segments of the 'None' participants that selected the C&A, or the C/O options, perceive themselves as customizers, even though that the 'Common' participants might find themselves as 'Manufacturers', or 'Producers' in case of a small size fully 3D printable products.

**User.** This type of user represents users that have interest in using the product only (RSDP), or they might have interest in customizing the products, but due to closeness of the architecture of the product, they interact with it as users only. By referring to the questionnaire, the segment of the 'None' participants that selected the 'From catalogue' option, represent this type.

## 4.6. Conclusions

The review of the personal 3D printing market has revealed few important insights and conclusions that were not mentioned in the literary sources that were reviewed as part of the general theoretical basis. Despite that many potential users are willing to adopt the technology, and that desktop P3DP are already being offered for sale in affordable prices, and that suitable platforms are available on the web, there is a significant gap between the potential to the reality.

First general conclusion points that the market suffers from adolescence difficulties. By starting at the origin point, which is the design process, there is lack of uniformity among the CAD software. Basic actions, e.g. moving, rotating, selecting, etc. are being implemented differently in each software. It is the same as if every word processing software will determine different shortcuts for basic actions like copy (Ctrl C), paste (Ctrl V), save (Ctrl S), select all (Ctrl A), etc. This uniformity impacts not only on Indie designers that aspire to discover the 3D printing world, but also on other potential users that might want to do changes in ready-made designs. Additionally, absence of optimization and engineering failure features (even basic features), reduces the functional reliability of the designed parts, and even might cause safety-in-use problems.

Second general conclusion that regard to the design of the P3DPs, points that in wide context, there is lack of standardization in the P3DP field. Each company produces P3DPs with different build volume, and there is no standard definition of what can be considered as P3DP, and / or what it should include. The digital 2D printers represent conceptual continuation of typewriters. Hence, it was obvious from the first moment that the personal 2D digital printers must work with standard sheet format. This understanding does not exist in the P3DP field, and it is one of the reasons for the gap that exists between the potential users to the market. No standardization, means uncertainty. Indie designers, and companies cannot rely on basic standards, such as the build volume, and therefore cannot know for certain, if their products can be 3D printed by the user. As a products designer, I can say that this lack of standardization situation, creates unseen blockage, and prevents from product designers to willingly promote P3DP. Under the context of the standardization, the workflow is not fluent in the clear majority of the P3DP, unlike the parallel workflow of the digital printers. The industry still refers to P3DPs as an independent CNC machines, which shows that there is misunderstanding, or unawareness to the significance of the human-machine interaction. The current design preserves a conception that 3DPs are designated to machines operators, rather than to the common people.

Third general conclusion refers to the platforms that relate to the 3D printed products. The clear majority of the websites and the businesses, refer to the potential customers as manufacturers, and / or users. Except 'Nervous System' and 'Thingiverse', which present an understanding that the customization factor is **the** most required issue, and the P3DP is just the mean that should enable it to be implemented, the rest of businesses misses this point, and offer relatively expensive exotic ready-made 3D printed products, or rigid suitable for 3D printing files. Except 'Nervous System's' dynamic platform, which implements all the MCP factors, but do not provides suitable for 3D printing files, no such a sophisticated platform that enable delivery of suitable files, were found in the free market. Even though this kind of dynamic platform is a game changer, businesses can follow 'Normal's approach, or the questionnaire-like approach, which means to collect data from the user, and finalize the design according to the user constrains. After finalization of the customized design, it is only a matter of delivery of file through the cyber-space. Once the 3D printing industry will internalize that the customization factor is the competitive advantage, and not the manufacturing independency, most of mentioned barriers will be removed, because it is a matter of different philosophical perception that puts the end user in the center.

# CHAPTER 5

# PRODUCT DESIGN METHODOLOGY FOR PERSONAL 3D PRINTERS (P3DP)

The transition of the manufacturing mean from factories and workshops to the user's home environment is a game changer that requires a shift in perception from a simultaneous, continuous effort to merge design, manufacturing, marketing, and other logistic considerations to a pure, user-oriented perception.

## 5.1. The General Iterative Process: Introduction

The general iterative process, in the context of sustainable products, is the process that represents the life cycle of a product and consists of all the steps that need to be taken in order to realize ideas into utilitarian products that people use. By comparing the life cycle of almost every sustainable product with each other, two main distinguished perceptions emerge: from cradle to grave, and, the more advanced perception, from cradle to cradle. The cradle to grave approach refers to products that end their life cycle as waste and it can include considerations on how to treat these products as waste or not. The cradle to cradle approach refers to products that end their life cycle as a raw material source for new products, and, hence, this approach holds more up-to-date sustainability values. Principally, 3DPTs can follow both approaches depending on the type of technology. FFF technologies and DLMS technologies use recyclable raw materials (thermoplastic polymers and metal alloys with no binders) while the rest of the technologies use raw materials which are non-recyclable and, thus, are left without much utility after use. However, one of the advantages of 3DPTs, as cited by Berman (2011), Patrick & Simpson (2013), Barnatt (2013), and Weller et al. (2015), is prolonging the life of products through the ability to produce spare parts and new, improved parts without complicated implications. Hence, 3DPTs bring back, without effort, value like product repair and expand the upgrade value. Thus, in every perspective, 3DPTs can be considered as more sustainable technologies in comparison to most conventional technologies. As a result, a product's life cycle might become more like a dynamic organic process in which the product evolves and gets fixed selectively if necessary, rather than remaining a static creation.

According to the models that were presented in the previous chapter, the phases that comprise the value chain of fully/semi-democratic products (Figure 5.1A) are as follows: the ideation, the design, the distribution, the domestic manufacturing and assembly, the use, and the feedbacks phases. Logically, the same stages are also represented in other methodologies that were reviewed, but the order is not exactly the same and the way each step is implemented is different.

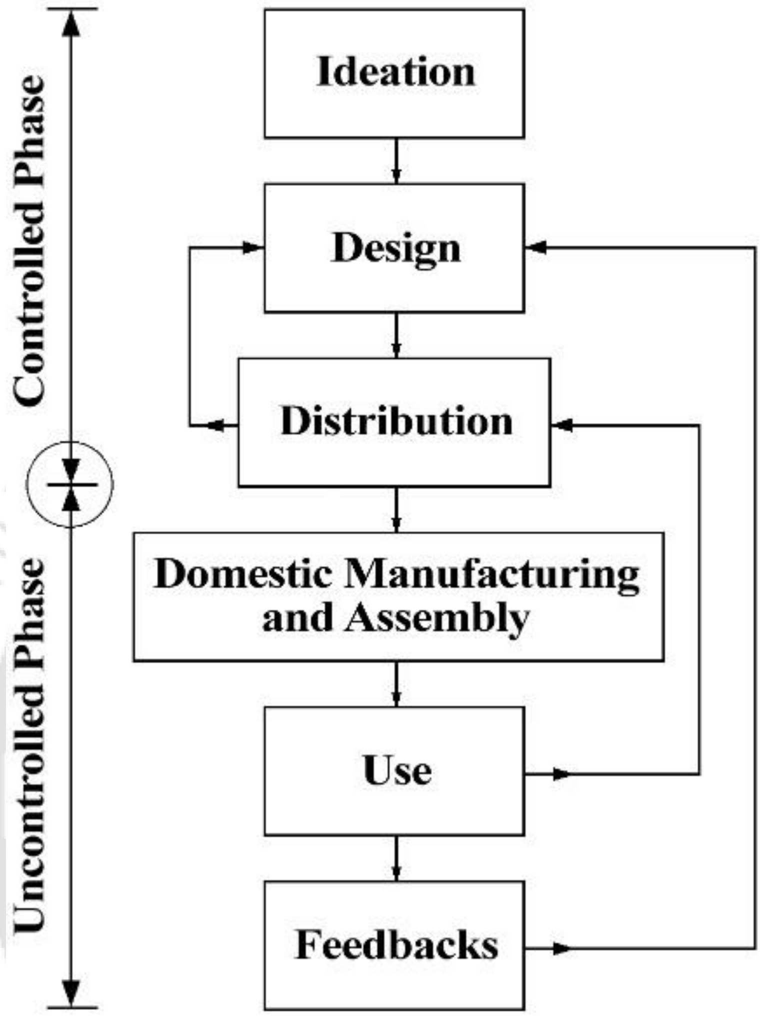



**Figure 5.1A – From Ideation to Use - The General Iterative Process.**

***The Ideation Phase***

The ideation phase, which is the starting point of every new product or of a product that needs upgrading, instantly takes on a new meaning. The fact that the manufacturing mean is at the user's home environment presents constraints in advance design thinking, questions regarding technological availability, and considerations of the abilities and limitations of the available technologies. From the business (indie/organized) perspective, the steps that need to be implemented at the ideation phase remain the same, i.e., to determine the product strategy and to come up with a new business plan (Roozenburg & Eekels, 1995). However, at this point, an initial strategic decision should be taken on whether the product will be fully or semi-democratic. Execution of a fully democratic product requires the setting of a frame that defines the conditions so that the product will be considered fully democratic, i.e., what the minimum build volume of the P3DP will be and which raw material will be required. If it is decided that the product will be semi-democratic, then an additional decision will need to be made regarding which parts will be 3D printable by the users and which complementary parts the user has to get from an external source (and where he/she can get it). In both cases, another subsequent decision must be taken right after which is on whether the design will be customizable according to the MCP factors (flexible) or whether the architecture of the product will be closed (rigid). In case of a flexible product, the design source should decide how the user will influence the design, i.e., actively, through a dynamic interactive platform, or passively, by supplying required information.

### *The Design Phase*

Following the ideation phase comes the design process in which the designers (indie/salaried) need to take into consideration P3DP as the manufacturing mean and to design accordingly while keeping in mind the strategic decisions that were taken. At this stage, the professional level of the designer is crucial since amateur designers are most likely unaware of engineering considerations, and their ability to set design equations that maintain the factor of safety (FOS) of the parts, in case of a flexible product, is questionable. Regarding flexible products, changes in the design according the user's demands should be considered from an engineering standpoint and should only be allowed under certain constraints in order to prevent functional failures. In the case of rigid products, the main advantage that professional designers have is the ability to optimize the design, i.e., to apply functional requirements with minimal raw material consumption and with the shortest manufacturing time.

### *The Distribution Phase*

Once the design process is completed, the virtual product becomes ready for distribution. Prior to the distribution phase, the design source should gather relevant information that, on one hand, should guide and support the user, and, on the other hand, should encourage people to get the product (marketing content). The supportive information should include the minimum required build volume and the recommendation for the best raw material that should be used, as well as the best orientation in which the 3D printed part should be placed, printing resolution, other relevant technical recommendations (nozzle's temperature, tray's temperature, working speed, etc.), instructions for doing post-manufacturing processes (if required), and assembly instructions (if required). In the case of semi-democratic products, it should also include additional information regarding the complementary parts (parts details, and where and how the user can get them). The marketing content should include renderings of the virtual model, real pictures, and a few words about the products (if there is any ideology behind it, the behind-the-scenes story, etc.). As can be noticed, logistic distribution considerations that are made in conventional methods become irrelevant. If the design source has an intention to develop a distinctive distribution platform, then it should be done parallel to the design process. Alternatively, a few of the mentioned websites (Thingiverse, Shapeways, etc.) provide a free distribution platform that gathers all the mentioned information (supportive and marketing).

The three mentioned phases thus far are considered controlled phases or, from a different perspective, once the virtual product is distributed, the design source can no longer control the rest of the process. In between the controlled and the uncontrolled phases, the first round of feedbacks begins (prior to the manufacturing and the assembly phase). For instance, as mentioned in the 'Research Motivation' sub-chapter (p.22), in the case of the Q-tips holder that I designed and distributed through the mentioned designated websites, one user gave feedback on the design and wondered if it is possible for me to remove the nose-stick and just leave a simple hole so that a regular Q-tip could be placed there instead, and, by doing so, avoid the necessity to use support material. I have adopted this feedback and changed the design accordingly. This case lawfully represents the contributive influence of the uncontrolled phase, in its initial stage, on the controlled phase.

### *The Domestic Manufacturing and Assembly Phase*

This phase represents the readiness of the user to start the manufacturing and the assembly (if required) processes. Readiness means that a transaction involving the delivery of the suitable 3D printing files has been made (most likely through the internet) and that the user gets access to all the relevant information. This includes official information, which is provided by the design source, and non-official information, which constantly flows from other users (feedbacks). This phase also determines whether the product is fully or semi-democratic from the perspective of the user, or none of the above, i.e., if the product was designed to be fully democratic but the user does not have the proper raw materials, or if the build volume of the P3DP does not enable 3D printing of the product (fully/partially), in which case, regardless of the intentions of the design source, the product will turn out to be semi-democratic or simply irrelevant for domestic manufacturing. This example clearly demonstrates that the status of the products (fully/semi-democratic) does not depend only on the design source but, rather, **depends on the matching between the strategy of the product and the ability of each user to implement it, separately.**

In the case of a fully democratic product, at this phase, the user should 3D print the product, assemble it (if required), and make it ready for use. In the case of a semi-democratic product, the user can start to 3D print the relevant parts, but the product will be considered ready for use only after the non-3D printable complementary parts are received and integrated in the product.

***The Use and the Feedbacks Phases***

These phases represent the completion of the localized goal. Once the user has finished the manufacturing and the assembly processes, the product is considered ready for use, and, basically, there should be no difference in the usage of 3D printed products and other products. However, there is one major distinction that differentiates democratic products and non-democratic products. As mentioned in the literature review chapter, the ability to modify and upgrade the products constantly, and the ability to 3D reprint broken parts if necessary should immensely prolong the usage time of products. The level of satisfaction of the user from the quality of the product along with the usage experience, and the level of satisfaction from the whole process (including post-transaction support and services if needed) are supposed to lead to three possible final reaction scenarios:

1. **Further voluntary supportive marketing** by the user, i.e., the high level of satisfaction of the user might and will most likely lead to positive feedbacks/high ranking and other methods for providing positive feedback. Furthermore, there is always a possibility that satisfied users will share their experience with others in all the varied platforms that enable it.

2. **Further voluntary critic marketing** by the user, i.e., the low level of satisfaction of the user will most likely lead to negative feedbacks/low ranking, etc. In addition, there is always a possibility that disappointed users will share their experience with others.

3. **Indifference**, i.e., regardless of the level of satisfaction of the user, from the user's perspective, the process ended once the transaction was completed, and he/she has no interest in leaving any kind of feedback. The user's level of satisfaction from the product remains discreet.

Businesses should regard the feedbacks phase very seriously. First, they must encourage people to leave feedbacks by integrating the feedback platform with the whole process and by emphasizing its importance. Second, the feedback platform should be experiential and should leave an impression that every feedback matters so that the number of indifferent users will be as low as possible. Third, a policy of reactions to feedbacks should be determined since rewarding feedback providers positively could create loyal returning customers, and reacting badly to critics instead of learning from them can lead to the creation of a bad reputation which comes with all its consequences.

As mentioned at the beginning of this sub-chapter, a product's life cycle might become more like an organic process in which a product evolves, gets fixed selectively if necessary, and declines gradually rather than remaining a static creation that stops its life at a single moment. This description resembles a spiral with a tail shape rather than a circular one, and the main difference between the types of democratic products (fully/semi) is the status of the architecture of the product (flexible/rigid). In the case of flexible fully/semi-democratic products (Figure 5.1B), the user can, at any time, go back to the design stage, modify parts at the distribution platform, reproduce the required parts, use the product, and so on until he/she decides not to use the product anymore or until the product's life comes to its end.

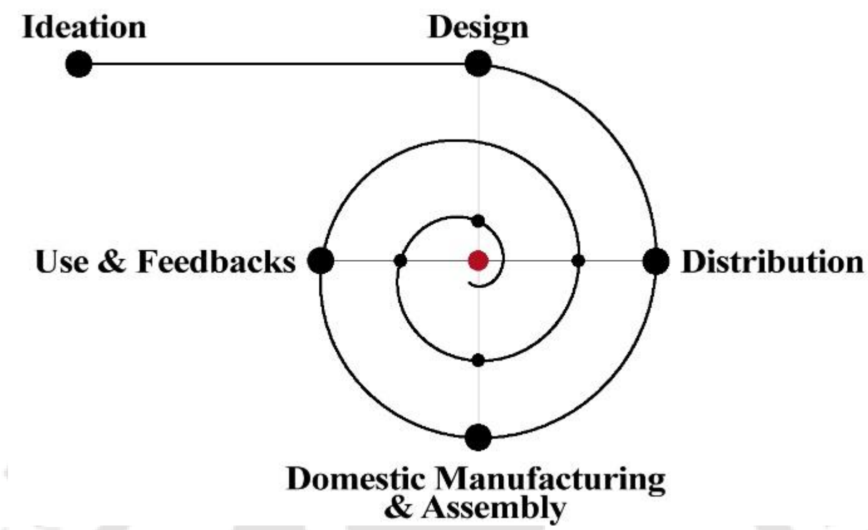



**Figure 5.1B – The Spiral Life Cycle of Flexible Fully/Semi-Democratic Products.**

In the case of rigid fully/semi-democratic products (Figure 5.1C), the user can, at any time, go back to the distribution platform to get upgraded/spare parts, reproduce parts, use the product, and so on until he/she decides not to use the product anymore or until the product's life comes to its end.

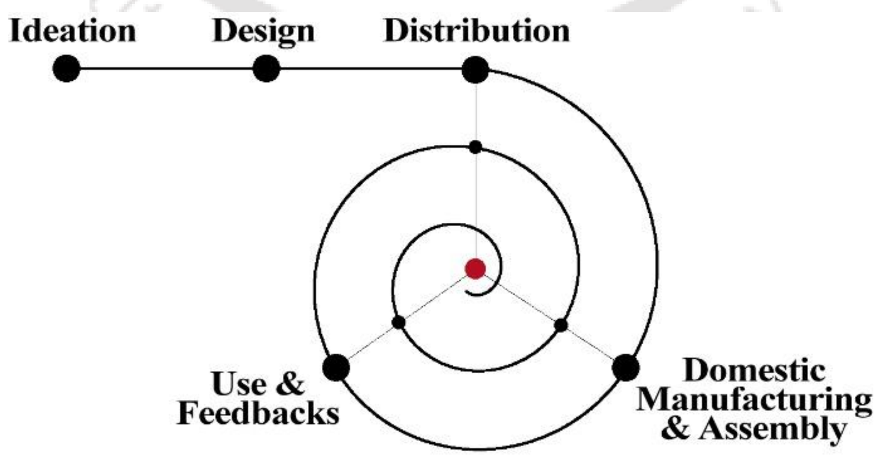



**Figure 5.1C – The Spiral Life Cycle of Rigid Fully/Semi-Democratic Products.**

## 5.2. The Phases of the Methodology

The design phase, similar to the whole process, is substantially influenced by the fact that the manufacturing mean (P3DP) is a fixed constraint and, also, by the fact that the manufacturer is a non-professional source which is not familiar with technical terms and professional processes. Conventional design methodologies (Pahl & Beitz, 1984; VDI Guideline 2221, 1987; Baxter, 1995) refer to the design process, along with the manufacturing process, as a bridge that should support realizing the business plan by fulfilling it into a real, profitable product. The reference to the manufacturing process is as an independent source that represents a bank of technological availabilities, and, with correlation to the design, costs, and other logistical considerations, the most suitable manufacturing process should be selected. In view of this justified reference that leans on mass production processes, the design methodologies suggest following three distinct sub-design iterative stages:

1. Concept (Pahl & Beitz, and Baxter), or principle solution (VDI 2221).

2. Preliminary design (Pahl & Beitz, and VDI 2221), or embodiment design (Baxter).

3. Definitive design (Pahl & Beitz, and VDI 2221), or detail design (Baxter).

These three main stages have been proven as effective for the professional design process since they've managed to define a process that is supposed to lead to minimal bridging iterations between design and manufacturing.

The new scenario, in which the manufacturing mean (P3DP) is a known-in-advance constraint and not a bank of available technologies, coupled with the fact that the user is no longer just a user but, rather, can also act as a producer, a manufacturer, or an assembler, brings new values to the design process and simplifies it. Businesses should ensure that the whole interactive process (including the controllable and the uncontrollable phases) will be perceived by their clients as a good experience, and designers must support this approach since most of the expectational phases in the uncontrollable phase (the manufacturing, the assembly, and the use phases) are tightly and directly influenced by the design of the product. On one hand, the necessity to produce a distinct concept as an initial step to the preliminary design outcome is no longer required since there is no question regarding the means of manufacturing. One of the main questions that should be asked when moving from the concept to the preliminary design phase is how the concept should be manufactured, and, since this question has one answer, the concept and the preliminary design can be merged into one distinct stage. Hence, it simplifies the design process. On the other hand, designers must think like meta-designers and take into consideration new values that derive from the fact that the user should experience the design (in case of flexible products), manufacturing (fully/partially), assembly, use, and maintenance of the product.

Accordingly, in comparison to the methodologies that were mentioned, the general design process of 3D printed products that are supposed to be manufactured (fully/partially) by P3DP (Figure 5.2A) is not much structurally different. Moreover, it involves the same values and behaves iteratively in the same manner, but the context inserts new, unique considerations that designers must be aware of.

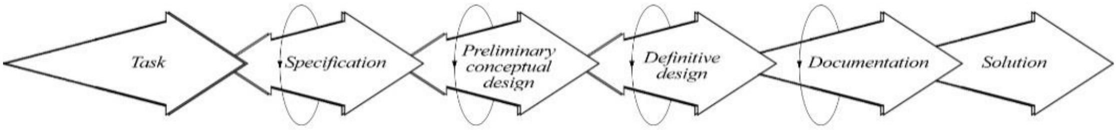



**Figure 5.2A – The general process of the design phase.**

***The Task***

The design task, as a derivative of the business plan, should provide the designer with fundamental strategic information which should be expressed in the design of the product. Aside from the conventional questions, businesses should think in advance and ask: What is the best type of product model that would maximize our competitive advantage? For example, companies that produce products with non-3D printable components can follow the flexible/rigid semi-democratic model and share the final production and assembly with the user. For instance, a company that produces a non-3D printable windup mechanism can offer this mechanism for sale, and, through the web, offer an infinite number of 3D printable parts for products that are operated by this mechanism. One more example would be that some toy companies can fully hand over the manufacturing process to the user, and, thus, follow the flexible/rigid democratic model. For instance, a company that sells structural toys can, through the web, offer an enormous number of design configurations of parts, and the user can buy these parts without limitation. The elimination of the box can open new, continuous selling experiences and opportunities that did not exist before the advent of the situation in which the user could function as the manufacturer as well.

The characteristic of the architecture of the product should also be taken in consideration at the task definition phase, and businesses should think in advance about whether there is any value in enabling customization that would leverage their competitive advantage. The customization issue should be considered with respect to the MCP factors, and, tightly in parallel to these considerations, businesses should also think about the customization platform. They should decide whether to develop/use a dynamic interactive platform or to produce a passive customization form.

Regarding indie designers specifically, it is better for them to follow the flexible/rigid democratic model unless they find an interest, like companies, in creating a dependency on non-3D printable components or unless they think that a specific non-3D printable component is essential for the product. Typically, indie designers have less financial resources than companies, and, therefore, enabling customization should be considered carefully since there are no available open-source generic dynamic platforms (except for a very few websites that have a limited option to add 3D text in some designs) and since gathering data from the user through a passive form and generating a customized configuration, accordingly, would require a lot of time.

***The Specifications***

The design specifications phase is the phase where the design process actually starts. This phase is considered to be the theoretical basis of the design, and its quality directly affects the following phases. Besides the conventional information that should be gathered, e.g., characterization of the users, environmental effects, market review, safety standards, etc., designers must take into account issues that relate specifically to the P3DP market. As a first step, the designer should identify from the business plan or determine by him/herself which type of product model to follow (FDP, FSDP, RDP, RSDP) and specify the best personal 3D printing method accordingly (if not dictated in advance by the management/client). Since there is no standardization regarding the build volume of P3DPs, following the first step, the designer should select a representative P3DP (if not dictated in advance) that defines the minimum required build volume. Correlative to the 3D printing method and to the specified P3DP, the designer should specify the raw material and design the product according to all the noted specifications.

In the case of semi-democratic products, at this phase, the designer should specify the non-3D printable complementary parts/components and their specifications since they are considered as constraints that need to be integrated in the product. In case of a flexible product, the designer should determine and define the required level of customization with reference to the MCP factors (if not dictated in advance) and should determine how and through which platform the user will make the customization (if not dictated in advance).

Indie designers, depending on their experience and level of professionalism, usually cross these first two phases intuitively and with less awareness of the process. Since there is a lack of standardization and since there are differences among the offered P3DPs for sale (in quality, in size, and in the case of FFF P3DPs, in the diameter of the wired raw material), this unawareness of the whole process could significantly increase the iterations in the design process, hence prolonging the time required to accomplish the design task and, moreover, significantly reducing the probability of success. Therefore, it is highly recommended for indie designers to be aware of the considerations that specifically relate to the characteristics of the P3DP market.

***The Preliminary Conceptual Design***

As noted previously, since the manufacturing mean is a known-in-advance constraint, the design process can descriptively and practically be shortened by unifying the concept and preliminary design phases. At this phase, the designer should establish an initial design concept through any of the conventional methods (hand sketching, mockups making, CAD modeling, etc.), and the separate focus on the shape and the function, as an initial step, could be done similarly to the known methods (artist concept and functional diagram). However, the technological considerations should be implemented (even roughly) at this phase since there is no question regarding the manufacturing technology to be used (P3DP, as specified in the design specifications phase).

At this phase, professional designers are usually required to produce design alternatives so that the best alternative is eventually chosen in the process of evaluating each alternative against relevant specifications. Once the best design alternative is selected, the designer should produce a CAD model that should represent the preliminary conceptual design.

In case of a semi-democratic product, at this phase, the designer should produce a list of schematic CAD models of the complementary parts/components and integrate them in the virtual assembly of the product. In case of a flexible product, the designer should map the parts that need to be changed in favor of user customization, locate the dimensions and/or the features needed to enable the changeability of each part, set changeability limitations (maximum/minimum dimension), and examine the effect of the changeability of the parts that should be customized on the whole assembly.

Indie designers are not obligated to follow these methodical steps, and, as evidence, many of the parts and products that are offered for download at relevant websites were never 3D printed as part of the design process. This is one of the two-bladed swords mentioned by Lipson & Kurman (2013) that refer to the consumer safety and the quality assurance aspects.

***The Definitive Design***

Once the preliminary conceptual design is completed, the next step that the designer should take is to elaborate the design and develop it until the completion of the design of the product. The professional level of the designer is expressed prominently at this phase and directly affects the quality of the design. Aside from the need to adjust the design to the manufacturing technology (P3DP), the designer also needs to apply fit tolerances (in case of an assembled product), elaborate the shape, optimize the design by reducing excess raw material, and evaluate the design through finite elements analysis features. All of these actions require knowledge and experience both in design and in engineering. Since the P3DP market is open for all levels of designers and since there is no automatic software that can perform these actions for non-professional designers, professional designers have a clear and significant advantage over non-professional ones. Along with the obvious advantage in the quality of the product, professional designers can emphasize their advantage as marketing information.

Similar to the other phases, this phase is also a self-iterative process in which the designer virtually designs the product and produces real test models whenever he/she thinks that something (functional, ergonomic, etc.) needs to be tested realistically. The test models drag changes back into the virtual design, and this iteration runs until the designer thinks that the design task has been accomplished. The last outcome of the last iteration can be considered as the definitive design, and strict tests should also be done on this last configuration until full satisfaction is reached.

In the case of a semi-democratic product, at this phase, the designer should add essential details to the CAD models of the complementary parts/components and reintegrate them in the virtual developed assembly. Moreover, at this phase, the designer should get the real complementary parts/components and integrate them in the test models. In case of a flexible product, at this phase, the designer should locate all the specific requirements for changing dimensions/entities and produce a generic, flexible configuration. Once all the dimensions/entities have been located, the designer should set dependent equations that enable changeability under conditions that preserve the quality of the product, i.e., its functionality and its shape proportionality aspects. This action requires a high level of professionalism, and not all designers/engineers are experienced in it.

Indie designers, depending on their level of professionalism, should follow the same steps as professional ones even though they are not obligated to strictly follow the professional methodology. Moreover, most likely, an indie designer will pay less attention to the differences between the preliminary conceptual phase and the definitive design phase and might practically treat them as one phase. As mentioned previously, in a different context, eventually, they will arrive at a solution and will generally follow the same steps, but the unawareness of the whole process could draw many more iterations in the process, and, therefore, lead to more time spent.

***The Documentation***

Once the product design process is completed, the designer needs to orderly group all the process resources that can be documented, prepare QA technical drawings for statistical examinations of the quality of the production, and prepare all the required information and resources for the distribution platform. The resources that need to be prepared for the distribution platform include:

1. A P3DP suitable file (.stl, .xt, or any other suitable Parasolid file).
2. Renderings and/or real pictures of the product in different representative views for publication (videos and pictures of the product in use could positively support the marketing effort).
3. Production instructions, e.g., the minimum required build volume, recommended raw material, recommended orientation of the part on the build platform of the P3DP, recommendation for 3D printing resolution, recommendation for working temperature, and recommendation regarding the use of support material (if required).
4. Assembly instructions (if required).
5. Operating instructions (if not obvious).

In the case of a semi-democratic product, the designer should also prepare a list of the complementary parts/components for the user and specify how he/she can get them. In case of a flexible product, depending on the type of the platform, the designer should set the changing conditions on the virtual model (in case of a dynamic interactive platform) or gather the required information that need to be collected from the user (in case of a passive form).

For indie designers, except for the need to produce QA technical drawings and the need to orderly group the process resources that can be documented, all other actions that were noted are obligatory, and, just like salaried designers, they need to follow the same steps in order to ensure that all the marketing values will be covered in the best way.

***The Solution***

The solution represents the completion of the general design phase, hence the readiness for manufacturing or for further realization (VDI 2221). In the mass production market, the completion of the design phase leads to the production, distribution and sale, and use phases (Roozenburg & Eekels, 1995). The transition from the distribution and sale phase to the use phase depends mostly on the accessibility and affordability aspects. In the P3DP market, as mentioned previously, the status of the products (fully/semi-democratic) does not depend only on the design source but, rather, depends on the matching between the strategy of the product and the ability of each user to implement it, separately. Thus, the transition from the design phase to the use phase (according to the value chain of the general process that was presented previously) depends not only on the accessibility and the affordability aspects but also on an additional aspect, which is the manufacturability aspect.

On one hand, in the P3DP products market, the solution can be referred to narrowly as the end of the general design phase, but, on the other hand, it should also be referred to widely as the possibility for the user to execute the product strategy, i.e., to manufacture and use the product. The solution diagram (Figure 5.2B) accordingly presents the steps that define the real solution. As can be seen in the diagram, the determination of the product strategy phase leads to the product design phase, and only when the accessibility, affordability, and manufacturability aspects come into a match with the user can the actual use represent the real solution.

The accessibility aspect refers to the availability of the suitable P3DP file (on the internet or through other ways), and, in the case of semi-democratic products, it also refers to the accessibility of the complementary parts/components. The affordability aspect refers to the willingness of the user to pay for the files, the required raw material, and other considerations, and, in the case of semi-democratic products, the willingness of the user to pay for the complementary parts/components. The manufacturability aspect refers to the matching between the size of the parts and the P3DP, and the type of P3DP of each user. The use, or, more specifically, the readiness for use, represents the success point both from the design source's and the user's perspective.

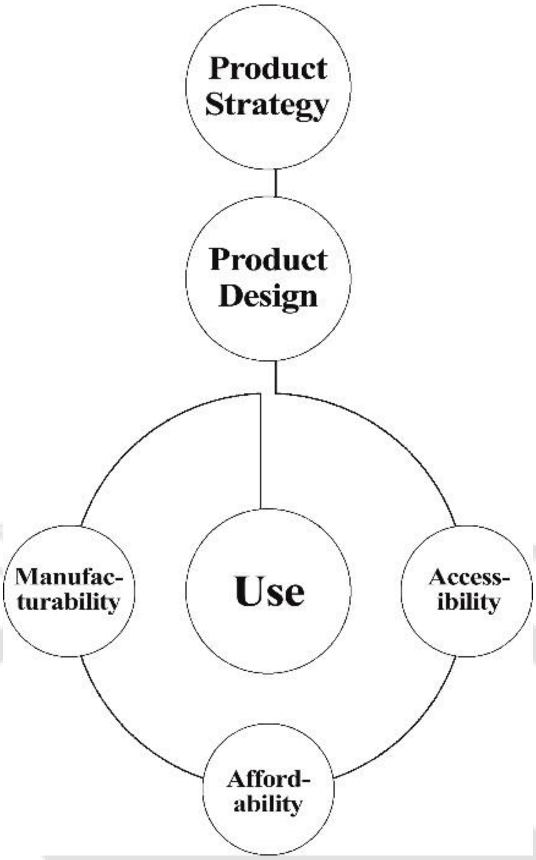



**Figure 5.2B – The Solution Diagram.**

## 5.3. The Structure of the Methodology

Regarding the research question $Q_1$ (p.24) and the first research objective (p.24), according to the noted phases, I have formed a structure that graphically describes the methodology and its inner flow ([15]Figure 5.3A). The methodology was constructed linearly from top to bottom, and the wide middle column indicates the steps that need to be taken and followed in designing every product that is designated to be manufactured by P3DP. The right column indicates the additional steps that need to be taken and followed in case of a flexible product, and the left column indicates the additional steps that need to be taken and followed in case of a semi-democratic product. Each row indicates the steps that need to be taken and followed in each phase, and each polygon represents the phase that is comprised of the steps that define it.

[15] Please refer to the enlarged figure at the end of the dissertation.

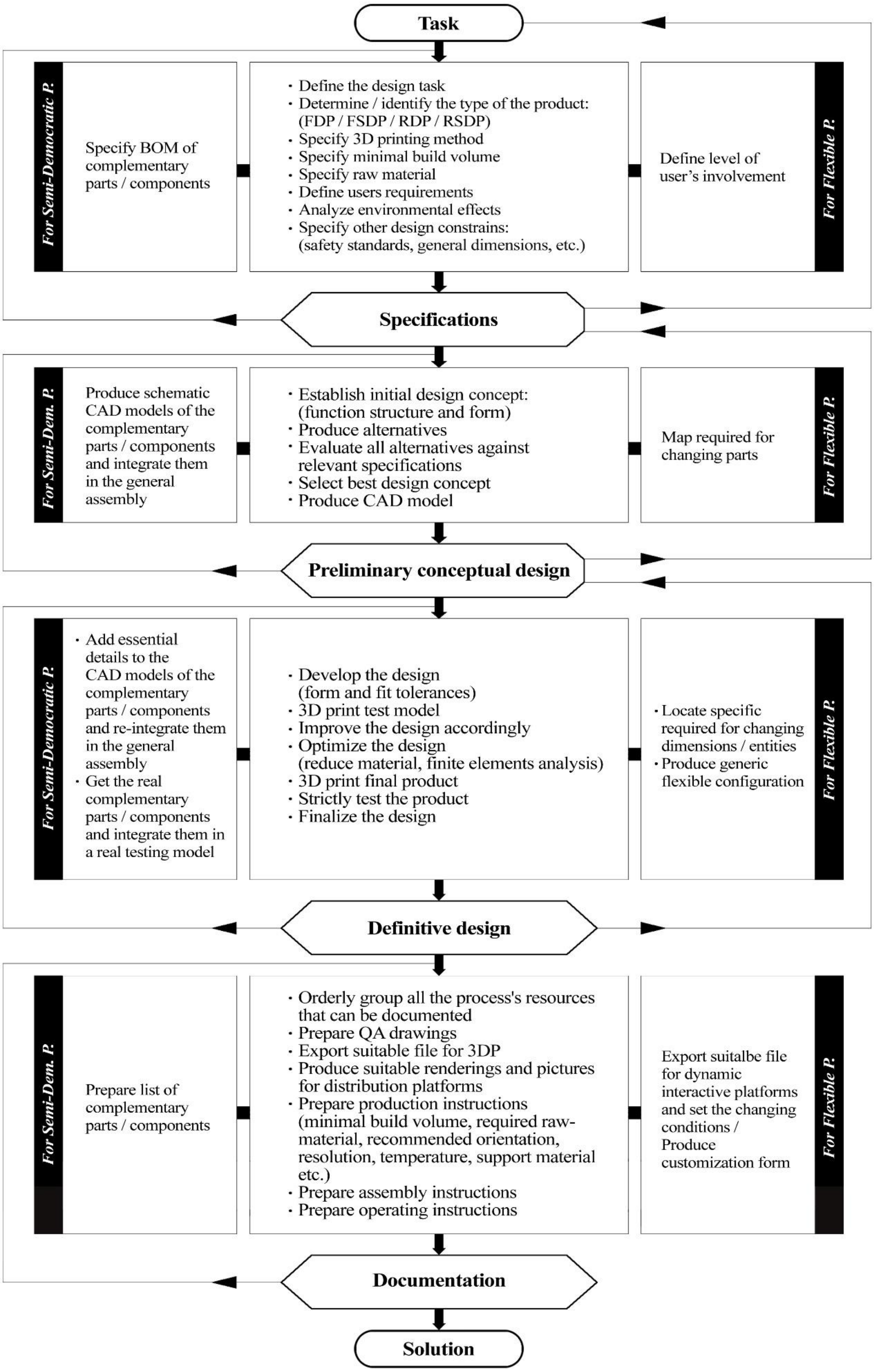



**Figure 5.3A – Product Design Methodology for P3DP.**

The thin lead lines with the arrowheads on the right side describe the possibility of each phase to apply changes in prior phases and actually describe the iterations in the whole process. The thin lead lines with the arrowheads on the left side describe the possibility of each phase to be internally iterative.

From the perspective of the design source, the lack of standardization in the P3DP market is the main cause that makes the result of the design effort uncertain. It is clearly reflected that the P3DP industry focuses on the uniqueness of the technology and its exotic appeal and pays less attention to the user-friendliness of the operation of the P3DPs (mostly from the perspective of an amateur user). It pays even less attention, possibly just out of unawareness, to basic standardization that should serve the market as a whole. For instance, the lack of standardization for defining what can be considered as the standard format of P3DPs, i.e., the dimensions of the build volume, is the main cause for the uncertainty that was mentioned above. The companies can offer a variety of P3DPs, just like I have offered in the research questionnaire, and even expand the selection to large-sized, medium-sized, and mini-sized P3DPs. However, one way or another, the companies must decide on one build volume standard for each category so that the design sources and the designers would be able to know for certain that their efforts will pay off. As mentioned previously, the current situation can be compared to a situation in which there is no standard sheet format (A4) in the digital printer market.

Another difficulty that arose from the market examination, which is emphasized in the methodology, is the option to produce flexible products. As reflected in the results of the research questionnaire, ≈87% out of all the participants showed interest in customizing the product, and almost 100% of the participants who have selected the option to own a P3DP showed a similar interest. There is an absence of open-source dynamic platforms that enable customization of virtual models, and, despite the fact that there is a high demand for customization, this aspect is not sufficiently developed. 'Thingiverse' enables adding text in a few models, but this is a very limited customization option. 'Nervous System' enables full customization, but the dynamic virtual customization platform is tailor-made especially for this studio and is not available for everyone. Therefore, even though the customization aspect is highly desired by potential users and even though it is the most significant competitive advantage factor, it is the least developed aspect, and design sources should be aware of that issue.

# CHAPTER 6

# RESULTS AND DISCUSSIONS

The prime motivation for this research stemmed from the interest to investigate the potentialities and possibilities in the P3DPs market from the perspective of the product designer. This nascent market offers revolutionary capabilities which could dramatically change the way in which people consume and interact with products. However, despite the fact that the promises of this market have, as yet, not been fulfilled, neither the literature nor other sources of information on 3D printing technologies, provide explanations for this shortcoming. The research did not aspire to fully answer this question, since this failure is due to numerous reasons that relate to various fields. At the same time, as an experienced product designer, and as an RPT academic supervisor engaged intensively with 3DPTs, I have concentrated my full efforts in order to contribute insights that might enhance understanding of the current situation, and provide tools (methodology) for product designers, in order to foster their efforts as they design products intended to be manufactured by P3DPs.

## 6.1. Summary of the description of the research motivation

Regarding the initial research motivation as described at the beginning of this dissertation and above, a table (Table 6.1A) containing references for the secondary motivations is presented for clarification.

The first motivation describing the exploration of the capabilities and limitations of P3DPs is described in chapter 2 (Literature Review), sub-chapter 2.1 (3D Printing) along with all its secondary sub-chapters. In general, I would note that the main advantage of 3DPTs in comparison to conventional mass-production manufacturing technologies, is the ability to produce parts without molds / dies, or fixed operating commands, which therefore far more easily enables customizations, if required, as well as general changes in designs. Moreover, this capability, along with the fact that 3DPs are automatic machines that do not produce waste during the manufacturing process, e.g. milling machines, makes 3DPs suitable for the home environment.

**Table 6.1A - Research Motivations References Clarification Table.**

| Motivations | References |
|---|---|
| To explore about the abilities and the limitations of the personal 3DP, in order to know inside-out the potential of it as a personal manufacturing mean. | **Section 2 - Literature Review.** Sub-Section 2.1 - 3D Printing. **Section 4 - The New 3D Printed Products Marekt.** Secondary Sub-Section 4.1.2 - The Indie Product Design Process. |
| To analyze the current 3D printed products market, for widely and deeply understanding of the current situation, and to identify types of users and products in this market. | **Section 4 - The New 3D Printed Products Market.** Sub-Section 4.3 - Types of Products. Sub-Section 4.4 - Types of Users. |
| To study about practical product design methodologies, and examine their relevancy to the personal 3DPs market. | **Section 2 - Literature Review.** Sub-Section 2.2 - Product Design Methodologies. **Section 5 - Product Design Methodology for Personal 3D Printers (P3DP).** |
| To review Mass Customization (MC) methods and paradigms as reference for advance approaches for strategies in the products market. | **Section 2 - Literature Review.** Sub-Section 2.3 - Mass Customization. |
| To review user involvement methods and paradigms as reference for advance approaches in products design and use. | **Section 2 - Literature Review.** Sub-Section 2.4 - User Involvement. |

The current limitations and disadvantages, as mentioned in the literature review chapter, as well as other limitations, e.g. the fact that certain components (e.g., batteries, microchips, etc.) cannot be produced by 3DPT, along with the fact that there are certain types of products whose size makes them unsuitable for production by P3DP, were not found to be obstacles which prevent 3DPs from being integrated into the home environment. Moreover, a number of these limitations and disadvantages aided in clarifying understanding of the market, and assisted in drawing the conclusions of the second motivation. Unexpectedly, a significant problem arose during the examination of the 3D printed products market (chapter 4), i.e. the break in the workflow. This break constitutes a symptom of a bigger problem that relates to the design of P3DPs, which is the lack of user friendliness, and may suggest why the general public has not enthusiastically adopted the technology. An additional, a significant problem that arose was the lack of standardization regarding the build volume of P3DPs, as well as the diameter of the raw material wire (in case of FFF P3DPs). This latter problem was discovered during the effort to formulate the methodology, which was worked out in order to provide product designers with a clear and comprehensive understanding regarding the product design process of products intended to be printed in 3D by a P3DP, with the goal of ensuring a solution at the conclusion of the practical process. The lack of the mentioned standards was discovered to be a deterrent factor that prevents designers from being able to design a product that will fit all P3DPs with certainty, or at least fit for a distinct portion of P3DPs.

The second motivation is described in chapter 4 (The New 3D Printed Products Market). The examination of the market revealed that its infrastructure is still in a process of formation, and that there are several models and possibilities with respect to the types of products, users and design sources. Regarding design sources, designers' ability to distribute their designs via cyberspace, and communicate directly with potential customers who own P3DPs, enables the market to expand in new directions but generates some controversy. On one hand, this option offers unique opportunities for trained designers to present and sell their designs wholly independent of marketers, vendors, manufacturers, or other intermediaries. On the other hand, untrained individuals / amateurs who wish to design a product for themselves or for this market can access free CAD software with little effort and subsequently offer designs for sale in identical manner. These untrained designers can unwittingly produce unsafe designs which may end up injuring users, and regardless of the level of professionalism of the designers, literary sources, and many other coverage sources highlight this issue of the misuse and deleterious exploitation of the technology, as well as the issue of free design tools which can be used to produce harmful products. This disturbing scenario is already occurring. Suitable files for P3DP for gun parts can be found nowadays on the dark-net, and it appears that governments do not know how to regulate this market or are not aware of this problem.

Regarding the types of products and users, I refer to the 3D printing market in general, and sort the types of users according to the source of ownership of the 3DP and the degree of involvement in the final design process. The analysis of each type of user was in accordance with these cited factors and with the types of products, and this examination subsequently provided a better understanding of how to approach the 3DP market. The new definitions that were established have become significant factors in the methodology, and they provide theoretical, strategic knowledge for every stakeholder (academic / commercial).

The general conclusion that emerged from the comprehensive review and the examination of the P3DP market indicates that the same development has taken place in other industries that have been democratized and most likely will happen in the products market, i.e. P3DPs will expand the market and will offer solutions that fit the relevant context, in parallel to the continued existence of the mass-produced products market. Moreover, there is a probability that 3D printed parts will be integrated with mass-produced parts and there will be no distinct border between 3D printed products and mass-produced products. As presented in chapter 4, the semi-democratic types of products represent this exact type of scenario.

The third and the fourth motivations that refer to the study of practical product design methodologies and mass-customization methods are described in chapter 2 (Literature Review). The examination of the methods that relate to the mass-customization field, and the insights that were subsequently gained, assisted me in formulating the research questionnaire and in establishing its theoretical basis. Moreover, the examination of the P3DP market has shown that the existence of P3DPs in the home environment can potentially sustain highly developed levels of mass-customization, e.g. tailored customization and pure customization (Lampel and Mintzberg, 1996). In the context of the theoretical developments of this research, the Customized-Democratic model (p.160) represents the highest level of customization that can be achieved (pure customization) and which can be practically implemented thanks to P3DPs.

The review and examination of the methodologies that relate to the product design field helped me to, firstly, thoroughly understand this theoretical field and its requirements and secondly, to establish the theoretical basis for the methodology that was formulated at the end of this research. I would note that ultimately the methodology was based conceptually on the structure and the flow of the already proven existing methodologies. However, new considerations and required adjustments that relate specifically to the P3DPs market have changed slightly and reduced the number of the phases that comprise the process, and have added new considerations and requirements that relate exclusively to the design of products intended to be fully / partially manufactured by a P3DP.

The last motivation that refers to the study and the examination of user involvement methods is described in chapter 2 (Literature Review). The fact that all the methods refer to user involvement in a design process for products intended to be manufactured by conventional manufacturing systems has resulted in the identification of another gap. This gap was less thoroughly examined and relates to user involvement in the open-architecture / flexible-architecture of products. The research questionnaire, and the taxonomy of the types of users as presented in sub-chapter 4.4 (Types of Users), were inspired by a few non-studied user-involvement practices which were reviewed and examined in chapter 2, sub-chapter 2.3 (Mass-Customization), and secondary sub-chapter 2.3.3 (Unstudied Cases). Consequently, I have concluded that this field has unique characteristics and considerations which require further studies, and testing.

## 6.2. Summary of the Research Questions

Regarding the main research questions as presented at the beginning of this dissertation, for purpose of clarification a table is provided that shows where each question is backed by references (Table 6.2A). I would note at this point that all the questions provided a compass for the general research, and I have concentrated my full efforts in order to find genuine answers to these questions.

**Table 6.2A - Research Questions References Clarification Table.**

| Research Questions | References |
|---|---|
| $Q_1$ – What are the stages, and what needs to be included in a design process of a product intended to be manufactured by a personal 3D printers? | Chapter 5 - Product Design Methodology for Personal 3D Printers. |
| $Q_{1.1}$ – Which types of products might be designed and be suitable for personal 3D printers? | Chapter 4 - The New 3D Printed Products Market. |
| $Q_2$ – What type of personal 3D printer people will want to have, if any? | Chapter 3 - Research Questionnaire. |
| $Q_{2.1}$ – Will a person with personal 3D printer prefer to 3D print standard, or customized products, or it depends on the type of the product? | Chapter 3 - Research Questionnaire. |

The answer to the first main question ($Q_1$) began to be formulated during the literature review of the product design methodologies. The reviewed conventional methodologies were the reference point on whose structure I have derived the methodology, which from the outset has been the aim of this research. Further to the literature review, I have examined the 3D printed products market, and a few new insights and answers that relate to the first secondary research question ($Q_{1.1}$) have provided substantial material which was eventually integrated into the methodology. Thus, the final answer for the first main question was provided in the form of the methodology (p.185).

In general, there are four issues that characterize and distinguish the methodology that was derived, compared to existing ones:

1. The description of the process was shortened (the concept and the preliminary design phases were merged into one phase) due to the fact that the means of manufacturing (P3DP) is a predetermined constraint.

2. New general values that relate specifically to considerations that need to be taken into account in a design process for products intended to be fully/partially manufactured by P3DP were integrated into the methodology, along with regular design considerations.

3. Unique new values that relate to the type of the product (FDP/FSDP/RDP/RSDP) were added to the methodology.

4. The success of the solution is not guaranteed, due to the lack of standardization in the P3DPs market.

The answer to the first secondary question ($Q_{1.1}$) began to be formulated during the examination of the unstudied cases (secondary sub-chapter 2.3.3, pp.84-86), and continued during the examination of the 3D printed products market, and was finally expressed by way of the taxonomy matrix (Figure 4.3A, p.163) that characterized types of products according to the dependency of each product on non-3D-printable components, and to the architectonic status of the product and its ability to enable users to be involved in the determination of the final design. As mentioned above, the characterization of the types of products has become a cornerstone in the theoretical understanding of the market for products that are intended to be fully/partially manufactured by P3DPs. Moreover, this was fundamentally seen in the methodology, and is also one of the factors that proves that P3DPs will expand the products market and will accompany mass-production systems and their mass-produced products/components.

The answer to the second main question ($Q_2$) began to be formulated during the literature review of 3D printing technologies. The review and comparison of the 3DPs that are marketed as desktop P3DP (Tables 2.3 and 2.4, pp.39-40) have attempted to establish an initial understanding of the distinct types of P3DPs, by which point I have already identified the problem of the inability to classify types of P3DPs due to an absence of standards that define what can be considered and be marketed as a desktop P3DP. However, I have noticed that, in general, the P3DPs can be divided into relatively big and relatively small groups, and accordingly I have formulated the research questionnaire that was designed to provide answers to the second main question.

The definitive answer to the second main question is provided in sub-chapter 3.5 (Questionnaire Analysis), and as can be seen, 34% of the participants selected the 'Makers' option (large size P3DP), 31% selected the 'Common' option (small size P3DP), and 35% selected the 'None' option. These results have presented an interesting distribution of 65% which showed interest in P3DPs, and 35% which showed no interest at all (mostly females and participants more than 40 years old). This significant share of 65% indicates that there is a willingness to adopt and use the technology, and that people are aware of it. Since P3DPs are already accessible and affordable, this statistic had led to the conclusion that the reason for the market gap is most probably due to design faults (as deduced and validated in chapter 4), and not because of a lack of awareness or interest.

Regarding the second secondary question ($Q_{2.1}$), the results of the questionnaire have shown that the customization aspect is perceived as more significant than the self-manufacturing aspect. As presented in sub-chapter 3.5 (Questionnaire Analysis), ≈98% of the participants that selected the options 'Makers' or 'Common', chose to customize the products, and 62% of those who checked the 'None' option, also showed interest in customizing the product. Taking into consideration all the participants, ≈87% showed interest in customizing the product, or 25% more in comparison to those who showed interest in self-manufacturing. Looking at these statistics from the opposite perspective, ≈13% of the participants have opted to follow the standard approach, i.e. to choose a readymade product from a catalogue. This clear distribution might suggest that the self-manufacturing issue is only second to the customization issue, and that individuals tend to give more significance to customization value.

The second secondary question ends with considerations regarding the dependency between the desire to customize according to the type of product. The theoretical basis of the questionnaire, along with considerations that relate to the first main question ($Q_1$), had led to an examination of a single product (bicycle) which might highlight the differences between large size and small size P3DPs. Thus, this consideration remained with no clear answer, and I realized that this modest consideration should actually be a separate question that should be examined independently, and I intend to examine this issue in the framework of follow-up research.

## 6.3. Summary of the Research Objectives

Regarding the research objectives as presented at the beginning of this dissertation, for purposes of clarification a table is provided that shows where each objective was accomplished, along with associated references (Table 6.3A).

The first objective was accomplished in chapter 5, in accordance with the theoretical basis that was established from conclusions that arose mainly in chapter 2 and chapter 4. In light of the wording of this objective, I would note that the conventional methodologies do not differentiate between the design processes of standard, one-off, and tailor-made products, since they successfully prove that there are no substantial differences in the design process of these cited products types. The methodology that was presented follows this same logic, with a few adjustments, and inserts unique considerations that relate specifically to products intended to be manufactured by a P3DP.

Table 6.3A- Research Objectives References Clarification Table.

| Research Objectives | References |
|---|---|
| To set a methodology for product designers which relates to design of products for desktop personal 3DP, for understanding of the differences between this methodology, and methodologies for mass-produced standard, or one-of, tailor-made, products. | **Chapter 5 - Product Design Methodology for Personal 3D Printers (P3DP).** |
| To identify the factors that integrate the value chain that links designers, 3D printable products, and home-users, for knowing all the factors that involved in this interaction. | **Chapter 4 - The New 3D Printed Products Market.** |
| To define types of products in a desktop personal 3DPs market, in order to assist to establish strategic plans. | **Chapter 4 - The New 3D Printed Products Market.** |
| To define types of users in a desktop personal 3DPs-market, in order to punctuate the understanding, in a direct interaction scenario. | **Chapter 4 - The New 3D Printed Products Market.** |
| To exam how potential homes users perceive 3DP, in order to better understand the market gap that was mentioned previously, from the perspective of the potential user. | **Chapter 3 - Research Questionnaire.** |

The second, third, and fourth objectives are closely related to each other. The second objective was accomplished as part of the conclusions which arose from the market review in chapter 4, and was used as the theoretical basis to accomplish the third and the fourth objectives. As noted above, these three objectives have become a substantial part of the theoretical basis of the methodology that was presented at the end of chapter 5.

The fifth and last objective was accomplished in chapter 3, where the examination of how participants perceive P3DPs was conducted in light of the combination of three factors: the type of P3DP selected (large or small size), the perceived level of professionalism, and the willingness to pay a certain price range. The main conclusion that arose from the results indicated that the semi-professional 'Common' participants (participants who selected a small size P3DP and perceive P3DPs to be equivalent to a smartphone) are the segment which is the most aligned with the market regarding the price that they are willing to pay in order to buy a P3DP, unlike the 'Makers', who showed willingness to pay a price that is outside to the realistic market price range.

These results have provided another explanation for the gap that exists between the P3DPs market and potential users, which relates to the aspects of affordability.

## 6.4. Summary of the Research Hypotheses

Regarding the research hypotheses as presented at the beginning of this dissertation, for clarification purposes a clarification table has been provided that shows where each hypothesis was examined, along with associated references (Table 6.4A).

**Table 6.4A - Research Hypotheses References Clarification Table.**

| Research Hypotheses | References |
|---|---|
| $H_1$ – Once desktop personal 3D printers and its raw-materials will be affordable and accessible for the common people, they will prefer to have one. | Chapter 3 - Research Questionnaire. |
| $H_2$ – Users that will own desktop personal 3D printers will prefer to customize their products according to their needs. | Chapter 3 - Research Questionnaire. |
| $H_3$ – A methodology for product designers, which will communicate how to design products for the personal 3D printers, will help them to deeply understand the challenges and the opportunities in this market. | Chapter 5 - Product Design Methodology for Personal 3D Printers (P3DP). |

The first hypothesis assumed that the revolutionary capabilities offered by P3DPs are so powerful that the general public is aware of them, appreciate them, and that therefore the reasons for the gap between the P3DPs market and potential users is essentially an issue tied to gaps relating to the aspects of accessibility and affordability. This research has provided a complex answer, as reflected in the research questionnaire. According to the initial assumption, the first question of the questionnaire was designed to neutralize these aspects by eliminating the affordability aspect and by offering P3DPs without alternatives (beside the 'None' option). As mentioned previously, the results show a significant statistic of 65% who are willing to adopt the technology, along with 35% who showed no interest in it. First, the 35% portion is a statistic that should not be ignored, and represents a matrix of causes that do not relate to the aspects of affordability or accessibility. Secondly, out of the 65%, only 9% were found as aligned with market prices (12 semi-professional 'Common' participants). This offers practical proof that the affordability aspect is one of the main reasons for the cited gap among those who are willing to adopt the technology. Additionally, women were found to be much less likely to be associated with the 3D printing field. The reasons for this should be examined separately. Moreover, the research has revealed more reasons that relate to design faults (e.g., the workflow and the interface) and problems deriving from a lack of standardization. All these reasons can shed light on the area relating the causes not related to the aspects of affordability and accessibility and could explain the 35% share, as well as the fact that women do not recognize the revolutionary advantages that the technology is capable of delivering.

The second hypothesis was strongly validated by the results of the questionnaire: not only that participants who selected one of the P3DPs options showed great interest in product customization, but also those who showed no interest at all in self-manufacturing demonstrated great interest in the aspect of customization. The questionnaire examined all the questions that relate to 3D printing and the customization aspects by using a single product (a bicycle) that was found to be the most suitable product in establishing the theoretical basis of the questionnaire. Therefore, all these questions should be examined on the basis of other products in follow-up research, nevertheless this conclusion should be of note to the 3D printing industry, and marketers should consider emphasizing the customization aspect as a more important desire in comparison to the self-manufacturing aspect.

The third hypothesis assumed that a unique methodology would be formed at the end of the process, and therefore it should be practically examined. The theoretical basis of the methodology, along with insights that emerged from the comprehensive market review, have led to a formation of a well-established methodology, and thus it was not required for practical examination. The fact that the structure and the flow of the represented process of the methodology rely on the same structure of the proven

methodologies, along with the fact that all the unique considerations that were inserted were derived from an examination of real cases, and that there are no other methodologies to be compared which refer to a design process of products intended to be manufactured by a P3DP, have made the need to practically examine the methodology in order to validate it redundant.

## 6.5. Conclusions and Scope for Follow-Up Researches

The framework of this research has managed to accomplish all the objectives, answer all the questions, and validate the hypotheses in complex manner. Some of the reasons responsible for the gap that exists between the P3DPs market and potential users were discovered, and are related to the gap between the potential users' willingness to pay a certain price range and the actual market prices. Since undertaking this research, the price of a few DIY P3DPs has dropped, and this trend represents an awareness of the above-cited issue.

Other problems that were revealed are related to design and to the lack of standardization. As long as P3DPs producers continue to design P3DPs as an independent CNC machine and do not improve the interface and the fluidity of the workflow, the general public will continue to ignore the technology. Additionally, as long as producers do not establish standards which define a standard build volume, and what can be considered to be a standard configuration of raw materials, product designers will not be able to maximize their contribution to the development of the 3D printing field. Since this research started, one company has debuted a P3DP with a fluid workflow. This could be merely a swallow heralding the arrival of spring that indicated a local awareness of this lack, or it may represent a wider awareness of this issue.

The analysis of the questionnaire has resulted in the conclusion that women are much less interested in the 3D printing field in comparison to men. Far fewer women participated in the questionnaire, and even those who participated showed much less interest in P3DPs. The reason for this phenomenon was not deeply examined, and requires follow-up research which might reveal a hidden answer that might contribute more insights into the aforementioned gap.

The questionnaire examined how the general public perceives P3DPs and, in order to put the P3DPs in context, the questionnaire presented a product (bicycle) and allowed participants to choose whether to be involved in its design, as well as select their level of involvement in its manufacture of it (fully/partially/none). The questionnaire aspired to cover all the types of products that were defined in chapter 4 (The New 3D Printed Products Market – sub-chapter 4.3 – Types of Products) on the basis of one product. Based on the selection of the P3DP type, each participant determined the status of the product with regard to its dependency on complementary parts/components, i.e. participants who selected the 'Makers' option and chose to customize the product followed the FDP type of product model, while participants who selected the 'Common' option and chose to customize the product followed the FSDP model. This theoretical examination is the first of its kind, and additional examination is required. Initial follow-up research should focus on real P3DPs and should examine how people perceive their interaction with P3DPs in real life. This research should evaluate the experience and the quality of the outcomes, in comparison to the interaction with mass-produced products. Subsequent follow-up research should thoroughly examine the type of product models (Figure 4.3A, p.163) on the basis of the theory in this doctoral research, and by examining additional types of products.

Information that was gathered as part of the literature review of 3D printing technologies has led to a comparative analysis of P3DPs. At this point, the issue of the lack of standardization has been identified, and follow-up research should expand upon this examination and formulate an established recommendation for recommended standards for the build volumes of P3DPs.

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## Chapter 1 - Introduction

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**Figure 1.2. "Monocoque 2". Neri Oxman, 2007** – Materialecology. (30.06.2016). http://www.materialecology.com/projects/details/monocoque-2#prettyPhoto

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## Chapter 2 – Literature Review

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**Figure 2.3W - The dynamic interactive online design platform** – Nervous System Studio. (27.05.2015). https://n-e-r-v-o-u-s.com/cellCycle/?t=0

**Figure 2.3X – Exploded view of Normal's earphones** – Nrml. (12.09.2014). http://www.3ders.org/articles/20140709-normal-makes-customized-3d-prin ted-earph ones-that-perfectly-fit-your-ears.html

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# Appendixes

## Appendixes of Sub-Chapter 2.1. – 3D Printing

### Appendix 2.1.1A – Types of 'Material Extrusion' 3D printers.

Stratasys 'MakerBot – Replicator Mini' FDM personal desktop size 3DP, with external dimensions of 295 X 310 X 381 mm, weights 8 kg, and has one nozzle (can print one color parts).

[16]**App. Figure 2.1.1A-1**

Stratasys 'Dimension Elite' industrial 3DP, with build size of 203 X 203 X 305 mm. Can print multi-colors models.

[17]**App. Figure 2.1.1A-2**

[16] Source: https://store.makerbot.com/replicator-mini
[17] Source: http://www.stratasys.com/3d-printers/design-series/dimension-elite

Stratasys 'Fortus-900mc' FDM industrial 3DP, with build size of 914 X 610 X 914 mm.

[18]**App. Figure 2.1.1A-3**

Material extrusion 3D printing of ceramics, by the industrial designer Oliver van Herpt (oliviervanherpt.com).

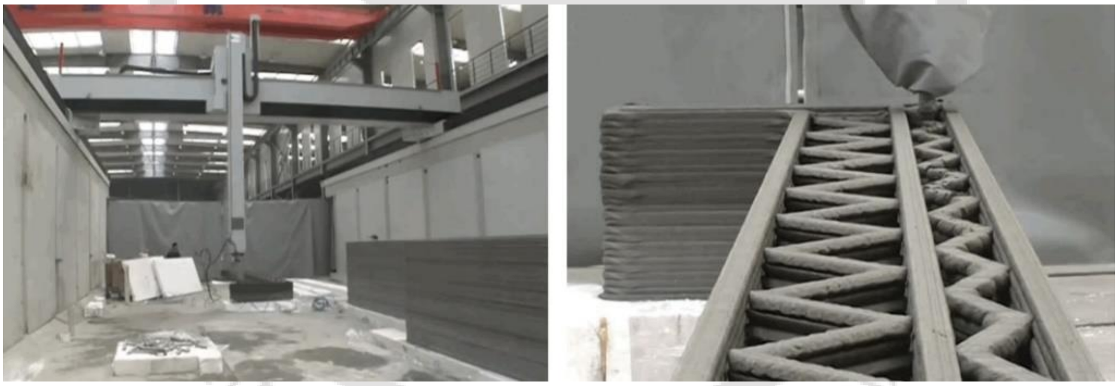
[19]**App. Figure 2.1.1A-4**

[18] Source: https://all3dp.com/biggest-3d-printers-world/
[19] Source: http://oliviervanherpt.com/3d-printing-ceramics/

Material extrusion 3D printing of food in the Dutch restaurant 'Food Ink'.

[20]**App. Figure 2.1.1A-5**

Large scale material extrusion 3DP that prints concrete for building houses in china. There is an interesting influence of the technology on the design, as can be seen in the cross-section of the wall.



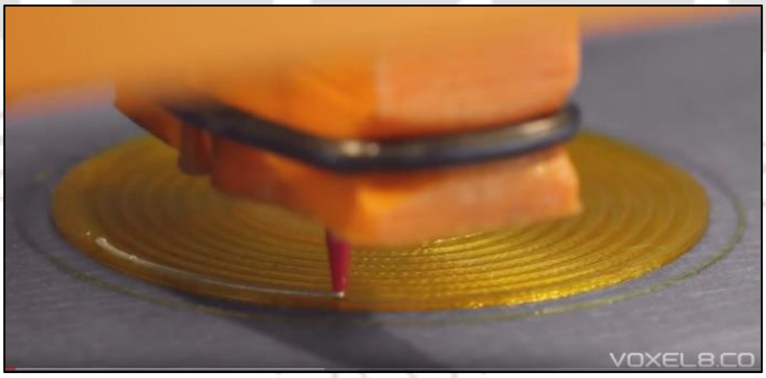
[21]**App. Figure 2.1.1A-6**

[20] Source: http://www.thefoodrush.com/blog/3d-printing-food-for-an-entire-restaurant-menu/

[21] Source: https://all3dp.com/biggest-3d-printers-world/

Voxel's 3D Electronics Printer, desktop size, FFF Pneumatic Direct Write 3DPT, with build volume of 150 X 150 X 100.


**[22]App. Figure 2.1.1A-7**




**[23]App. Figure 2.1.1A-8**

[22] Source: http://www.voxel8.co/
[23] Source: http://www.voxel8.co/

**Appendix 2.1.1B – Types of 'Photopolymers Solidification' 3D-printers.**

'Form 2', desktop personal SLA 3DP by 'Form LABS' with external dimensions of 350 X 330 X 520 mm.

[24]**App. Figure 2.1.1B-1**

'PROJET 7000 HD", industrial SLA 3DP by '3D Systems' with build volume of 380 X 380 X 250 mm.

[25]**App. Figure 2.1.1B-2**

[24] Source: http://formlabs.com/products/3d-printers/form-2/
[25] Source: https://www.3dsystems.com/3d-printers/professional/projet-7000-hd

'ProX 950", large scale, additive manufacturing and complementary technology industrial SLA 3DP by '3D Systems' with build volume of 1500 X 750 X 550 mm.

[26]**App. Figure 2.1.1B-3**

'OLO', personal mini DLP 3DP by 'OLO', with external dimensions of 172 X 115 X 148 mm, prints object by using smartphone.

[27]**App. Figure 2.1.1B-4**

[26] Source: https://www.3dsystems.com/3d-printers/production/prox-950
[27] Source: http://www.olo3d.net/

'Ember', desktop personal DLP 3DP by 'Autodesk', with external dimensions of 325 X 340 X 434 mm, and weight of 10 Kg.

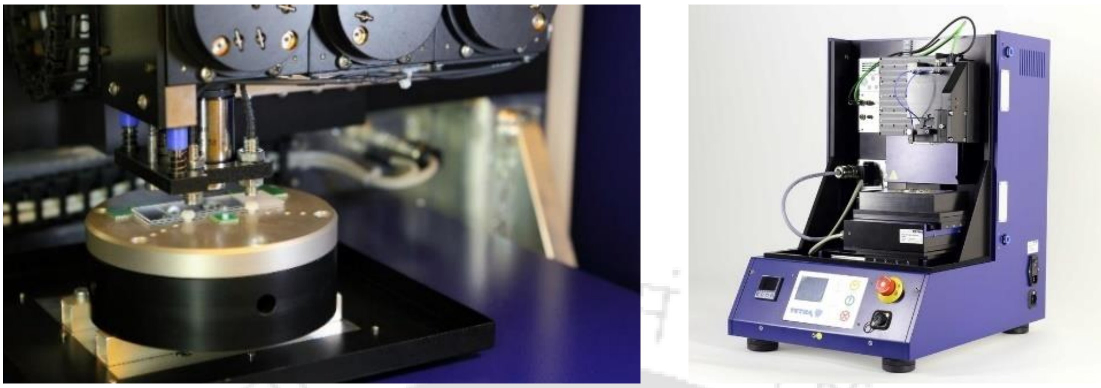
[28]**App. Figure 2.1.1B-5**

Industrial DLP 3DPs by 'ENVISIONTEC. Left picture: 'ULTRA 3SP' 3DP with build volume of 266 X 175 X 193 mm. Right picture: 'XEDE 3SP' 3DP with build volume of 457 X 457 X 457 mm.


[29]**App. Figure 2.1.1B-6**

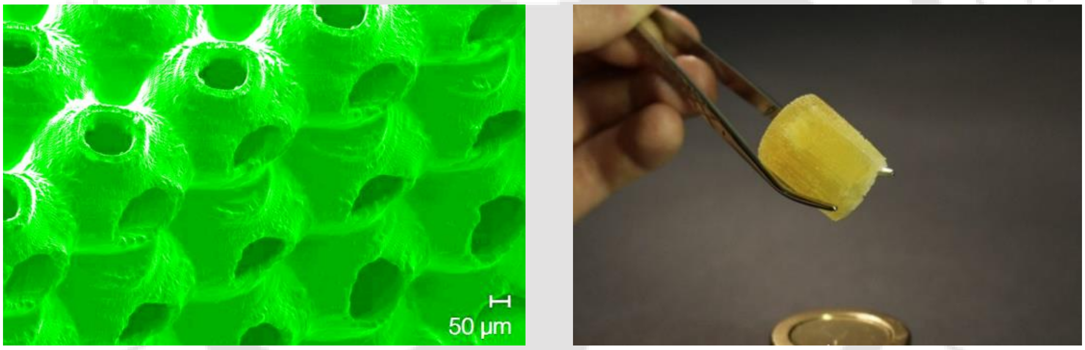
[28] Source: http://www.3ders.org/articles/20141030-autodesk-announces-million-inves tment-fund-for-3d-printing-companies.html
[29] Source: http://envisiontec.com/3d-printers/

'BASALT N2' 2PP 3DP by 'TETRA', that can produce 3D printed models with resolution of less than 100 nm.



[30]**App. Figure 2.1.1B-7**

An example for 3D printed Nanometer structure that was printed by 2PP technology.




[31]**App. Figure 2.1.1B-8**

[30] Source: Left Picture-https://3dprint.com/49406/tetra-3d-printer-record/; Right Picture-http://trends.directindustry.com/tetra-gmbh/project-121425-143001.html
[31] Source: https://3dprint.com/49406/tetra-3d-printer-record/

**Appendix 2.1.1C – Types of 'Powders Solidification' 3D-printers.**

'X1', industrial binder jetting 3DP, by 'Addwii, with build volume of 200 X 160 X 150 mm. Can produce colorful models. '

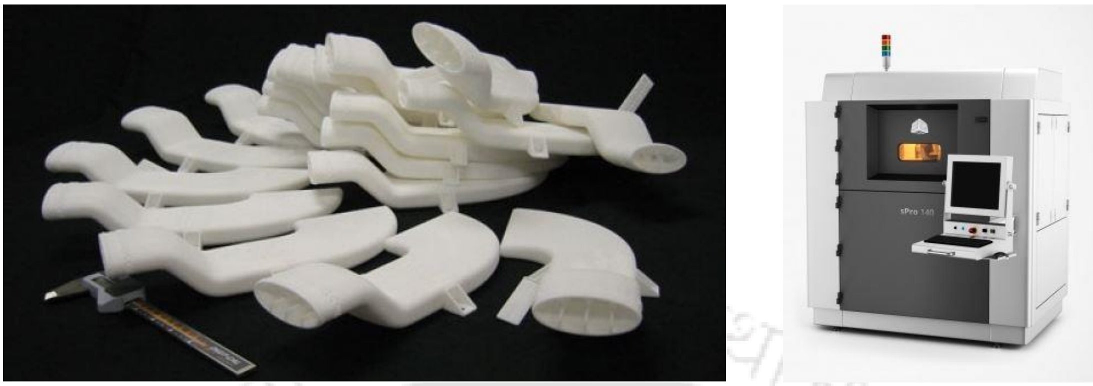
**[32]App. Figure 2.1.1C-1**

'Exerial', serial production, industrial, large scale binder jetting 3DP, by 'ExOne, with build volume of 2200 X 1200 X 700 mm. One of the largest 3DPs in the world.'


**[33]App. Figure 2.1.1C-2**

[32] Source: https: https://3dprint.com/90013/addwii-x1-3d-printer/
[33] Source: https://www.3dsystems.com/3d-printers/production/spro-140

's-Pro 140' industrial SLS 3DP by '3D Systems' with build volume of 550 X 550 X 460 mm.



**[34]App. Figure 2.1.1C-3**

Industrial 'Direct Metal Printing' (DMP) 3DP, by '3D System'. Left picture: 'ProX DMP 100', with build volume of 100 X 100 X 100 mm. Right picture: 'ProX DMP 300', with build volume of 250 X 250 X 330 mm.

**[35]App. Figure 2.1.1C-4**

[34] Source: https://www.3dsystems.com/3d-printers/production/spro-140

[35] Source: https://www.3dsystems.com/sites/www.3dsystems.com/files/dmp_brochure_0116_usen_web_1.pdf

## Appendix 2.1.1D– Types of 'Polyjet' 3D-printers.

'Objet 30', marketed as desktop 'Polyjet' 3DP, by Stratasys', with build volume of 300 X 200 X 150 mm.

[36]**App. Figure 2.1.1D-1**

'Objet 260' (the small one), industrial 'Polyjet' 3DP, by 'Stratasys', with build volume of 255 X 252 X 200 mm, and 'Objet 500', with build volume of 490 X 390 X 200 mm.

[37]**App. Figure 2.1.1D-2**

[36] Source: http://www.stratasys.com/3d-printers/design-series/objet30
[37] Source: http://www.stratasys.com/3d-printers/dental-series/dental-selection-systems #content-slider-1

## Appendix 2.1.1E – Types of 'Sheets Lamination' 3D-printers.

'SD 300' marketed as desktop 'LOM' 3DP, by 'Cubic Technologies', with maximum model size of 210 X 160 X 135 mm.


[38]App. Figure 2.1.1E-1

'IRIS', industrial Inkjet A4 standard papers 'LOM' 3DP, by 'MCOR', with build size of 256 X 169 X 150 mm.

[39]App. Figure 2.1.1E-2

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[38] Source: Left picture: http://www.fabbaloo.com/blog/2009/12/11/solido-sd300-pro .html; Right picture: http://www.cubictechnologies.com/SD300.htm
[39] Source: Left picture: http://www.laptopmag.com/articles/staples-to-offer-easy-3d-printing-in-2013; Right picture: http://mcortechnologies.com/industries /service-bureaus/

## Appendixes of Secondary Sub-Chapter 3.2.3 – The Product

### Appendix 3.2.3A – 3D Printed Garments

3D printed top garment by Iris van Herpen.

**[40]App. Figure 3.2.3A-1**

[40] Source: http://www.irisvanherpen.com/DOCS/IVH-Crystallization.pdf

3D printed top garments by Neri Oxman.

[41]**App. Figure 3.2.3A-2**

[42]**App. Figure 3.2.3A-3**

3D printed garments by Danit Peleg.

[43]**App. Figure 3.2.3A-4**

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[41] Source: http://www.materialecology.com/projects/details/zuhal#prettyPhoto[zuhal] /5/

[42] Source: http://www.materialecology.com/projects/details/otaared#prettyPhoto[ota ared]/2/

[43] Source: http://www.the3dzone.co.il/%D7%A2%D7%99%D7%A6%D7%95%D7%91/%D7%9E%D7%A2%D7%A6%D7%91%D7%AA-%D7%90%D7%95%D7%A4%D7%A0%D7%94-%D7%91%D7%95%D7%92%D7%A8%D7%AA-%D7%A9%D7%A0%D7%A7%D7%A8-%D7%94%D7%93%D7%A4%D7%99%D7%A1%D7%94-4-%D7%A7%D7%95%D7%9C%D7%A7%D7%A6%D7%99%D7%94/

## Appendix 3.2.3B – 3D Printed Bicycle Frame

Folding bicycle with 3D printed aluminum frame, by 'Shapeways' and 'Montague Bike'.


[44]App. Figure 3.2.3B-1

Titanium alloy 3D printed bicycle frame, by the British company 'Empire Cycles'.

[45]App. Figure 3.2.3B-2

[44] Source: https://www.montaguebikes.com/montague-bikes-in-the-news/
[45] Source: http://www.renishaw.com/en/first-metal-3d-printed-bicycle-frame--31906

Luna 3D printed bicycle (SLS - nylon), designed by Omer Sagiv.


**[46]App. Figure 3.2.3B-3**



[46] Source: http://bicycledesign.net/2014/11/luna-3d-printed-bicycle-by-omer-sagiv/

## Appendixes of Sub-Chapter 3.5. – Questionnaire Analysis

## Appendix 3.5A – Statistics of the second page

**Table 3.5A1 – Number of Participants**

| Total | Males | Males % | Females | Females % |
|---|---|---|---|---|
| 127 | 95 | 75% | 32 | 25% |

**Table 3.5A2 – Number of participants – Age range**

| | Total | Total % | Males | Males % | Females | Females |
|---|---|---|---|---|---|---|
| **15-20** | 19 | 15.0% | 15 | 16% | 4 | 12.5% |
| **20-30** | 62 | 49.0% | 45 | 47% | 17 | 53.0% |
| **30-40** | 28 | 22.0% | 21 | 22% | 7 | 22% |
| **40-50** | 15 | 12.0% | 11 | 12% | 4 | 12.5% |
| **50-60** | 2 | 1.5% | 2 | 2% | 0 | 0% |
| **60-70** | 1 | 0.5% | 1 | 1% | 0 | 0% |
| **Total** | 127 | 100% | 95 | 100% | 32 | 100% |

**Table 3.5A3 – Type of 3DP**

| | Total | Total % | Males | Males % | Females | Females |
|---|---|---|---|---|---|---|
| **'Makers'** | 43 | 34% | 35 | 37% | 8 | 25% |
| **'Common'** | 40 | 31% | 35 | 37% | 5 | 16% |
| **'None'** | 44 | 35% | 25 | 26% | 19 | 59% |
| **Total** | 127 | 100% | 95 | 100.00% | 32 | 100.00% |

**Table 3.5A4 – Type of 3DP – 'If None'**

| | Total | Total % | Males | Males % | Females | Females |
|---|---|---|---|---|---|---|
| **Customize & Assemble** | 10 | 23% | 6 | 23% | 4 | 22% |
| **Customize Only** | 17 | 38.5% | 10 | 38% | 7 | 39% |
| **From Catalogue** | 17 | 38.5% | 10 | 38% | 7 | 39% |
| **Total** | 44 | 100.00% | 26 | 100% | 18 | 100% |

## Appendix 3.5B – Statistics of the third page

## Basic Functional Components

### Table 3.5B1 – Frame – Type of 3DP and Customizers

| Type of 3DP – General | S | S% | M | M% | D | D% | C | C% |
|---|---|---|---|---|---|---|---|---|
| 'Makers' (43) | 25 | 58% | 24 | 56% | 18 | 42% | 25 | 58% |
| 'Common' (40) | 27 | 68% | 22 | 55% | 29 | 73% | 27 | 68% |
| 'None' – C&A | 5 | 50% | 3 | 30% | 4 | 40% | 6 | 60% |
| 'None' – CO (17) | 11 | 65% | 8 | 47% | 11 | 65% | 13 | 76% |
| **Total** | **68** | **62%** | **57** | **52%** | **62** | **56%** | **71** | **65%** |
| **Average** | | **60%** | | **47%** | | **55%** | | **66%** |
| **ST.DEV** | | **0.08** | | **0.12** | | **0.16** | | **0.08** |
| **Males** | | | | | | | | |
| 'Makers' (35) | 21 | 60% | 20 | 57% | 17 | 49% | 21 | 60% |
| 'Common' (35) | 24 | 69% | 22 | 63% | 27 | 77% | 25 | 71% |
| 'None' – C&A (6) | 2 | 33% | 2 | 33% | 2 | 33% | 3 | 50% |
| 'None' – CO (10) | 5 | 50% | 6 | 60% | 6 | 60% | 7 | 70% |
| **Total** | **52** | **60%** | **50** | **58%** | **52** | **60%** | **56** | **65%** |
| **Average** | | **53%** | | **53%** | | **55%** | | **63%** |
| **ST.DEV** | | **0.15** | | **0.14** | | **0.18** | | **0.10** |
| **Females** | | | | | | | | |
| 'Makers' (8) | 4 | 50% | 4 | 50% | 1 | 13% | 4 | 50% |
| 'Common' (5) | 3 | 60% | 0 | 0% | 2 | 40% | 2 | 40% |
| 'None' – C&A (4) | 3 | 75% | 1 | 25% | 2 | 50% | 3 | 75% |
| 'None' – CO (7) | 6 | 86% | 2 | 29% | 5 | 71% | 6 | 86% |
| **Total** | **16** | **67%** | **7** | **29%** | **10** | **42%** | **15** | **63%** |
| **Average** | | **68%** | | **26%** | | **43%** | | **63%** |
| **ST.DEV** | | **0.16** | | **0.20** | | **0.24** | | **0.21** |

### Table 3.5B2 – Frame – Age Range.

| Age Range - General | S | S% | M | M% | D | D% | C | C% |
|---|---|---|---|---|---|---|---|---|
| 15-20 (18) | 11 | 61% | 5 | 28% | 9 | 50% | 13 | 72% |
| 20-30 (58) | 29 | 50% | 29 | 50% | 29 | 50% | 34 | 59% |
| 30-40 (26) | 21 | 81% | 17 | 65% | 16 | 62% | 18 | 69% |
| 40-50 (7) | 6 | 86% | 5 | 71% | 7 | 100% | 5 | 71% |
| 50-60 (1) | 1 | 100% | 1 | 100% | 1 | 100% | 0 | 0% |
| **Total** | **68** | **62%** | **57** | **52%** | **62** | **56%** | **70** | **64%** |
| **Average** | | **69%** | | **54%** | | **65%** | | **68%** |
| **ST.DEV** | | **0.17** | | **0.19** | | **0.24** | | **0.06** |
| **Males** | | | | | | | | |
| 15-20 (14) | 8 | 57% | 5 | 36% | 8 | 57% | 10 | 71% |
| 20-30 (44) | 21 | 48% | 24 | 55% | 23 | 52% | 26 | 59% |
| 30-40 (19) | 16 | 84% | 15 | 79% | 13 | 68% | 14 | 74% |
| 40-50 (7) | 6 | 86% | 5 | 71% | 7 | 100% | 5 | 71% |
| 50-60 (1) | 1 | 100% | 1 | 100% | 1 | 100% | 0 | 0% |
| **Total** | **52** | **61%** | **50** | **59%** | **52** | **61%** | **55** | **65%** |
| **Average** | | **69%** | | **60%** | | **69%** | | **69%** |
| **ST.DEV** | | **0.19** | | **0.19** | | **0.21** | | **0.07** |
| **Females** | | | | | | | | |
| 15-20 (4) | 3 | 75% | 0 | 0% | 1 | 25% | 3 | 75% |
| 20-30 (14) | 8 | 57% | 5 | 36% | 6 | 43% | 8 | 57% |
| 30-40 (7) | 5 | 71% | 2 | 29% | 3 | 43% | 4 | 57% |
| 40-50 (0) | 0 | 0% | 0 | 0% | 0 | 0% | 0 | 0% |
| 50-60 (0) | 0 | 0% | 0 | 0% | 0 | 0% | 0 | 0% |
| **Total** | **16** | **64%** | **7** | **28%** | **10** | **40%** | **15** | **60%** |
| **Average** | | **51%** | | **16%** | | **28%** | | **47%** |
| **ST.DEV** | | **0.09** | | **0.19** | | **0.10** | | **0.10** |

## Table 3.5B3 – Frame – Type of 3DP ('Makers') - Age Range.

| Age Range - General | S | S% | M | M% | D | D% | C | C% |
|---|---|---|---|---|---|---|---|---|
| 15-20 (9) | 5 | 56% | 2 | 22% | 4 | 44% | 6 | 67% |
| 20-30 (22) | 9 | 41% | 12 | 55% | 7 | 32% | 11 | 50% |
| 30-40 (11) | 10 | 91% | 8 | 73% | 6 | 55% | 7 | 64% |
| 40-50 (0) | 0 | 0% | 0 | 0% | 0 | 0% | 0 | 0% |
| 50-60 (1) | 1 | 100% | 1 | 100% | 1 | 100% | 1 | 100% |
| **Total** | **25** | **58%** | **23** | **53%** | **18** | **42%** | **25** | **58%** |
| **Average** | | **62%** | | **50%** | | **44%** | | **60%** |
| **ST.DEV** | | **0.26** | | **0.26** | | **0.11** | | **0.09** |
| **Males** | | | | | | | | |
| 15-20 (7) | 4 | 57% | 2 | 29% | 4 | 57% | 5 | 71% |
| 20-30 (17) | 7 | 41% | 9 | 53% | 6 | 35% | 8 | 47% |
| 30-40 (10) | 9 | 90% | 7 | 70% | 6 | 60% | 7 | 70% |
| 40-50 (0) | 0 | 0% | 0 | 0% | 0 | 0% | 0 | 0% |
| 50-60 (1) | 1 | 100% | 1 | 100% | 1 | 100% | 1 | 100% |
| **Total** | **21** | **60%** | **19** | **54%** | **17** | **49%** | **21** | **60%** |
| **Average** | | **63%** | | **51%** | | **51%** | | **63%** |
| **ST.DEV** | | **0.25** | | **0.21** | | **0.14** | | **0.14** |
| **Females** | | | | | | | | |
| 15-20 (2) | 1 | 50% | 0 | 0% | 0 | 0% | 1 | 50% |
| 20-30 (5) | 2 | 40% | 3 | 60% | 1 | 20% | 3 | 60% |
| 30-40 (1) | 1 | 100% | 1 | 100% | 0 | 0% | 0 | 0% |
| 40-50 (0) | 0 | 0% | 0 | 0% | 0 | 0% | 0 | 0% |
| 50-60 (0) | 0 | 0% | 0 | 0% | 0 | 0% | 0 | 0% |
| **Total** | **4** | **50%** | **4** | **50%** | **1** | **13%** | **4** | **50%** |
| **Average** | | **63%** | | **53%** | | **7%** | | **37%** |
| **ST.DEV** | | **0.32** | | **0.50** | | **0.12** | | **0.32** |

## Table 3.5B4 – Frame – Type of 3DP ('Common') - Age Range.

| Age Range - General | S | S% | M | M% | D | D% | C | C% |
|---|---|---|---|---|---|---|---|---|
| 15-20 (5) | 4 | 80% | 2 | 40% | 3 | 60% | 5 | 100% |
| 20-30 (21) | 12 | 57% | 10 | 48% | 15 | 71% | 12 | 57% |
| 30-40 (7) | 5 | 71% | 5 | 71% | 4 | 57% | 5 | 71% |
| 40-50 (7) | 6 | 86% | 5 | 71% | 7 | 100% | 5 | 71% |
| 50-60 (0) | 0 | 0% | 0 | 0% | 0 | 0% | 0 | 0% |
| **Total** | **27** | **68%** | **22** | **55%** | **29** | **73%** | **27** | **68%** |
| **Average** | | **74%** | | **58%** | | **72%** | | **75%** |
| **ST.DEV** | | **0.12** | | **0.16** | | **0.20** | | **0.18** |
| **Males** | | | | | | | | |
| 15-20 (4) | 3 | 75% | 2 | 50% | 3 | 75% | 4 | 100% |
| 20-30 (18) | 11 | 61% | 10 | 56% | 13 | 72% | 12 | 67% |
| 30-40 (6) | 4 | 67% | 5 | 83% | 4 | 67% | 4 | 67% |
| 40-50 (7) | 6 | 86% | 5 | 71% | 7 | 100% | 5 | 71% |
| 50-60 (0) | 0 | 0% | 0 | 0% | 0 | 0% | 0 | 0% |
| **Total** | **24** | **69%** | **22** | **63%** | **27** | **77%** | **25** | **71%** |
| **Average** | | **72%** | | **65%** | | **78%** | | **76%** |
| **ST.DEV** | | **0.11** | | **0.15** | | **0.15** | | **0.16** |
| **Females** | | | | | | | | |
| 15-20 (1) | 1 | 100% | 0 | 0% | 0 | 0% | 1 | 100% |
| 20-30 (3) | 1 | 33% | 0 | 0% | 2 | 67% | 0 | 0% |
| 30-40 (1) | 1 | 100% | 0 | 0% | 0 | 0% | 1 | 100% |
| 40-50 (7) | 0 | 0% | 0 | 0% | 0 | 0% | 0 | 0% |
| 50-60 (0) | 0 | 0% | 0 | 0% | 0 | 0% | 0 | 0% |
| **Total** | **3** | **60%** | **0** | **0%** | **2** | **40%** | **2** | **40%** |
| **Average** | | **78%** | | **0%** | | **22%** | | **67%** |
| **ST.DEV** | | **0.38** | | **0.00** | | **0.38** | | **0.58** |

## Table 3.5B5 – Frame – Type of 3DP ('None' – Customize & Assemble) - Age Range.

| Age Range - General | S | S% | M | M% | D | D% | C | C% |
|---|---|---|---|---|---|---|---|---|
| 15-20 (3) | 1 | 33% | 1 | 33% | 1 | 33% | 1 | 33% |
| 20-30 (6) | 4 | 67% | 2 | 33% | 3 | 50% | 5 | 83% |
| 30-40 (1) | 0 | 0% | 0 | 0% | 0 | 0% | 0 | 0% |
| 40-50 (0) | 0 | 0% | 0 | 0% | 0 | 0% | 0 | 0% |
| 50-60 (0) | 0 | 0% | 0 | 0% | 0 | 0% | 0 | 0% |
| Total | 5 | 50% | 3 | 30% | 4 | 40% | 6 | 60% |
| Average | | 33% | | 22% | | 28% | | 39% |
| ST.DEV | | 0.33 | | 0.19 | | 0.25 | | 0.42 |
| Males | | | | | | | | |
| 15-20 (3) | 1 | 33% | 1 | 33% | 1 | 33% | 1 | 33% |
| 20-30 (3) | 1 | 33% | 1 | 33% | 1 | 33% | 2 | 67% |
| 30-40 (0) | 0 | 0% | 0 | 0% | 0 | 0% | 0 | 0% |
| 40-50 (0) | 0 | 0% | 0 | 0% | 0 | 0% | 0 | 0% |
| 50-60 (0) | 0 | 0% | 0 | 0% | 0 | 0% | 0 | 0% |
| Total | 2 | 33% | 2 | 33% | 2 | 33% | 3 | 50% |
| Average | | 33% | | 33% | | 33% | | 50% |
| ST.DEV | | 0.00 | | 0.00 | | 0.00 | | 0.24 |
| Females | | | | | | | | |
| 15-20 (0) | 0 | 0% | 0 | 0% | 0 | 0% | 0 | 0% |
| 20-30 (3) | 3 | 100% | 1 | 33% | 2 | 67% | 3 | 100% |
| 30-40 (1) | 0 | 0% | 0 | 0% | 0 | 0% | 0 | 0% |
| 40-50 (0) | 0 | 0% | 0 | 0% | 0 | 0% | 0 | 0% |
| 50-60 (0) | 0 | 0% | 0 | 0% | 0 | 0% | 0 | 0% |
| Total | 3 | 75% | 1 | 25% | 2 | 50% | 3 | 75% |
| Average | | 50% | | 17% | | 33% | | 50% |
| ST.DEV | | 0.71 | | 0.24 | | 0.47 | | 0.71 |

## Table 3.5B6 – Frame – Type of 3DP ('None' – 'Customize Only') - Age Range.

| Age Range - General | S | S% | M | M% | D | D% | C | C% |
|---|---|---|---|---|---|---|---|---|
| 15-20 (1) | 1 | 100% | 0 | 0% | 1 | 100% | 1 | 100% |
| 20-30 (9) | 4 | 44% | 3 | 33% | 4 | 44% | 6 | 67% |
| 30-40 (7) | 6 | 86% | 4 | 57% | 6 | 86% | 6 | 86% |
| 40-50 (0) | 0 | 0% | 0 | 0% | 0 | 0% | 0 | 0% |
| 50-60 (0) | 0 | 0% | 0 | 0% | 0 | 0% | 0 | 0% |
| Total | 11 | 65% | 7 | 41% | 11 | 65% | 13 | 76% |
| Average | | 77% | | 30% | | 77% | | 84% |
| ST.DEV | | 0.29 | | 0.29 | | 0.29 | | 0.17 |
| Males | | | | | | | | |
| 15-20 (0) | 0 | 0% | 0 | 0% | 0 | 0% | 0 | 0% |
| 20-30 (6) | 2 | 33% | 2 | 33% | 3 | 50% | 4 | 67% |
| 30-40 (3) | 3 | 100% | 3 | 100% | 3 | 100% | 3 | 100% |
| 40-50 (0) | 0 | 0% | 0 | 0% | 0 | 0% | 0 | 0% |
| 50-60 (0) | 0 | 0% | 0 | 0% | 0 | 0% | 0 | 0% |
| Total | 5 | 56% | 5 | 56% | 6 | 67% | 7 | 78% |
| Average | | 67% | | 67% | | 75% | | 83% |
| ST.DEV | | 0.47 | | 0.47 | | 0.35 | | 0.24 |
| Females | | | | | | | | |
| 15-20 (1) | 1 | 100% | 0 | 0% | 1 | 100% | 1 | 100% |
| 20-30 (3) | 2 | 67% | 1 | 33% | 1 | 33% | 2 | 67% |
| 30-40 (4) | 3 | 75% | 1 | 25% | 3 | 75% | 3 | 75% |
| 40-50 (0) | 0 | 0% | 0 | 0% | 0 | 0% | 0 | 0% |
| 50-60 (0) | 0 | 0% | 0 | 0% | 0 | 0% | 0 | 0% |
| Total | 6 | 75% | 2 | 25% | 5 | 63% | 6 | 75% |
| Average | | 81% | | 19% | | 69% | | 81% |
| ST.DEV | | 0.17 | | 0.17 | | 0.34 | | 0.17 |

## Table 3.5B7 – Fork – Type of 3DP and Customizers

| Type of 3DP - General | S | S% | M | M% | D | D% | C | C% |
|---|---|---|---|---|---|---|---|---|
| 'Makers' (43) | 12 | 28% | 19 | 44% | 11 | 26% | 14 | 33% |
| 'Common' (40) | 18 | 45% | 18 | 45% | 15 | 38% | 19 | 48% |
| 'None' – C&A (10) | 3 | 30% | 2 | 20% | 2 | 20% | 4 | 40% |
| 'None' – CO (17) | 7 | 41% | 5 | 29% | 5 | 29% | 11 | 65% |
| **Total** | **40** | **36%** | **44** | **40%** | **33** | **30%** | **48** | **44%** |
| **Average** | | **36%** | | **35%** | | **28%** | | **46%** |
| **ST.DEV** | | **0.08** | | **0.12** | | **0.07** | | **0.14** |
| **Males** | | | | | | | | |
| 'Makers' (35) | 12 | 34% | 18 | 51% | 11 | 31% | 12 | 34% |
| 'Common' (35) | 17 | 49% | 18 | 51% | 13 | 37% | 16 | 46% |
| 'None' – C&A (6) | 1 | 17% | 2 | 33% | 2 | 33% | 2 | 33% |
| 'None' – CO (10) | 5 | 50% | 4 | 40% | 3 | 30% | 6 | 60% |
| **Total** | **35** | **41%** | **42** | **49%** | **29** | **34%** | **36** | **42%** |
| **Average** | | **37%** | | **44%** | | **33%** | | **43%** |
| **ST.DEV** | | **0.16** | | **0.09** | | **0.03** | | **0.12** |
| **Females** | | | | | | | | |
| 'Makers' (8) | 0 | 0% | 1 | 13% | 0 | 0% | 2 | 25% |
| 'Common' (5) | 1 | 20% | 0 | 0% | 2 | 40% | 3 | 60% |
| 'None' – C&A (4) | 2 | 50% | 0 | 0% | 0 | 0% | 2 | 50% |
| 'None' – CO (7) | 2 | 29% | 1 | 14% | 2 | 29% | 5 | 71% |
| **Total** | **5** | **21%** | **2** | **8%** | **4** | **17%** | **12** | **50%** |
| **Average** | | **25%** | | **7%** | | **17%** | | **52%** |
| **ST.DEV** | | **0.21** | | **0.08** | | **0.20** | | **0.20** |

## Table 3.5B8 – Fork – Age Range.

| Age Range - General | S | S% | M | M% | D | D% | C | C% |
|---|---|---|---|---|---|---|---|---|
| 15-20 (18) | 6 | 33% | 5 | 28% | 3 | 17% | 6 | 33% |
| 20-30 (58) | 15 | 26% | 20 | 34% | 11 | 19% | 21 | 36% |
| 30-40 (26) | 12 | 46% | 15 | 58% | 13 | 50% | 15 | 58% |
| 40-50 (7) | 5 | 71% | 3 | 43% | 5 | 71% | 6 | 86% |
| 50-60 (1) | ~~1~~ | ~~100%~~ | ~~1~~ | ~~100%~~ | ~~1~~ | ~~100%~~ | ~~0~~ | ~~0%~~ |
| **Total** | **39** | **35%** | **44** | **40%** | **33** | **30%** | **48** | **44%** |
| **Average** | | **44%** | | **41%** | | **39%** | | **53%** |
| **ST.DEV** | | **0.20** | | **0.13** | | **0.26** | | **0.24** |
| **Males** | | | | | | | | |
| 15-20 (14) | 6 | 43% | 5 | 36% | 3 | 21% | 5 | 36% |
| 20-30 (44) | 12 | 27% | 20 | 45% | 9 | 20% | 14 | 32% |
| 30-40 (19) | 10 | 53% | 13 | 68% | 11 | 58% | 11 | 58% |
| 40-50 (7) | 5 | 71% | 3 | 43% | 5 | 71% | 6 | 86% |
| 50-60 (1) | ~~1~~ | ~~100%~~ | ~~1~~ | ~~100%~~ | ~~1~~ | ~~100%~~ | ~~0~~ | ~~0%~~ |
| **Total** | **34** | **40%** | **42** | **49%** | **29** | **34%** | **36** | **42%** |
| **Average** | | **49%** | | **48%** | | **43%** | | **53%** |
| **ST.DEV** | | **0.18** | | **0.14** | | **0.26** | | **0.25** |
| **Females** | | | | | | | | |
| 15-20 (4) | 0 | 0% | 0 | 0% | 0 | 0% | 1 | 25% |
| 20-30 (14) | 3 | 21% | 0 | 0% | 2 | 14% | 7 | 50% |
| 30-40 (7) | 2 | 29% | 2 | 29% | 2 | 29% | 4 | 57% |
| 40-50 (0) | ~~0~~ | ~~0%~~ | ~~0~~ | ~~0%~~ | ~~0~~ | ~~0%~~ | ~~0~~ | ~~0%~~ |
| 50-60 (0) | ~~0~~ | ~~0%~~ | ~~0~~ | ~~0%~~ | ~~0~~ | ~~0%~~ | ~~0~~ | ~~0%~~ |
| **Total** | **5** | **20%** | **2** | **8%** | **4** | **16%** | **12** | **48%** |
| **Average** | | **13%** | | **7%** | | **11%** | | **33%** |
| **ST.DEV** | | **0.15** | | **0.16** | | **0.14** | | **0.17** |

## Table 3.5B9 – Fork – Type of 3DP ('Makers') - Age Range.

| Age Range - General | S | S% | M | M% | D | D% | C | C% |
|---|---|---|---|---|---|---|---|---|
| 15-20 (9) | 2 | 22% | 2 | 22% | 2 | 22% | 2 | 22% |
| 20-30 (22) | 4 | 18% | 8 | 36% | 3 | 14% | 6 | 27% |
| 30-40 (11) | 5 | 45% | 8 | 73% | 5 | 45% | 6 | 55% |
| 40-50 (0) | 0 | 0% | 0 | 0% | 0 | 0% | 0 | 0% |
| 50-60 (1) | 1 | 100% | 1 | 100% | 1 | 100% | 0 | 0% |
| **Total** | **12** | **28%** | **19** | **44%** | **11** | **26%** | **14** | **33%** |
| **Average** | | **29%** | | **44%** | | **27%** | | **35%** |
| **ST.DEV** | | **0.15** | | **0.26** | | **0.16** | | **0.17** |
| **Males** | | | | | | | | |
| 15-20 (7) | 2 | 29% | 2 | 29% | 2 | 29% | 2 | 29% |
| 20-30 (17) | 4 | 24% | 8 | 47% | 3 | 18% | 4 | 24% |
| 30-40 (10) | 5 | 50% | 7 | 70% | 5 | 50% | 6 | 60% |
| 40-50 (0) | 0 | 0% | 0 | 0% | 0 | 0% | 0 | 0% |
| 50-60 (1) | 1 | 100% | 1 | 100% | 1 | 100% | 0 | 0% |
| **Total** | **12** | **34%** | **18** | **51%** | **11** | **31%** | **12** | **34%** |
| **Average** | | **34%** | | **49%** | | **32%** | | **37%** |
| **ST.DEV** | | **0.14** | | **0.21** | | **0.16** | | **0.20** |
| **Females** | | | | | | | | |
| 15-20 (2) | 0 | 0% | 0 | 0% | 0 | 0% | 0 | 0% |
| 20-30 (5) | 0 | 0% | 0 | 0% | 0 | 0% | 2 | 40% |
| 30-40 (1) | 0 | 0% | 1 | 100% | 0 | 0% | 0 | 0% |
| 40-50 (0) | 0 | 0% | 0 | 0% | 0 | 0% | 0 | 0% |
| 50-60 (0) | 0 | 0% | 0 | 0% | 0 | 0% | 0 | 0% |
| **Total** | **0** | **0%** | **1** | **13%** | **0** | **0%** | **2** | **25%** |
| **Average** | | **0%** | | **33%** | | **0%** | | **13%** |
| **ST.DEV** | | **0.00** | | **0.58** | | **0.00** | | **0.23** |

## Table 3.5B10 – Fork – Type of 3DP ('Common') - Age Range.

| Age Range - General | S | S% | M | M% | D | D% | C | C% |
|---|---|---|---|---|---|---|---|---|
| 15-20 (5) | 3 | 60% | 2 | 40% | 0 | 0% | 2 | 40% |
| 20-30 (21) | 7 | 33% | 9 | 43% | 7 | 33% | 7 | 33% |
| 30-40 (7) | 2 | 29% | 4 | 57% | 3 | 43% | 4 | 57% |
| 40-50 (7) | 5 | 71% | 3 | 43% | 5 | 71% | 6 | 86% |
| 50-60 (0) | 0 | 0% | 0 | 0% | 0 | 0% | 0 | 0% |
| **Total** | 17 | 43% | 18 | 45% | 15 | 38% | 19 | 48% |
| **Average** | | **48%** | | **46%** | | **37%** | | **54%** |
| **ST.DEV** | | **0.21** | | **0.08** | | **0.29** | | **0.23** |
| **Males** | | | | | | | | |
| 15-20 (4) | 3 | 75% | 2 | 50% | 0 | 0% | 2 | 50% |
| 20-30 (18) | 6 | 33% | 9 | 50% | 5 | 28% | 5 | 28% |
| 30-40 (6) | 2 | 33% | 4 | 67% | 3 | 50% | 3 | 50% |
| 40-50 (7) | 5 | 71% | 3 | 43% | 5 | 71% | 6 | 86% |
| 50-60 (0) | 0 | 0% | 0 | 0% | 0 | 0% | 0 | 0% |
| **Total** | **16** | **46%** | **18** | **51%** | **13** | **37%** | **16** | **46%** |
| **Average** | | **53%** | | **52%** | | **37%** | | **53%** |
| **ST.DEV** | | **0.23** | | **0.10** | | **0.31** | | **0.24** |
| **Females** | | | | | | | | |
| 15-20 (1) | 0 | 0% | 0 | 0% | 0 | 0% | 0 | 0% |
| 20-30 (3) | 1 | 33% | 0 | 0% | 2 | 67% | 2 | 67% |
| 30-40 (1) | 0 | 0% | 0 | 0% | 0 | 0% | 1 | 100% |
| 40-50 (7) | 0 | 0% | 0 | 0% | 0 | 0% | 0 | 0% |
| 50-60 (0) | 0 | 0% | 0 | 0% | 0 | 0% | 0 | 0% |
| **Total** | 1 | 20% | 0 | 0% | 2 | 40% | 3 | 60% |
| **Average** | | **11%** | | **0%** | | **22%** | | **56%** |
| **ST.DEV** | | **0.19** | | **0.00** | | **0.38** | | **0.51** |

## Table 3.5B11 – Fork – Type of 3DP ('None' – Customize & Assemble) - Age Range.

| Age Range - General | S | S% | M | M% | D | D% | C | C% |
|---|---|---|---|---|---|---|---|---|
| 15-20 (3) | 1 | 33% | 1 | 33% | 1 | 33% | 1 | 33% |
| 20-30 (6) | 2 | 33% | 1 | 17% | 1 | 17% | 3 | 50% |
| 30-40 (1) | 0 | 0% | 0 | 0% | 0 | 0% | 0 | 0% |
| 40-50 (0) | 0 | 0% | 0 | 0% | 0 | 0% | 0 | 0% |
| 50-60 (0) | 0 | 0% | 0 | 0% | 0 | 0% | 0 | 0% |
| Total | 3 | 30% | 2 | 20% | 2 | 20% | 4 | 40% |
| Average | | 22% | | 17% | | 17% | | 28% |
| ST.DEV | | 0.19 | | 0.17 | | 0.17 | | 0.25 |
| Males | | | | | | | | |
| 15-20 (3) | 1 | 33% | 1 | 33% | 1 | 33% | 1 | 33% |
| 20-30 (3) | 0 | 0% | 1 | 33% | 1 | 33% | 1 | 33% |
| 30-40 (0) | 0 | 0% | 0 | 0% | 0 | 0% | 0 | 0% |
| 40-50 (0) | 0 | 0% | 0 | 0% | 0 | 0% | 0 | 0% |
| 50-60 (0) | 0 | 0% | 0 | 0% | 0 | 0% | 0 | 0% |
| Total | 1 | 17% | 2 | 33% | 2 | 33% | 2 | 33% |
| Average | | 17% | | 33% | | 33% | | 33% |
| ST.DEV | | 0.24 | | 0.00 | | 0.00 | | 0.00 |
| Females | | | | | | | | |
| 15-20 (0) | 0 | 0% | 0 | 0% | 0 | 0% | 0 | 0% |
| 20-30 (3) | 2 | 67% | 0 | 0% | 0 | 0% | 2 | 67% |
| 30-40 (1) | 0 | 0% | 0 | 0% | 0 | 0% | 0 | 0% |
| 40-50 (0) | 0 | 0% | 0 | 0% | 0 | 0% | 0 | 0% |
| 50-60 (0) | 0 | 0% | 0 | 0% | 0 | 0% | 0 | 0% |
| Total | 2 | 50% | 0 | 0% | 0 | 0% | 2 | 50% |
| Average | | 33% | | 0% | | 0% | | 33% |
| ST.DEV | | 0.47 | | 0.00 | | 0.00 | | 0.47 |

## Table 3.5B12 – Fork – Type of 3DP ('None' – 'Customize Only') - Age Range.

| Age Range - General | S | S% | M | M% | D | D% | C | C% |
|---|---|---|---|---|---|---|---|---|
| 15-20 (1) | 0 | 0% | 0 | 0% | 0 | 0% | 1 | 100% |
| 20-30 (9) | 2 | 22% | 2 | 22% | 0 | 0% | 5 | 56% |
| 30-40 (7) | 5 | 71% | 3 | 43% | 5 | 71% | 5 | 71% |
| 40-50 (0) | 0 | 0% | 0 | 0% | 0 | 0% | 0 | 0% |
| 50-60 (0) | 0 | 0% | 0 | 0% | 0 | 0% | 0 | 0% |
| Total | 7 | 41% | 5 | 29% | 5 | 29% | 11 | 65% |
| Average | | 31% | | 22% | | 24% | | 76% |
| ST.DEV | | 0.37 | | 0.21 | | 0.41 | | 0.23 |
| Males | | | | | | | | |
| 15-20 (0) | 0 | 0% | 0 | 0% | 0 | 0% | 0 | 0% |
| 20-30 (6) | 2 | 33% | 2 | 33% | 0 | 0% | 4 | 67% |
| 30-40 (3) | 3 | 100% | 2 | 67% | 3 | 100% | 2 | 67% |
| 40-50 (0) | 0 | 0% | 0 | 0% | 0 | 0% | 0 | 0% |
| 50-60 (0) | 0 | 0% | 0 | 0% | 0 | 0% | 0 | 0% |
| Total | 5 | 56% | 4 | 44% | 3 | 33% | 6 | 67% |
| Average | | 67% | | 50% | | 50% | | 67% |
| ST.DEV | | 0.47 | | 0.24 | | 0.71 | | 0.00 |
| Females | | | | | | | | |
| 15-20 (1) | 0 | 0% | 0 | 0% | 0 | 0% | 1 | 100% |
| 20-30 (3) | 0 | 0% | 0 | 0% | 0 | 0% | 1 | 33% |
| 30-40 (4) | 2 | 50% | 1 | 25% | 2 | 50% | 3 | 75% |
| 40-50 (0) | 0 | 0% | 0 | 0% | 0 | 0% | 0 | 0% |
| 50-60 (0) | 0 | 0% | 0 | 0% | 0 | 0% | 0 | 0% |
| Total | 2 | 25% | 1 | 13% | 2 | 25% | 5 | 63% |
| Average | | 17% | | 8% | | 17% | | 69% |
| ST.DEV | | 0.29 | | 0.14 | | 0.29 | | 0.34 |

## Table 3.5B13 – Wheels – Type of 3DP and Customizers

| Type of 3DP - General | S | S% | C | C% |
|---|---|---|---|---|
| 'Makers' (43) | 36 | 84% | 19 | 44% |
| 'Common' (40) | 33 | 83% | 20 | 50% |
| 'None' – C&A (10) | 6 | 60% | 5 | 50% |
| 'None' – CO (17) | 14 | 82% | 11 | 65% |
| **Total** | **89** | **81%** | **55** | **50%** |
| **Average** | | **77%** | | **52%** |
| **ST.DEV** | | **0.11** | | **0.09** |
| **Males** | | | | |
| 'Makers' (35) | 30 | 86% | 16 | 46% |
| 'Common' (35) | 31 | 89% | 19 | 54% |
| 'None' – C&A (6) | 3 | 50% | 3 | 50% |
| 'None' – CO (10) | 8 | 80% | 6 | 60% |
| **Total** | **72** | **84%** | **44** | **51%** |
| **Average** | | **76%** | | **53%** |
| **ST.DEV** | | **0.18** | | **0.06** |
| **Females** | | | | |
| 'Makers' (8) | 6 | 75% | 7 | 88% |
| 'Common' (5) | 2 | 40% | 1 | 20% |
| 'None' – C&A (4) | 3 | 75% | 2 | 50% |
| 'None' – CO (7) | 6 | 86% | 5 | 71% |
| **Total** | **17** | **71%** | **15** | **63%** |
| **Average** | | **69%** | | **57%** |
| **ST.DEV** | | **0.20** | | **0.29** |

## Table 3.5B14 – Wheels – Age Range.

| Age Range - General | S | S% | C | C% |
|---|---|---|---|---|
| 15-20 (18) | 13 | 72% | 9 | 50% |
| 20-30 (58) | 46 | 79% | 26 | 45% |
| 30-40 (26) | 23 | 88% | 13 | 50% |
| 40-50 (7) | 7 | 100% | 5 | 71% |
| 50-60 (1) | 1 | 100% | 1 | 100% |
| **Total** | **90** | **82%** | **54** | **49%** |
| **Average** | | **85%** | | **54%** |
| **ST.DEV** | | **0.12** | | **0.12** |
| **Males** | | | | |
| 15-20 (14) | 10 | 71% | 7 | 50% |
| 20-30 (44) | 37 | 84% | 22 | 50% |
| 30-40 (19) | 18 | 95% | 8 | 42% |
| 40-50 (7) | 7 | 100% | 5 | 71% |
| 50-60 (1) | 1 | 100% | 1 | 100% |
| **Total** | **73** | **86%** | **43** | **51%** |
| **Average** | | **88%** | | **53%** |
| **ST.DEV** | | **0.13** | | **0.13** |
| **Females** | | | | |
| 15-20 (4) | 3 | 75% | 2 | 50% |
| 20-30 (14) | 9 | 64% | 4 | 29% |
| 30-40 (7) | 5 | 71% | 5 | 71% |
| 40-50 (0) | 0 | 0% | 0 | 0% |
| 50-60 (0) | 0 | 0% | 0 | 0% |
| **Total** | **17** | **68%** | **11** | **44%** |
| **Average** | | **53%** | | **38%** |
| **ST.DEV** | | **0.05** | | **0.21** |

## Table 3.5B15 – Wheels – Type of 3DP ('Makers') - Age Range.

| Age Range - General | S | S% | C | C% |
|---|---|---|---|---|
| 15-20 (9) | 8 | 89% | 4 | 44% |
| 20-30 (22) | 17 | 77% | 9 | 41% |
| 30-40 (11) | 10 | 91% | 5 | 45% |
| 40-50 (0) | 0 | 0% | 0 | 0% |
| 50-60 (1) | 1 | 100% | 1 | 100% |
| **Total** | **36** | **84%** | **19** | **44%** |
| **Average** | | **86%** | | **44%** |
| **ST.DEV** | | **0.07** | | **0.02** |
| **Males** | | | | |
| 15-20 (7) | 6 | 86% | 3 | 43% |
| 20-30 (17) | 14 | 82% | 8 | 47% |
| 30-40 (10) | 9 | 90% | 4 | 40% |
| 40-50 (0) | 0 | 0% | 0 | 0% |
| 50-60 (1) | 1 | 100% | 0 | 0% |
| **Total** | **30** | **86%** | **15** | **43%** |
| **Average** | | **86%** | | **43%** |
| **ST.DEV** | | **0.04** | | **0.04** |
| **Females** | | | | |
| 15-20 (2) | 2 | 100% | 1 | 50% |
| 20-30 (5) | 3 | 60% | 1 | 20% |
| 30-40 (1) | 1 | 100% | 1 | 100% |
| 40-50 (0) | 0 | 0% | 0 | 0% |
| 50-60 (0) | 0 | 0% | 0 | 0% |
| **Total** | **6** | **75%** | **3** | **38%** |
| **Average** | | **87%** | | **57%** |
| **ST.DEV** | | **0.23** | | **0.40** |

## Table 3.5B16 – Wheels – Type of 3DP ('Common') - Age Range.

| Age Range - General | S | S% | C | C% |
|---|---|---|---|---|
| 15-20 (5) | 3 | 60% | 3 | 60% |
| 20-30 (21) | 17 | 81% | 9 | 43% |
| 30-40 (7) | 7 | 100% | 3 | 43% |
| 40-50 (7) | 7 | 100% | 5 | 71% |
| 50-60 (0) | 0 | 0% | 0 | 0% |
| **Total** | **34** | **85%** | **20** | **50%** |
| **Average** | | **85%** | | **54%** |
| **ST.DEV** | | **0.19** | | **0.14** |
| **Males** | | | | |
| 15-20 (4) | 3 | 75% | 3 | 75% |
| 20-30 (18) | 16 | 89% | 9 | 50% |
| 30-40 (6) | 6 | 100% | 2 | 33% |
| 40-50 (7) | 7 | 100% | 5 | 71% |
| 50-60 (0) | 0 | 0% | 0 | 0% |
| **Total** | **32** | **91%** | **19** | **54%** |
| **Average** | | **91%** | | **57%** |
| **ST.DEV** | | **0.12** | | **0.19** |
| **Females** | | | | |
| 15-20 (1) | 0 | 0% | 0 | 0% |
| 20-30 (3) | 1 | 33% | 0 | 0% |
| 30-40 (1) | 1 | 100% | 1 | 100% |
| 40-50 (7) | 0 | 0% | 0 | 0% |
| 50-60 (0) | 0 | 0% | 0 | 0% |
| **Total** | **2** | **40%** | **1** | **20%** |
| **Average** | | **44%** | | **33%** |
| **ST.DEV** | | **0.51** | | **0.58** |

**Table 3.5B17 – Wheels – Type of 3DP ('None' – Customize & Assemble) - Age Range.**

| Age Range - General | S | S% | C | C% |
|---|---|---|---|---|
| 15-20 (3) | 1 | 33% | 1 | 33% |
| 20-30 (6) | 5 | 83% | 4 | 67% |
| 30-40 (1) | 0 | 0% | 0 | 0% |
| 40-50 (0) | 0 | 0% | 0 | 0% |
| 50-60 (0) | 0 | 0% | 0 | 0% |
| Total | 6 | 60% | 5 | 50% |
| Average | | 39% | | 33% |
| ST.DEV | | 0.42 | | 0.33 |
| Males | | | | |
| 15-20 (3) | 1 | 33% | 1 | 33% |
| 20-30 (3) | 2 | 67% | 2 | 67% |
| 30-40 (0) | 0 | 0% | 0 | 0% |
| 40-50 (0) | 0 | 0% | 0 | 0% |
| 50-60 (0) | 0 | 0% | 0 | 0% |
| Total | 3 | 50% | 3 | 50% |
| Average | | 50% | | 50% |
| ST.DEV | | 0.24 | | 0.24 |
| Females | | | | |
| 15-20 (0) | 0 | 0% | 0 | 0% |
| 20-30 (3) | 3 | 100% | 2 | 67% |
| 30-40 (1) | 0 | 0% | 0 | 0% |
| 40-50 (0) | 0 | 0% | 0 | 0% |
| 50-60 (0) | 0 | 0% | 0 | 0% |
| Total | 3 | 75% | 2 | 50% |
| Average | | 50% | | 33% |
| ST.DEV | | 0.71 | | 0.47 |

**Table 3.5B18 – Wheels – Type of 3DP ('None' – 'Customize Only') - Age Range.**

| Age Range - General | S | S% | C | C% |
|---|---|---|---|---|
| 15-20 (1) | 1 | 100% | 1 | 100% |
| 20-30 (9) | 7 | 78% | 4 | 44% |
| 30-40 (7) | 6 | 86% | 5 | 71% |
| 40-50 (0) | 0 | 0% | 0 | 0% |
| 50-60 (0) | 0 | 0% | 0 | 0% |
| Total | 14 | 82% | 10 | 59% |
| Average | | 88% | | 72% |
| ST.DEV | | 0.11 | | 0.28 |
| Males | | | | |
| 15-20 (0) | 0 | 0% | 0 | 0% |
| 20-30 (6) | 5 | 83% | 3 | 50% |
| 30-40 (3) | 3 | 100% | 2 | 67% |
| 40-50 (0) | 0 | 0% | 0 | 0% |
| 50-60 (0) | 0 | 0% | 0 | 0% |
| Total | 8 | 89% | 5 | 56% |
| Average | | 92% | | 58% |
| ST.DEV | | 0.12 | | 0.12 |
| Females | | | | |
| 15-20 (1) | 1 | 100% | 1 | 100% |
| 20-30 (3) | 2 | 67% | 1 | 33% |
| 30-40 (4) | 3 | 75% | 3 | 75% |
| 40-50 (0) | 0 | 0% | 0 | 0% |
| 50-60 (0) | 0 | 0% | 0 | 0% |
| Total | 6 | 75% | 5 | 63% |
| Average | | 81% | | 69% |
| ST.DEV | | 0.17 | | 0.34 |

## Appendix 3.5C – Statistics of the third page

## User Adjustment components

### Table 3.5C1 – Saddle – Type of 3DP and Customizers

| Type of 3DP - General | S | S% | M | M% | D | D% | C | C% |
|---|---|---|---|---|---|---|---|---|
| 'Makers' (43) | 26 | 60% | 25 | 58% | 24 | 56% | 21 | 49% |
| 'Common' (40) | 30 | 75% | 26 | 65% | 31 | 78% | 22 | 55% |
| 'None' – C&A (10) | 6 | 60% | 5 | 50% | 4 | 40% | 5 | 50% |
| 'None' – CO (17) | 11 | 65% | 11 | 65% | 12 | 71% | 8 | 47% |
| **Total** | **73** | **66%** | **67** | **61%** | **71** | **65%** | **56** | **51%** |
| **Average** | | **65%** | | **59%** | | **61%** | | **50%** |
| **ST.DEV** | | **0.07** | | **0.07** | | **0.17** | | **0.03** |
| **Males** | | | | | | | | |
| 'Makers' (35) | 22 | 63% | 19 | 54% | 19 | 54% | 18 | 51% |
| 'Common' (35) | 25 | 71% | 22 | 63% | 26 | 74% | 20 | 57% |
| 'None' – C&A (6) | 3 | 50% | 2 | 33% | 3 | 50% | 2 | 33% |
| 'None' – CO (10) | 6 | 60% | 6 | 60% | 8 | 80% | 5 | 50% |
| **Total** | **56** | **65%** | **49** | **57%** | **56** | **65%** | **45** | **52%** |
| **Average** | | **61%** | | **53%** | | **65%** | | **48%** |
| **ST.DEV** | | **0.09** | | **0.13** | | **0.15** | | **0.10** |
| **Females** | | | | | | | | |
| 'Makers' (8) | 4 | 50% | 6 | 75% | 5 | 63% | 3 | 38% |
| 'Common' (5) | 5 | 100% | 4 | 80% | 5 | 100% | 2 | 40% |
| 'None' – C&A (4) | 3 | 75% | 3 | 75% | 1 | 25% | 3 | 75% |
| 'None' – CO (7) | 5 | 71% | 5 | 71% | 4 | 57% | 3 | 43% |
| **Total** | **17** | **71%** | **18** | **75%** | **15** | **63%** | **11** | **46%** |
| **Average** | | **74%** | | **75%** | | **61%** | | **49%** |
| **ST.DEV** | | **0.20** | | **0.04** | | **0.31** | | **0.18** |

### Table 3.5C2 – Saddle – Age Range.

| Age Range - General | S | S% | M | M% | D | D% | C | C% |
|---|---|---|---|---|---|---|---|---|
| 15-20 (18) | 8 | 44% | 10 | 56% | 12 | 67% | 9 | 50% |
| 20-30 (58) | 40 | 69% | 33 | 57% | 34 | 59% | 27 | 47% |
| 30-40 (26) | 18 | 69% | 18 | 69% | 19 | 73% | 15 | 58% |
| 40-50 (7) | 6 | 86% | 5 | 71% | 5 | 71% | 5 | 71% |
| 50-60 (1) | ~~1~~ | ~~100%~~ | ~~1~~ | ~~100%~~ | ~~1~~ | ~~100%~~ | ~~1~~ | ~~100%~~ |
| **Total** | **73** | **66%** | **67** | **61%** | **71** | **65%** | **57** | **52%** |
| **Average** | | **67%** | | **63%** | | **67%** | | **56%** |
| **ST.DEV** | | **0.17** | | **0.08** | | **0.06** | | **0.11** |
| **Males** | | | | | | | | |
| 15-20 (14) | 7 | 50% | 7 | 50% | 9 | 64% | 8 | 57% |
| 20-30 (44) | 29 | 66% | 22 | 50% | 26 | 59% | 20 | 45% |
| 30-40 (19) | 13 | 68% | 14 | 74% | 15 | 79% | 11 | 58% |
| 40-50 (7) | 6 | 86% | 5 | 71% | 5 | 71% | 5 | 71% |
| 50-60 (1) | ~~1~~ | ~~100%~~ | ~~1~~ | ~~100%~~ | ~~1~~ | ~~100%~~ | ~~1~~ | ~~100%~~ |
| **Total** | **56** | **66%** | **49** | **58%** | **56** | **66%** | **45** | **53%** |
| **Average** | | **68%** | | **61%** | | **68%** | | **58%** |
| **ST.DEV** | | **0.15** | | **0.13** | | **0.09** | | **0.11** |
| **Females** | | | | | | | | |
| 15-20 (4) | 1 | 25% | 3 | 75% | 3 | 75% | 1 | 25% |
| 20-30 (14) | 11 | 79% | 11 | 79% | 8 | 57% | 7 | 50% |
| 30-40 (7) | 5 | 71% | 4 | 57% | 4 | 57% | 4 | 57% |
| 40-50 (0) | ~~0~~ | ~~0%~~ | ~~0~~ | ~~0%~~ | ~~0~~ | ~~0%~~ | ~~0~~ | ~~0%~~ |
| 50-60 (0) | ~~0~~ | ~~0%~~ | ~~0~~ | ~~0%~~ | ~~0~~ | ~~0%~~ | ~~0~~ | ~~0%~~ |
| **Total** | **17** | **68%** | **18** | **72%** | **15** | **60%** | **12** | **48%** |
| **Average** | | **44%** | | **53%** | | **47%** | | **33%** |
| **ST.DEV** | | **0.29** | | **0.11** | | **0.10** | | **0.17** |

## Table 3.5C3 – Saddle – Type of 3DP ('Makers') - Age Range.

| Age Range - General | S | S% | M | M% | D | D% | C | C% |
|---|---|---|---|---|---|---|---|---|
| 15-20 (9) | 4 | 44% | 7 | 78% | 6 | 67% | 4 | 44% |
| 20-30 (22) | 14 | 64% | 9 | 41% | 9 | 41% | 10 | 45% |
| 30-40 (11) | 7 | 64% | 8 | 73% | 8 | 73% | 6 | 55% |
| 40-50 (0) | 0 | 0% | 0 | 0% | 0 | 0% | 0 | 0% |
| 50-60 (1) | 1 | 100% | 1 | 100% | 1 | 100% | 1 | 100% |
| **Total** | **26** | **60%** | **25** | **58%** | **24** | **56%** | **21** | **49%** |
| **Average** | | **57%** | | **64%** | | **60%** | | **48%** |
| **ST.DEV** | | **0.11** | | **0.20** | | **0.17** | | **0.06** |
| **Males** | | | | | | | | |
| 15-20 (7) | 4 | 57% | 5 | 71% | 4 | 57% | 4 | 57% |
| 20-30 (17) | 11 | 65% | 6 | 35% | 6 | 35% | 7 | 41% |
| 30-40 (10) | 6 | 60% | 7 | 70% | 8 | 80% | 6 | 60% |
| 40-50 (0) | 0 | 0% | 0 | 0% | 0 | 0% | 0 | 0% |
| 50-60 (1) | 1 | 100% | 1 | 100% | 1 | 100% | 1 | 100% |
| **Total** | **22** | **63%** | **19** | **54%** | **19** | **54%** | **18** | **51%** |
| **Average** | | **61%** | | **59%** | | **57%** | | **53%** |
| **ST.DEV** | | **0.04** | | **0.20** | | **0.22** | | **0.10** |
| **Females** | | | | | | | | |
| 15-20 (2) | 0 | 0% | 2 | 100% | 2 | 100% | 0 | 0% |
| 20-30 (5) | 3 | 60% | 3 | 60% | 3 | 60% | 3 | 60% |
| 30-40 (1) | 1 | 100% | 1 | 100% | 0 | 0% | 0 | 0% |
| 40-50 (0) | 0 | 0% | 0 | 0% | 0 | 0% | 0 | 0% |
| 50-60 (0) | 0 | 0% | 0 | 0% | 0 | 0% | 0 | 0% |
| **Total** | **4** | **50%** | **6** | **75%** | **5** | **63%** | **3** | **38%** |
| **Average** | | **53%** | | **87%** | | **53%** | | **20%** |
| **ST.DEV** | | **0.50** | | **0.23** | | **0.50** | | **0.35** |

## Table 3.5C4 – Saddle – Type of 3DP ('Common') - Age Range.

| Age Range - General | S | S% | M | M% | D | D% | C | C% |
|---|---|---|---|---|---|---|---|---|
| 15-20 (5) | 3 | 60% | 2 | 40% | 4 | 80% | 3 | 60% |
| 20-30 (21) | 15 | 71% | 14 | 67% | 17 | 81% | 10 | 48% |
| 30-40 (7) | 6 | 86% | 5 | 71% | 5 | 71% | 4 | 57% |
| 40-50 (7) | 6 | 86% | 5 | 71% | 5 | 71% | 5 | 71% |
| 50-60 (0) | 0 | 0% | 0 | 0% | 0 | 0% | 0 | 0% |
| **Total** | **30** | **75%** | **26** | **65%** | **31** | **78%** | **22** | **55%** |
| **Average** | | **76%** | | **62%** | | **76%** | | **59%** |
| **ST.DEV** | | **0.12** | | **0.15** | | **0.05** | | **0.10** |
| **Males** | | | | | | | | |
| 15-20 (4) | 2 | 50% | 1 | 25% | 3 | 75% | 3 | 75% |
| 20-30 (18) | 12 | 67% | 12 | 67% | 14 | 78% | 9 | 50% |
| 30-40 (6) | 5 | 83% | 4 | 67% | 4 | 67% | 3 | 50% |
| 40-50 (7) | 6 | 86% | 5 | 71% | 5 | 71% | 5 | 71% |
| 50-60 (0) | 0 | 0% | 0 | 0% | 0 | 0% | 0 | 0% |
| **Total** | **25** | **71%** | **22** | **63%** | **26** | **74%** | **20** | **57%** |
| **Average** | | **71%** | | **57%** | | **73%** | | **62%** |
| **ST.DEV** | | **0.17** | | **0.22** | | **0.05** | | **0.13** |
| **Females** | | | | | | | | |
| 15-20 (1) | 1 | 100% | 1 | 100% | 1 | 100% | 0 | 0% |
| 20-30 (3) | 3 | 100% | 2 | 67% | 3 | 100% | 1 | 33% |
| 30-40 (1) | 1 | 100% | 1 | 100% | 1 | 100% | 1 | 100% |
| 40-50 (7) | 0 | 0% | 0 | 0% | 0 | 0% | 0 | 0% |
| 50-60 (0) | 0 | 0% | 0 | 0% | 0 | 0% | 0 | 0% |
| **Total** | **5** | **100%** | **4** | **80%** | **5** | **100%** | **2** | **40%** |
| **Average** | | **100%** | | **89%** | | **100%** | | **44%** |
| **ST.DEV** | | **0.00** | | **0.19** | | **0.00** | | **0.51** |

## Table 3.5C5 – Saddle – Type of 3DP ('None' – Customize & Assemble) - Age Range.

| Age Range - General | S | S% | M | M% | D | D% | C | C% |
|---|---|---|---|---|---|---|---|---|
| 15-20 (3) | 1 | 33% | 1 | 33% | 2 | 67% | 1 | 33% |
| 20-30 (6) | 4 | 67% | 4 | 67% | 1 | 17% | 3 | 50% |
| 30-40 (1) | 1 | 100% | 0 | 0% | 1 | 100% | 1 | 100% |
| 40-50 (0) | 0 | 0% | 0 | 0% | 0 | 0% | 0 | 0% |
| 50-60 (0) | 0 | 0% | 0 | 0% | 0 | 0% | 0 | 0% |
| Total | 6 | 60% | 5 | 50% | 4 | 40% | 5 | 50% |
| Average | | 67% | | 33% | | 61% | | 61% |
| ST.DEV | | 0.33 | | 0.33 | | 0.42 | | 0.35 |
| **Males** | | | | | | | | |
| 15-20 (3) | 1 | 33% | 1 | 33% | 2 | 67% | 1 | 33% |
| 20-30 (3) | 2 | 67% | 1 | 33% | 1 | 33% | 1 | 33% |
| 30-40 (0) | 0 | 0% | 0 | 0% | 0 | 0% | 0 | 0% |
| 40-50 (0) | 0 | 0% | 0 | 0% | 0 | 0% | 0 | 0% |
| 50-60 (0) | 0 | 0% | 0 | 0% | 0 | 0% | 0 | 0% |
| Total | 3 | 50% | 2 | 33% | 3 | 50% | 2 | 33% |
| Average | | 50% | | 33% | | 50% | | 33% |
| ST.DEV | | 0.24 | | 0.00 | | 0.24 | | 0.00 |
| **Females** | | | | | | | | |
| 15-20 (0) | 0 | 0% | 0 | 0% | 0 | 0% | 0 | 0% |
| 20-30 (3) | 2 | 67% | 3 | 100% | 0 | 0% | 2 | 67% |
| 30-40 (1) | 1 | 100% | 0 | 0% | 1 | 100% | 1 | 100% |
| 40-50 (0) | 0 | 0% | 0 | 0% | 0 | 0% | 0 | 0% |
| 50-60 (0) | 0 | 0% | 0 | 0% | 0 | 0% | 0 | 0% |
| Total | 3 | 75% | 3 | 75% | 1 | 25% | 3 | 75% |
| Average | | 83% | | 50% | | 50% | | 83% |
| ST.DEV | | 0.24 | | 0.71 | | 0.71 | | 0.24 |

## Table 3.5C6 – Saddle – Type of 3DP ('None' – 'Customize Only') - Age Range.

| Age Range - General | S | S% | M | M% | D | D% | C | C% |
|---|---|---|---|---|---|---|---|---|
| 15-20 (1) | 0 | 0% | 0 | 0% | 0 | 0% | 1 | 100% |
| 20-30 (9) | 7 | 78% | 6 | 67% | 7 | 78% | 3 | 33% |
| 30-40 (7) | 4 | 57% | 5 | 71% | 5 | 71% | 4 | 57% |
| 40-50 (0) | 0 | 0% | 0 | 0% | 0 | 0% | 0 | 0% |
| 50-60 (0) | 0 | 0% | 0 | 0% | 0 | 0% | 0 | 0% |
| Total | 11 | 65% | 11 | 65% | 12 | 71% | 8 | 47% |
| Average | | 45% | | 46% | | 50% | | 63% |
| ST.DEV | | 0.40 | | 0.40 | | 0.43 | | 0.34 |
| **Males** | | | | | | | | |
| 15-20 (0) | 0 | 0% | 0 | 0% | 0 | 0% | 0 | 0% |
| 20-30 (6) | 4 | 67% | 3 | 50% | 5 | 83% | 3 | 50% |
| 30-40 (3) | 2 | 67% | 3 | 100% | 3 | 100% | 2 | 67% |
| 40-50 (0) | 0 | 0% | 0 | 0% | 0 | 0% | 0 | 0% |
| 50-60 (0) | 0 | 0% | 0 | 0% | 0 | 0% | 0 | 0% |
| Total | 6 | 67% | 6 | 67% | 8 | 89% | 5 | 56% |
| Average | | 67% | | 75% | | 92% | | 58% |
| ST.DEV | | 0.00 | | 0.35 | | 0.12 | | 0.12 |
| **Females** | | | | | | | | |
| 15-20 (1) | 0 | 0% | 0 | 0% | 0 | 0% | 1 | 100% |
| 20-30 (3) | 3 | 100% | 3 | 100% | 2 | 67% | 0 | 0% |
| 30-40 (4) | 2 | 50% | 2 | 50% | 2 | 50% | 2 | 50% |
| 40-50 (0) | 0 | 0% | 0 | 0% | 0 | 0% | 0 | 0% |
| 50-60 (0) | 0 | 0% | 0 | 0% | 0 | 0% | 0 | 0% |
| Total | 5 | 63% | 5 | 63% | 4 | 50% | 3 | 38% |
| Average | | 50% | | 50% | | 39% | | 50% |
| ST.DEV | | 0.50 | | 0.50 | | 0.35 | | 0.50 |

## Table 3.5C7 – Handlebars – Type of 3DP and Customizers

| Type of 3DP - General | S | S% | M | M% | D | D% | C | C% |
|---|---|---|---|---|---|---|---|---|
| 'Makers' (43) | 31 | 72% | 18 | 42% | 19 | 44% | 16 | 37% |
| 'Common' (40) | 33 | 83% | 24 | 60% | 24 | 60% | 19 | 48% |
| 'None' – C&A (10) | 7 | 70% | 2 | 20% | 4 | 40% | 5 | 50% |
| 'None' – CO (17) | 10 | 59% | 5 | 29% | 11 | 65% | 8 | 47% |
| **Total** | **81** | **74%** | **49** | **45%** | **58** | **53%** | **48** | **44%** |
| **Average** | | **71%** | | **38%** | | **52%** | | **45%** |
| **ST.DEV** | | **0.10** | | **0.17** | | **0.12** | | **0.06** |
| **Males** | | | | | | | | |
| 'Makers' (35) | 26 | 74% | 15 | 43% | 17 | 49% | 13 | 37% |
| 'Common' (35) | 29 | 83% | 21 | 60% | 22 | 63% | 17 | 49% |
| 'None' – C&A (6) | 3 | 50% | 1 | 17% | 3 | 50% | 2 | 33% |
| 'None' – CO (10) | 6 | 60% | 3 | 30% | 6 | 60% | 4 | 40% |
| **Total** | **64** | **74%** | **40** | **47%** | **48** | **56%** | **36** | **42%** |
| **Average** | | **67%** | | **37%** | | **55%** | | **40%** |
| **ST.DEV** | | **0.15** | | **0.18** | | **0.07** | | **0.06** |
| **Females** | | | | | | | | |
| 'Makers' (8) | 5 | 63% | 3 | 38% | 2 | 25% | 3 | 38% |
| 'Common' (5) | 4 | 80% | 3 | 60% | 2 | 40% | 2 | 40% |
| 'None' – C&A (4) | 4 | 100% | 1 | 25% | 1 | 25% | 3 | 75% |
| 'None' – CO (7) | 4 | 57% | 2 | 29% | 5 | 71% | 4 | 57% |
| **Total** | **17** | **71%** | **9** | **38%** | **10** | **42%** | **12** | **50%** |
| **Average** | | **75%** | | **38%** | | **40%** | | **52%** |
| **ST.DEV** | | **0.19** | | **0.16** | | **0.22** | | **0.17** |

## Table 3.5C8 – Handlebars – Age Range.

| Age Range - General | S | S% | M | M% | D | D% | C | C% |
|---|---|---|---|---|---|---|---|---|
| 15-20 (18) | 15 | 83% | 5 | 28% | 7 | 39% | 11 | 61% |
| 20-30 (58) | 40 | 69% | 27 | 47% | 28 | 48% | 19 | 33% |
| 30-40 (26) | 19 | 73% | 13 | 50% | 16 | 62% | 13 | 50% |
| 40-50 (7) | 6 | 86% | 5 | 71% | 6 | 86% | 4 | 57% |
| 50-60 (1) | 1 | 100% | 1 | 100% | 1 | 100% | 1 | 100% |
| **Total** | **81** | **74%** | **51** | **46%** | **58** | **53%** | **48** | **44%** |
| **Average** | | **78%** | | **49%** | | **59%** | | **50%** |
| **ST.DEV** | | **0.08** | | **0.18** | | **0.20** | | **0.13** |
| **Males** | | | | | | | | |
| 15-20 (14) | 11 | 79% | 4 | 29% | 6 | 43% | 9 | 64% |
| 20-30 (44) | 31 | 70% | 20 | 45% | 22 | 50% | 13 | 30% |
| 30-40 (19) | 15 | 79% | 10 | 53% | 13 | 68% | 9 | 47% |
| 40-50 (7) | 6 | 86% | 5 | 71% | 6 | 86% | 4 | 57% |
| 50-60 (1) | 1 | 100% | 1 | 100% | 1 | 100% | 1 | 100% |
| **Total** | **64** | **75%** | **40** | **47%** | **48** | **56%** | **36** | **42%** |
| **Average** | | **78%** | | **50%** | | **62%** | | **50%** |
| **ST.DEV** | | **0.06** | | **0.18** | | **0.19** | | **0.15** |
| **Females** | | | | | | | | |
| 15-20 (4) | 4 | 100% | 1 | 25% | 1 | 25% | 2 | 50% |
| 20-30 (14) | 9 | 64% | 7 | 50% | 6 | 43% | 6 | 43% |
| 30-40 (7) | 4 | 57% | 3 | 43% | 3 | 43% | 4 | 57% |
| 40-50 (0) | 0 | 0% | 0 | 0% | 0 | 0% | 0 | 0% |
| 50-60 (0) | 0 | 0% | 0 | 0% | 0 | 0% | 0 | 0% |
| **Total** | **17** | **68%** | **11** | **44%** | **10** | **40%** | **12** | **48%** |
| **Average** | | **55%** | | **29%** | | **28%** | | **38%** |
| **ST.DEV** | | **0.23** | | **0.13** | | **0.10** | | **0.07** |

## Table 3.5C9 – Handlebars – Type of 3DP ('Makers') - Age Range.

| Age Range - General | S | S% | M | M% | D | D% | C | C% |
|---|---|---|---|---|---|---|---|---|
| **15-20 (9)** | 8 | 89% | 3 | 33% | 4 | 44% | 4 | 44% |
| **20-30 (22)** | 14 | 64% | 10 | 45% | 10 | 45% | 6 | 27% |
| **30-40 (11)** | 8 | 73% | 4 | 36% | 4 | 36% | 5 | 45% |
| **40-50 (0)** | 0 | 0% | 0 | 0% | 0 | 0% | 0 | 0% |
| **50-60 (1)** | 1 | 100% | 1 | 100% | 1 | 100% | 1 | 100% |
| **Total** | **31** | **72%** | **18** | **42%** | **19** | **44%** | **16** | **37%** |
| **Average** | | **75%** | | **38%** | | **42%** | | **39%** |
| **ST.DEV** | | **0.13** | | **0.06** | | **0.05** | | **0.10** |
| **Males** | | | | | | | | |
| **15-20 (7)** | 6 | 86% | 2 | 29% | 4 | 57% | 4 | 57% |
| **20-30 (17)** | 11 | 65% | 8 | 47% | 8 | 47% | 4 | 24% |
| **30-40 (10)** | 8 | 80% | 4 | 40% | 4 | 40% | 4 | 40% |
| **40-50 (0)** | 0 | 0% | 0 | 0% | 0 | 0% | 0 | 0% |
| **50-60 (1)** | 1 | 100% | 1 | 100% | 1 | 100% | 1 | 100% |
| **Total** | **26** | **74%** | **15** | **43%** | **17** | **49%** | **13** | **37%** |
| **Average** | | **77%** | | **39%** | | **48%** | | **40%** |
| **ST.DEV** | | **0.11** | | **0.09** | | **0.09** | | **0.17** |
| **Females** | | | | | | | | |
| **15-20 (2)** | 2 | 100% | 1 | 50% | 0 | 0% | 0 | 0% |
| **20-30 (5)** | 3 | 60% | 2 | 40% | 2 | 40% | 2 | 40% |
| **30-40 (1)** | 0 | 0% | 0 | 0% | 0 | 0% | 1 | 100% |
| **40-50 (0)** | 0 | 0% | 0 | 0% | 0 | 0% | 0 | 0% |
| **50-60 (0)** | 0 | 0% | 0 | 0% | 0 | 0% | 0 | 0% |
| **Total** | **5** | **63%** | **3** | **38%** | **2** | **25%** | **3** | **38%** |
| **Average** | | **53%** | | **30%** | | **13%** | | **47%** |
| **ST.DEV** | | **0.50** | | **0.26** | | **0.23** | | **0.50** |

## Table 3.5C10 – Handlebars – Type of 3DP ('Common') - Age Range.

| Age Range - General | S | S% | M | M% | D | D% | C | C% |
|---|---|---|---|---|---|---|---|---|
| **15-20 (5)** | 5 | 100% | 1 | 20% | 1 | 20% | 5 | 100% |
| **20-30 (21)** | 16 | 76% | 12 | 57% | 10 | 48% | 7 | 33% |
| **30-40 (7)** | 5 | 71% | 5 | 71% | 6 | 86% | 3 | 43% |
| **40-50 (7)** | 6 | 86% | 5 | 71% | 6 | 86% | 4 | 57% |
| **50-60 (0)** | 0 | 0% | 0 | 0% | 0 | 0% | 0 | 0% |
| **Total** | **32** | **80%** | **23** | **58%** | **23** | **58%** | **19** | **48%** |
| **Average** | | **83%** | | **55%** | | **60%** | | **58%** |
| **ST.DEV** | | **0.13** | | **0.24** | | **0.32** | | **0.29** |
| **Males** | | | | | | | | |
| **15-20 (4)** | 4 | 100% | 1 | 25% | 1 | 25% | 4 | 100% |
| **20-30 (18)** | 15 | 83% | 11 | 61% | 9 | 50% | 6 | 33% |
| **30-40 (6)** | 4 | 67% | 4 | 67% | 6 | 100% | 3 | 50% |
| **40-50 (7)** | 6 | 86% | 5 | 71% | 6 | 86% | 4 | 57% |
| **50-60 (0)** | 0 | 0% | 0 | 0% | 0 | 0% | 0 | 0% |
| **Total** | **29** | **83%** | **21** | **60%** | **22** | **63%** | **17** | **49%** |
| **Average** | | **84%** | | **56%** | | **65%** | | **60%** |
| **ST.DEV** | | **0.14** | | **0.21** | | **0.34** | | **0.28** |
| **Females** | | | | | | | | |
| **15-20 (1)** | 1 | 100% | 0 | 0% | 0 | 0% | 1 | 100% |
| **20-30 (3)** | 1 | 33% | 1 | 33% | 1 | 33% | 1 | 33% |
| **30-40 (1)** | 1 | 100% | 1 | 100% | 0 | 0% | 0 | 0% |
| **40-50 (7)** | 0 | 0% | 0 | 0% | 0 | 0% | 0 | 0% |
| **50-60 (0)** | 0 | 0% | 0 | 0% | 0 | 0% | 0 | 0% |
| **Total** | **3** | **60%** | **2** | **40%** | **1** | **20%** | **2** | **40%** |
| **Average** | | **78%** | | **44%** | | **11%** | | **44%** |
| **ST.DEV** | | **0.38** | | **0.51** | | **0.19** | | **0.51** |

## Table 3.5C11 – Handlebars – Type of 3DP ('None' – Customize & Assemble) - Age Range.

| Age Range - General | S | S% | M | M% | D | D% | C | C% |
|---|---|---|---|---|---|---|---|---|
| 15-20 (3) | 1 | 33% | 1 | 33% | 1 | 33% | 1 | 33% |
| 20-30 (6) | 5 | 83% | 1 | 17% | 3 | 50% | 3 | 50% |
| 30-40 (1) | 1 | 100% | 0 | 0% | 0 | 0% | 1 | 100% |
| 40-50 (0) | 0 | 0% | 0 | 0% | 0 | 0% | 0 | 0% |
| 50-60 (0) | 0 | 0% | 0 | 0% | 0 | 0% | 0 | 0% |
| Total | 7 | 70% | 2 | 20% | 4 | 40% | 5 | 50% |
| Average | | 72% | | 17% | | 28% | | 61% |
| ST.DEV | | 0.35 | | 0.17 | | 0.25 | | 0.35 |
| Males | | | | | | | | |
| 15-20 (3) | 1 | 33% | 1 | 33% | 1 | 33% | 1 | 33% |
| 20-30 (3) | 2 | 67% | 0 | 0% | 2 | 67% | 1 | 33% |
| 30-40 (0) | 0 | 0% | 0 | 0% | 0 | 0% | 0 | 0% |
| 40-50 (0) | 0 | 0% | 0 | 0% | 0 | 0% | 0 | 0% |
| 50-60 (0) | 0 | 0% | 0 | 0% | 0 | 0% | 0 | 0% |
| Total | 1 | 50% | 1 | 17% | 3 | 50% | 2 | 33% |
| Average | | 50% | | 17% | | 50% | | 33% |
| ST.DEV | | 0.24 | | 0.24 | | 0.24 | | 0.00 |
| Females | | | | | | | | |
| 15-20 (0) | 0 | 0% | 0 | 0% | 0 | 0% | 0 | 0% |
| 20-30 (3) | 3 | 100% | 1 | 33% | 1 | 33% | 2 | 67% |
| 30-40 (1) | 1 | 100% | 0 | 0% | 0 | 0% | 1 | 100% |
| 40-50 (0) | 0 | 0% | 0 | 0% | 0 | 0% | 0 | 0% |
| 50-60 (0) | 0 | 0% | 0 | 0% | 0 | 0% | 0 | 0% |
| Total | 4 | 100% | 1 | 25% | 1 | 25% | 3 | 75% |
| Average | | 100% | | 17% | | 17% | | 83% |
| ST.DEV | | 0.00 | | 0.24 | | 0.24 | | 0.24 |

## Table 3.5C12 – Handlebars – Type of 3DP ('None' – 'Customize Only') - Age Range.

| Age Range - General | S | S% | M | M% | D | D% | C | C% |
|---|---|---|---|---|---|---|---|---|
| 15-20 (1) | 1 | 100% | 0 | 0% | 1 | 100% | 1 | 100% |
| 20-30 (9) | 4 | 44% | 3 | 33% | 4 | 44% | 3 | 33% |
| 30-40 (7) | 5 | 71% | 4 | 57% | 6 | 86% | 4 | 57% |
| 40-50 (0) | 0 | 0% | 0 | 0% | 0 | 0% | 0 | 0% |
| 50-60 (0) | 0 | 0% | 0 | 0% | 0 | 0% | 0 | 0% |
| Total | 10 | 59% | 7 | 41% | 11 | 65% | 8 | 47% |
| Average | | 72% | | 30% | | 77% | | 63% |
| ST.DEV | | 0.28 | | 0.29 | | 0.29 | | 0.34 |
| Males | | | | | | | | |
| 15-20 (0) | 0 | 0% | 0 | 0% | 0 | 0% | 0 | 0% |
| 20-30 (6) | 3 | 50% | 1 | 17% | 3 | 50% | 2 | 33% |
| 30-40 (3) | 3 | 100% | 2 | 67% | 3 | 100% | 2 | 67% |
| 40-50 (0) | 0 | 0% | 0 | 0% | 0 | 0% | 0 | 0% |
| 50-60 (0) | 0 | 0% | 0 | 0% | 0 | 0% | 0 | 0% |
| Total | 6 | 67% | 3 | 33% | 6 | 67% | 4 | 44% |
| Average | | 75% | | 42% | | 75% | | 50% |
| ST.DEV | | 0.35 | | 0.35 | | 0.35 | | 0.24 |
| Females | | | | | | | | |
| 15-20 (1) | 1 | 100% | 0 | 0% | 1 | 100% | 1 | 100% |
| 20-30 (3) | 1 | 33% | 2 | 67% | 1 | 33% | 1 | 33% |
| 30-40 (4) | 2 | 50% | 2 | 50% | 3 | 75% | 2 | 50% |
| 40-50 (0) | 0 | 0% | 0 | 0% | 0 | 0% | 0 | 0% |
| 50-60 (0) | 0 | 0% | 0 | 0% | 0 | 0% | 0 | 0% |
| Total | 4 | 50% | 4 | 50% | 5 | 63% | 4 | 50% |
| Average | | 61% | | 39% | | 69% | | 61% |
| ST.DEV | | 0.35 | | 0.35 | | 0.34 | | 0.35 |

## Table 3.5C13 – Pedals – Type of 3DP and Customizers

| Type of 3DP - General | S | S% | M | M% | D | D% | C | C% |
|---|---|---|---|---|---|---|---|---|
| 'Makers' (43) | 22 | 51% | 17 | 40% | 16 | 37% | 14 | 33% |
| 'Common' (40) | 23 | 58% | 18 | 45% | 29 | 73% | 13 | 33% |
| 'None' – C&A (10) | 2 | 20% | 2 | 20% | 2 | 20% | 3 | 30% |
| 'None' – CO (17) | 10 | 59% | 7 | 41% | 9 | 53% | 8 | 47% |
| **Total** | **57** | **52%** | **44** | **40%** | **56** | **51%** | **38** | **35%** |
| **Average** | | **47%** | | **36%** | | **46%** | | **36%** |
| **ST.DEV** | | **0.18** | | **0.11** | | **0.22** | | **0.08** |
| **Males** | | | | | | | | |
| 'Makers' (35) | 20 | 57% | 16 | 46% | 14 | 40% | 10 | 29% |
| 'Common' (35) | 21 | 60% | 15 | 43% | 26 | 74% | 12 | 34% |
| 'None' – C&A (6) | 1 | 17% | 2 | 33% | 1 | 17% | 1 | 17% |
| 'None' – CO (10) | 7 | 70% | 5 | 50% | 6 | 60% | 4 | 40% |
| **Total** | **49** | **57%** | **38** | **44%** | **47** | **55%** | **27** | **31%** |
| **Average** | | **51%** | | **43%** | | **48%** | | **30%** |
| **ST.DEV** | | **0.24** | | **0.07** | | **0.25** | | **0.10** |
| **Females** | | | | | | | | |
| 'Makers' (8) | 2 | 25% | 1 | 13% | 2 | 25% | 4 | 50% |
| 'Common' (5) | 2 | 40% | 3 | 60% | 3 | 60% | 1 | 20% |
| 'None' – C&A (4) | 1 | 25% | 0 | 0% | 1 | 25% | 2 | 50% |
| 'None' – CO (7) | 3 | 43% | 2 | 29% | 3 | 43% | 4 | 57% |
| **Total** | **8** | **33%** | **6** | **25%** | **9** | **38%** | **11** | **46%** |
| **Average** | | **33%** | | **25%** | | **38%** | | **44%** |
| **ST.DEV** | | **0.10** | | **0.26** | | **0.17** | | **0.17** |

## Table 3.5C14 – Pedals – Age Range.

| Age Range - General | S | S% | M | M% | D | D% | C | C% |
|---|---|---|---|---|---|---|---|---|
| 15-20 (18) | 11 | 61% | 6 | 33% | 9 | 50% | 7 | 39% |
| 20-30 (58) | 27 | 47% | 20 | 34% | 28 | 48% | 14 | 24% |
| 30-40 (26) | 15 | 58% | 14 | 54% | 15 | 58% | 13 | 50% |
| 40-50 (7) | 3 | 43% | 3 | 43% | 3 | 43% | 4 | 57% |
| 50-60 (1) | ~~1~~ | ~~100%~~ | ~~1~~ | ~~100%~~ | ~~1~~ | ~~100%~~ | ~~0~~ | ~~0%~~ |
| **Total** | **57** | **52%** | **44** | **40%** | **56** | **51%** | **38** | **35%** |
| **Average** | | **52%** | | **41%** | | **50%** | | **43%** |
| **ST.DEV** | | **0.09** | | **0.09** | | **0.06** | | **0.14** |
| **Males** | | | | | | | | |
| 15-20 (14) | 9 | 64% | 5 | 36% | 7 | 50% | 5 | 36% |
| 20-30 (44) | 22 | 50% | 17 | 39% | 23 | 52% | 7 | 16% |
| 30-40 (19) | 14 | 74% | 12 | 63% | 13 | 68% | 11 | 58% |
| 40-50 (7) | 3 | 43% | 3 | 43% | 3 | 43% | 4 | 57% |
| 50-60 (1) | ~~1~~ | ~~100%~~ | ~~1~~ | ~~100%~~ | ~~1~~ | ~~100%~~ | ~~0~~ | ~~0%~~ |
| **Total** | **49** | **58%** | **38** | **45%** | **47** | **55%** | **27** | **32%** |
| **Average** | | **58%** | | **45%** | | **53%** | | **42%** |
| **ST.DEV** | | **0.14** | | **0.12** | | **0.11** | | **0.20** |
| **Females** | | | | | | | | |
| 15-20 (4) | 2 | 50% | 1 | 25% | 2 | 50% | 2 | 50% |
| 20-30 (14) | 5 | 36% | 3 | 21% | 5 | 36% | 7 | 50% |
| 30-40 (7) | 1 | 14% | 2 | 29% | 2 | 29% | 2 | 29% |
| 40-50 (0) | ~~0~~ | ~~0%~~ | ~~0~~ | ~~0%~~ | ~~0~~ | ~~0%~~ | ~~0~~ | ~~0%~~ |
| 50-60 (0) | ~~0~~ | ~~0%~~ | ~~0~~ | ~~0%~~ | ~~0~~ | ~~0%~~ | ~~0~~ | ~~0%~~ |
| **Total** | **8** | **32%** | **6** | **24%** | **9** | **36%** | **11** | **44%** |
| **Average** | | **25%** | | **19%** | | **29%** | | **32%** |
| **ST.DEV** | | **0.18** | | **0.04** | | **0.11** | | **0.12** |

## Table 3.5C15 – Pedals – Type of 3DP ('Makers') - Age Range.

| Age Range - General | S | S% | M | M% | D | D% | C | C% |
|---|---|---|---|---|---|---|---|---|
| 15-20 (9) | 5 | 56% | 3 | 33% | 3 | 33% | 3 | 33% |
| 20-30 (22) | 10 | 45% | 6 | 27% | 6 | 27% | 5 | 23% |
| 30-40 (11) | 6 | 55% | 7 | 64% | 6 | 55% | 6 | 55% |
| 40-50 (0) | 0 | 0% | 0 | 0% | 0 | 0% | 0 | 0% |
| 50-60 (1) | 1 | 100% | 1 | 100% | 1 | 100% | 0 | 0% |
| **Total** | **22** | **51%** | **17** | **40%** | **16** | **37%** | **14** | **33%** |
| **Average** | | **52%** | | **41%** | | **38%** | | **37%** |
| **ST.DEV** | | **0.06** | | **0.19** | | **0.14** | | **0.16** |
| **Males** | | | | | | | | |
| 15-20 (7) | 5 | 71% | 3 | 43% | 2 | 29% | 2 | 29% |
| 20-30 (17) | 8 | 47% | 5 | 29% | 5 | 29% | 2 | 12% |
| 30-40 (10) | 6 | 60% | 7 | 70% | 6 | 60% | 6 | 60% |
| 40-50 (0) | 0 | 0% | 0 | 0% | 0 | 0% | 0 | 0% |
| 50-60 (1) | 1 | 100% | 1 | 100% | 1 | 100% | 0 | 0% |
| **Total** | **20** | **57%** | **16** | **46%** | **14** | **40%** | **10** | **29%** |
| **Average** | | **59%** | | **47%** | | **39%** | | **33%** |
| **ST.DEV** | | **0.12** | | **0.21** | | **0.18** | | **0.24** |
| **Females** | | | | | | | | |
| 15-20 (2) | 0 | 0% | 0 | 0% | 1 | 50% | 1 | 50% |
| 20-30 (5) | 2 | 40% | 1 | 20% | 1 | 20% | 3 | 60% |
| 30-40 (1) | 0 | 0% | 0 | 0% | 0 | 0% | 0 | 0% |
| 40-50 (0) | 0 | 0% | 0 | 0% | 0 | 0% | 0 | 0% |
| 50-60 (0) | 0 | 0% | 0 | 0% | 0 | 0% | 0 | 0% |
| **Total** | **2** | **25%** | **1** | **13%** | **2** | **25%** | **4** | **50%** |
| **Average** | | **13%** | | **7%** | | **23%** | | **37%** |
| **ST.DEV** | | **0.23** | | **0.12** | | **0.25** | | **0.32** |

## Table 3.5C16 – Pedals – Type of 3DP ('Common') - Age Range.

| Age Range - General | S | S% | M | M% | D | D% | C | C% |
|---|---|---|---|---|---|---|---|---|
| 15-20 (5) | 4 | 80% | 2 | 40% | 5 | 100% | 2 | 40% |
| 20-30 (21) | 11 | 52% | 9 | 43% | 16 | 76% | 4 | 19% |
| 30-40 (7) | 5 | 71% | 4 | 57% | 5 | 71% | 3 | 43% |
| 40-50 (7) | 3 | 43% | 3 | 43% | 3 | 43% | 3 | 43% |
| 50-60 (0) | 0 | 0% | 0 | 0% | 0 | 0% | 0 | 0% |
| **Total** | **23** | **58%** | **18** | **45%** | **29** | **73%** | **12** | **30%** |
| **Average** | | **62%** | | **46%** | | **73%** | | **36%** |
| **ST.DEV** | | **0.17** | | **0.08** | | **0.23** | | **0.12** |
| **Males** | | | | | | | | |
| 15-20 (4) | 3 | 75% | 1 | 25% | 4 | 100% | 2 | 50% |
| 20-30 (18) | 10 | 56% | 8 | 44% | 15 | 83% | 3 | 17% |
| 30-40 (6) | 5 | 83% | 3 | 50% | 4 | 67% | 3 | 50% |
| 40-50 (7) | 3 | 43% | 3 | 43% | 3 | 43% | 4 | 57% |
| 50-60 (0) | 0 | 0% | 0 | 0% | 0 | 0% | 0 | 0% |
| **Total** | **21** | **60%** | **15** | **43%** | **26** | **74%** | **12** | **34%** |
| **Average** | | **64%** | | **41%** | | **73%** | | **43%** |
| **ST.DEV** | | **0.18** | | **0.11** | | **0.24** | | **0.18** |
| **Females** | | | | | | | | |
| 15-20 (1) | 1 | 100% | 1 | 100% | 1 | 100% | 0 | 0% |
| 20-30 (3) | 1 | 33% | 1 | 33% | 1 | 33% | 1 | 33% |
| 30-40 (1) | 0 | 0% | 1 | 100% | 1 | 100% | 0 | 0% |
| 40-50 (7) | 0 | 0% | 0 | 0% | 0 | 0% | 0 | 0% |
| 50-60 (0) | 0 | 0% | 0 | 0% | 0 | 0% | 0 | 0% |
| **Total** | **2** | **40%** | **3** | **60%** | **3** | **60%** | **1** | **20%** |
| **Average** | | **44%** | | **78%** | | **78%** | | **11%** |
| **ST.DEV** | | **0.51** | | **0.38** | | **0.38** | | **0.19** |

## Table 3.5C17 – Pedals – Type of 3DP ('None' – Customize & Assemble) - Age Range.

| Age Range - General | S | S% | M | M% | D | D% | C | C% |
|---|---|---|---|---|---|---|---|---|
| 15-20 (3) | 1 | 33% | 1 | 33% | 1 | 33% | 1 | 33% |
| 20-30 (6) | 1 | 17% | 1 | 17% | 1 | 17% | 2 | 33% |
| 30-40 (1) | 0 | 0% | 0 | 0% | 0 | 0% | 0 | 0% |
| 40-50 (0) | 0 | 0% | 0 | 0% | 0 | 0% | 0 | 0% |
| 50-60 (0) | 0 | 0% | 0 | 0% | 0 | 0% | 0 | 0% |
| Total | 2 | 20% | 2 | 20% | 2 | 20% | 3 | 30% |
| Average | | 17% | | 17% | | 17% | | 22% |
| ST.DEV | | 0.17 | | 0.17 | | 0.17 | | 0.19 |
| Males | | | | | | | | |
| 15-20 (3) | 1 | 33% | 1 | 33% | 1 | 33% | 1 | 33% |
| 20-30 (3) | 0 | 0% | 1 | 33% | 0 | 0% | 0 | 0% |
| 30-40 (0) | 0 | 0% | 0 | 0% | 0 | 0% | 0 | 0% |
| 40-50 (0) | 0 | 0% | 0 | 0% | 0 | 0% | 0 | 0% |
| 50-60 (0) | 0 | 0% | 0 | 0% | 0 | 0% | 0 | 0% |
| Total | 1 | 17% | 2 | 33% | 1 | 17% | 1 | 17% |
| Average | | 17% | | 33% | | 17% | | 17% |
| ST.DEV | | 0.24 | | 0.00 | | 0.24 | | 0.24 |
| Females | | | | | | | | |
| 15-20 (0) | 0 | 0% | 0 | 0% | 0 | 0% | 0 | 0% |
| 20-30 (3) | 1 | 33% | 0 | 0% | 1 | 33% | 2 | 67% |
| 30-40 (1) | 0 | 0% | 0 | 0% | 0 | 0% | 0 | 0% |
| 40-50 (0) | 0 | 0% | 0 | 0% | 0 | 0% | 0 | 0% |
| 50-60 (0) | 0 | 0% | 0 | 0% | 0 | 0% | 0 | 0% |
| Total | 1 | 25% | 0 | 0% | 1 | 25% | 2 | 50% |
| Average | | 17% | | 0% | | 17% | | 33% |
| ST.DEV | | 0.24 | | 0.00 | | 0.24 | | 0.47 |

## Table 3.5C18 – Pedals – Type of 3DP ('None' – 'Customize Only') - Age Range.

| Age Range - General | S | S% | M | M% | D | D% | C | C% |
|---|---|---|---|---|---|---|---|---|
| 15-20 (1) | 1 | 100% | 0 | 0% | 0 | 0% | 1 | 100% |
| 20-30 (9) | 5 | 56% | 4 | 44% | 5 | 56% | 3 | 33% |
| 30-40 (7) | 4 | 57% | 3 | 43% | 4 | 57% | 4 | 57% |
| 40-50 (0) | 0 | 0% | 0 | 0% | 0 | 0% | 0 | 0% |
| 50-60 (0) | 0 | 0% | 0 | 0% | 0 | 0% | 0 | 0% |
| Total | 10 | 59% | 7 | 41% | 9 | 53% | 8 | 47% |
| Average | | 71% | | 29% | | 38% | | 63% |
| ST.DEV | | 0.25 | | 0.25 | | 0.33 | | 0.34 |
| Males | | | | | | | | |
| 15-20 (0) | 0 | 0% | 0 | 0% | 0 | 0% | 0 | 0% |
| 20-30 (6) | 4 | 67% | 3 | 50% | 3 | 50% | 2 | 33% |
| 30-40 (3) | 3 | 100% | 2 | 67% | 3 | 100% | 2 | 67% |
| 40-50 (0) | 0 | 0% | 0 | 0% | 0 | 0% | 0 | 0% |
| 50-60 (0) | 0 | 0% | 0 | 0% | 0 | 0% | 0 | 0% |
| Total | 7 | 78% | 5 | 56% | 6 | 67% | 4 | 44% |
| Average | | 83% | | 58% | | 75% | | 50% |
| ST.DEV | | 0.24 | | 0.12 | | 0.35 | | 0.24 |
| Females | | | | | | | | |
| 15-20 (1) | 1 | 100% | 0 | 0% | 0 | 0% | 1 | 100% |
| 20-30 (3) | 1 | 33% | 1 | 33% | 2 | 67% | 1 | 33% |
| 30-40 (4) | 1 | 25% | 1 | 25% | 1 | 25% | 2 | 50% |
| 40-50 (0) | 0 | 0% | 0 | 0% | 0 | 0% | 0 | 0% |
| 50-60 (0) | 0 | 0% | 0 | 0% | 0 | 0% | 0 | 0% |
| Total | 3 | 38% | 2 | 25% | 3 | 38% | 4 | 50% |
| Average | | 53% | | 19% | | 31% | | 61% |
| ST.DEV | | 0.41 | | 0.17 | | 0.34 | | 0.35 |

## Appendix 3.5D – Statistics of the third page

## Mechanism

### Table 3.5D1 – Gear – Type of 3DP and Customizers

| Type of 3DP - General | S | S% | C | C% |
|---|---|---|---|---|
| 'Makers' (43) | 29 | 67% | 8 | 19% |
| 'Common' (40) | 33 | 83% | 11 | 28% |
| 'None' – C&A (10) | 2 | 20% | 2 | 20% |
| 'None' – CO (17) | 10 | 59% | 6 | 35% |
| **Total** | **74** | **67%** | **27** | **25%** |
| **Average** | | **57%** | | **25%** |
| **ST.DEV** | | **0.27** | | **0.08** |
| **Males** | | | | |
| 'Makers' (35) | 25 | 71% | 6 | 17% |
| 'Common' (35) | 30 | 86% | 10 | 29% |
| 'None' – C&A (6) | 2 | 33% | 1 | 17% |
| 'None' – CO (10) | 6 | 60% | 4 | 40% |
| **Total** | **63** | **73%** | **21** | **24%** |
| **Average** | | **63%** | | **26%** |
| **ST.DEV** | | **0.22** | | **0.11** |
| **Females** | | | | |
| 'Makers' (8) | 4 | 50% | 2 | 25% |
| 'Common' (5) | 3 | 60% | 1 | 20% |
| 'None' – C&A (4) | 0 | 0% | 1 | 25% |
| 'None' – CO (7) | 4 | 57% | 2 | 29% |
| **Total** | **11** | **46%** | **6** | **25%** |
| **Average** | | **42%** | | **25%** |
| **ST.DEV** | | **0.28** | | **0.04** |

### Table 3.5D2 – Gear – Age Range.

| Age Range - General | S | S% | C | C% |
|---|---|---|---|---|
| 15-20 (18) | 13 | 72% | 7 | 39% |
| 20-30 (58) | 34 | 59% | 12 | 21% |
| 30-40 (26) | 21 | 81% | 6 | 23% |
| 40-50 (7) | 5 | 71% | 2 | 29% |
| 50-60 (1) | ~~1~~ | ~~100%~~ | ~~0~~ | ~~0%~~ |
| **Total** | **74** | **67%** | **27** | **25%** |
| **Average** | | **71%** | | **28%** |
| **ST.DEV** | | **0.09** | | **0.08** |
| **Males** | | | | |
| 15-20 (14) | 10 | 71% | 6 | 43% |
| 20-30 (44) | 30 | 68% | 8 | 18% |
| 30-40 (19) | 17 | 89% | 5 | 26% |
| 40-50 (7) | 5 | 71% | 2 | 29% |
| 50-60 (1) | ~~1~~ | ~~100%~~ | ~~0~~ | ~~0%~~ |
| **Total** | **63** | **74%** | **21** | **25%** |
| **Average** | | **75%** | | **29%** |
| **ST.DEV** | | **0.10** | | **0.10** |
| **Females** | | | | |
| 15-20 (4) | 3 | 75% | 1 | 25% |
| 20-30 (14) | 4 | 29% | 4 | 29% |
| 30-40 (7) | 4 | 57% | 1 | 14% |
| 40-50 (0) | ~~0~~ | ~~0%~~ | ~~0~~ | ~~0%~~ |
| 50-60 (0) | ~~0~~ | ~~0%~~ | ~~0~~ | ~~0%~~ |
| **Total** | **11** | **44%** | **6** | **24%** |
| **Average** | | **40%** | | **17%** |
| **ST.DEV** | | **0.23** | | **0.07** |

## Table 3.5D3 – Gear – Type of 3DP ('Makers') - Age Range.

| Age Range - General | S | S% | C | C% |
|---|---|---|---|---|
| 15-20 (9) | 6 | 67% | 3 | 33% |
| 20-30 (22) | 10 | 45% | 4 | 18% |
| 30-40 (11) | 11 | 100% | 2 | 18% |
| 40-50 (0) | 0 | 0% | 0 | 0% |
| 50-60 (1) | 1 | 100% | 0 | 0% |
| **Total** | **28** | **65%** | **9** | **21%** |
| **Average** | | **71%** | | **23%** |
| **ST.DEV** | | **0.27** | | **0.09** |
| **Males** | | | | |
| 15-20 (7) | 5 | 71% | 2 | 29% |
| 20-30 (17) | 9 | 53% | 2 | 12% |
| 30-40 (10) | 10 | 100% | 2 | 20% |
| 40-50 (0) | 0 | 0% | 0 | 0% |
| 50-60 (1) | 1 | 100% | 0 | 0% |
| **Total** | **25** | **71%** | **6** | **17%** |
| **Average** | | **75%** | | **20%** |
| **ST.DEV** | | **0.24** | | **0.08** |
| **Females** | | | | |
| 15-20 (2) | 1 | 50% | 1 | 50% |
| 20-30 (5) | 1 | 20% | 2 | 40% |
| 30-40 (1) | 1 | 100% | 0 | 0% |
| 40-50 (0) | 0 | 0% | 0 | 0% |
| 50-60 (0) | 0 | 0% | 0 | 0% |
| **Total** | **3** | **38%** | **3** | **38%** |
| **Average** | | **57%** | | **30%** |
| **ST.DEV** | | **0.40** | | **0.26** |

## Table 3.5D4 – Gear – Type of 3DP ('Common') - Age Range.

| Age Range - General | S | S% | C | C% |
|---|---|---|---|---|
| 15-20 (5) | 4 | 80% | 3 | 60% |
| 20-30 (21) | 18 | 86% | 5 | 24% |
| 30-40 (7) | 6 | 86% | 1 | 14% |
| 40-50 (7) | 5 | 71% | 2 | 29% |
| 50-60 (0) | 0 | 0% | 0 | 0% |
| **Total** | **33** | **83%** | **11** | **28%** |
| **Average** | | **81%** | | **32%** |
| **ST.DEV** | | **0.07** | | **0.20** |
| **Males** | | | | |
| 15-20 (4) | 4 | 100% | 3 | 75% |
| 20-30 (18) | 16 | 89% | 4 | 22% |
| 30-40 (6) | 5 | 83% | 1 | 17% |
| 40-50 (7) | 5 | 71% | 2 | 29% |
| 50-60 (0) | 0 | 0% | 0 | 0% |
| **Total** | **30** | **86%** | **10** | **29%** |
| **Average** | | **86%** | | **36%** |
| **ST.DEV** | | **0.12** | | **0.27** |
| **Females** | | | | |
| 15-20 (1) | 0 | 0% | 0 | 0% |
| 20-30 (3) | 2 | 67% | 1 | 33% |
| 30-40 (1) | 1 | 100% | 0 | 0% |
| 40-50 (7) | 0 | 0% | 0 | 0% |
| 50-60 (0) | 0 | 0% | 0 | 0% |
| **Total** | **3** | **60%** | **1** | **20%** |
| **Average** | | **56%** | | **11%** |
| **ST.DEV** | | **0.51** | | **0.19** |

## Table 3.5D5 – Gear – Type of 3DP ('None' – Customize & Assemble) - Age Range.

| Age Range - General | S | S% | C | C% |
|---|---|---|---|---|
| 15-20 (3) | 1 | 33% | 1 | 33% |
| 20-30 (6) | 1 | 17% | 1 | 17% |
| 30-40 (1) | 0 | 0% | 0 | 0% |
| 40-50 (0) | 0 | 0% | 0 | 0% |
| 50-60 (0) | 0 | 0% | 0 | 0% |
| Total | 2 | 20% | 2 | 20% |
| Average | | 17% | | 17% |
| ST.DEV | | 0.17 | | 0.17 |
| Males | | | | |
| 15-20 (3) | 1 | 33% | 1 | 33% |
| 20-30 (3) | 1 | 33% | 0 | 0% |
| 30-40 (0) | 0 | 0% | 0 | 0% |
| 40-50 (0) | 0 | 0% | 0 | 0% |
| 50-60 (0) | 0 | 0% | 0 | 0% |
| Total | 2 | 33% | 1 | 17% |
| Average | | 33% | | 17% |
| ST.DEV | | 0.00 | | 0.24 |
| Females | | | | |
| 15-20 (0) | 0 | 0% | 0 | 0% |
| 20-30 (3) | 0 | 0% | 1 | 33% |
| 30-40 (1) | 0 | 0% | 0 | 0% |
| 40-50 (0) | 0 | 0% | 0 | 0% |
| 50-60 (0) | 0 | 0% | 0 | 0% |
| Total | 0 | 0% | 1 | 25% |
| Average | | 0% | | 17% |
| ST.DEV | | 0.00 | | 0.24 |

## Table 3.5D6 – Gear – Type of 3DP ('None' – 'Customize Only') - Age Range.

| Age Range - General | S | S% | C | C% |
|---|---|---|---|---|
| 15-20 (1) | 1 | 100% | 1 | 100% |
| 20-30 (9) | 5 | 56% | 2 | 22% |
| 30-40 (7) | 4 | 57% | 3 | 43% |
| 40-50 (0) | 0 | 0% | 0 | 0% |
| 50-60 (0) | 0 | 0% | 0 | 0% |
| Total | 10 | 59% | 6 | 35% |
| Average | | 71% | | 55% |
| ST.DEV | | 0.25 | | 0.40 |
| Males | | | | |
| 15-20 (0) | 0 | 0% | 0 | 0% |
| 20-30 (6) | 4 | 67% | 2 | 33% |
| 30-40 (3) | 2 | 67% | 2 | 67% |
| 40-50 (0) | 0 | 0% | 0 | 0% |
| 50-60 (0) | 0 | 0% | 0 | 0% |
| Total | 6 | 67% | 4 | 44% |
| Average | | 67% | | 50% |
| ST.DEV | | 0.00 | | 0.24 |
| Females | | | | |
| 15-20 (1) | 1 | 100% | 1 | 100% |
| 20-30 (3) | 1 | 33% | 0 | 0% |
| 30-40 (4) | 2 | 50% | 1 | 25% |
| 40-50 (0) | 0 | 0% | 0 | 0% |
| 50-60 (0) | 0 | 0% | 0 | 0% |
| Total | 4 | 50% | 2 | 25% |
| Average | | 61% | | 42% |
| ST.DEV | | 0.35 | | 0.52 |

## Table 3.5D7 – Breaks – Type of 3DP and Customizers

| Type of 3DP - General | S | S% | C | C% |
|---|---|---|---|---|
| 'Makers' (43) | 34 | 79% | 8 | 19% |
| 'Common' (40) | 33 | 83% | 9 | 23% |
| 'None' – C&A (10) | 5 | 50% | 3 | 30% |
| 'None' – CO (17) | 15 | 88% | 8 | 47% |
| **Total** | **87** | **79%** | **28** | **25%** |
| **Average** | | **75%** | | **30%** |
| **ST.DEV** | | **0.17** | | **0.13** |
| **Males** | | | | |
| 'Makers' (35) | 27 | 77% | 6 | 17% |
| 'Common' (35) | 31 | 89% | 8 | 23% |
| 'None' – C&A (6) | 4 | 67% | 1 | 17% |
| 'None' – CO (10) | 9 | 90% | 5 | 50% |
| **Total** | **71** | **83%** | **20** | **23%** |
| **Average** | | **81%** | | **27%** |
| **ST.DEV** | | **0.11** | | **0.16** |
| **Females** | | | | |
| 'Makers' (8) | 7 | 88% | 2 | 25% |
| 'Common' (5) | 2 | 40% | 1 | 20% |
| 'None' – C&A (4) | 1 | 25% | 2 | 50% |
| 'None' – CO (7) | 6 | 86% | 3 | 43% |
| **Total** | **16** | **67%** | **8** | **33%** |
| **Average** | | **60%** | | **34%** |
| **ST.DEV** | | **0.32** | | **0.14** |

## Table 3.5D8 – Breaks – Age Range.

| Age Range - General | S | S% | C | C% |
|---|---|---|---|---|
| 15-20 (18) | 13 | 72% | 5 | 28% |
| 20-30 (58) | 43 | 74% | 10 | 17% |
| 30-40 (26) | 24 | 92% | 9 | 35% |
| 40-50 (7) | 6 | 86% | 4 | 57% |
| 50-60 (1) | ~~1~~ | ~~100%~~ | ~~0~~ | ~~0%~~ |
| **Total** | **87** | **79%** | **28** | **25%** |
| **Average** | | **81%** | | **34%** |
| **ST.DEV** | | **0.10** | | **0.17** |
| **Males** | | | | |
| 15-20 (14) | 10 | 71% | 4 | 29% |
| 20-30 (44) | 36 | 82% | 6 | 14% |
| 30-40 (19) | 18 | 95% | 6 | 32% |
| 40-50 (7) | 6 | 86% | 4 | 57% |
| 50-60 (1) | ~~1~~ | ~~100%~~ | ~~0~~ | ~~0%~~ |
| **Total** | **71** | **84%** | **20** | **24%** |
| **Average** | | **83%** | | **33%** |
| **ST.DEV** | | **0.10** | | **0.18** |
| **Females** | | | | |
| 15-20 (4) | 3 | 75% | 1 | 25% |
| 20-30 (14) | 7 | 50% | 4 | 29% |
| 30-40 (7) | 6 | 86% | 3 | 43% |
| 40-50 (0) | ~~0~~ | ~~0%~~ | ~~0~~ | ~~0%~~ |
| 50-60 (0) | ~~0~~ | ~~0%~~ | ~~0~~ | ~~0%~~ |
| **Total** | **16** | **64%** | **8** | **32%** |
| **Average** | | **53%** | | **24%** |
| **ST.DEV** | | **0.18** | | **0.09** |

## Table 3.5D9 – Breaks – Type of 3DP ('Makers') - Age Range.

| Age Range - General | S | S% | C | C% |
|---|---|---|---|---|
| 15-20 (9) | 6 | 67% | 2 | 22% |
| 20-30 (22) | 15 | 68% | 5 | 23% |
| 30-40 (11) | 11 | 100% | 2 | 18% |
| 40-50 (0) | 0 | 0% | 0 | 0% |
| 50-60 (1) | 1 | 100% | 0 | 0% |
| Total | 33 | 77% | 9 | 21% |
| Average | | 78% | | 21% |
| ST.DEV | | 0.19 | | 0.02 |
| **Males** | | | | |
| 15-20 (7) | 5 | 71% | 1 | 14% |
| 20-30 (17) | 11 | 65% | 3 | 18% |
| 30-40 (10) | 10 | 100% | 2 | 20% |
| 40-50 (0) | 0 | 0% | 0 | 0% |
| 50-60 (1) | 1 | 100% | 0 | 0% |
| Total | 27 | 77% | 6 | 17% |
| Average | | 79% | | 17% |
| ST.DEV | | 0.19 | | 0.03 |
| **Females** | | | | |
| 15-20 (2) | 1 | 50% | 1 | 50% |
| 20-30 (5) | 4 | 80% | 2 | 40% |
| 30-40 (1) | 1 | 100% | 0 | 0% |
| 40-50 (0) | 0 | 0% | 0 | 0% |
| 50-60 (0) | 0 | 0% | 0 | 0% |
| Total | 6 | 75% | 3 | 38% |
| Average | | 77% | | 30% |
| ST.DEV | | 0.25 | | 0.26 |

## Table 3.5D10 – Breaks – Type of 3DP ('Common') - Age Range.

| Age Range - General | S | S% | C | C% |
|---|---|---|---|---|
| 15-20 (5) | 4 | 80% | 2 | 40% |
| 20-30 (21) | 17 | 81% | 1 | 5% |
| 30-40 (7) | 6 | 86% | 2 | 29% |
| 40-50 (7) | 6 | 86% | 4 | 57% |
| 50-60 (0) | 0 | 0% | 0 | 0% |
| Total | 33 | 83% | 9 | 23% |
| Average | | 83% | | 33% |
| ST.DEV | | 0.03 | | 0.22 |
| **Males** | | | | |
| 15-20 (4) | 4 | 100% | 2 | 50% |
| 20-30 (18) | 16 | 89% | 1 | 6% |
| 30-40 (6) | 5 | 83% | 1 | 17% |
| 40-50 (7) | 6 | 86% | 4 | 57% |
| 50-60 (0) | 0 | 0% | 0 | 0% |
| Total | 31 | 89% | 8 | 23% |
| Average | | 89% | | 32% |
| ST.DEV | | 0.07 | | 0.25 |
| **Females** | | | | |
| 15-20 (1) | 0 | 0% | 0 | 0% |
| 20-30 (3) | 1 | 33% | 0 | 0% |
| 30-40 (1) | 1 | 100% | 1 | 100% |
| 40-50 (7) | 0 | 0% | 0 | 0% |
| 50-60 (0) | 0 | 0% | 0 | 0% |
| Total | 2 | 40% | 1 | 20% |
| Average | | 44% | | 33% |
| ST.DEV | | 0.51 | | 0.58 |

## Table 3.5D11 – Breaks – Type of 3DP ('None' – Customize & Assemble) - Age Range.

| Age Range - General | S | S% | C | C% |
|---|---|---|---|---|
| 15-20 (3) | 1 | 33% | 1 | 33% |
| 20-30 (6) | 4 | 67% | 2 | 33% |
| 30-40 (1) | 0 | 0% | 0 | 0% |
| 40-50 (0) | 0 | 0% | 0 | 0% |
| 50-60 (0) | 0 | 0% | 0 | 0% |
| **Total** | **5** | **50%** | **3** | **30%** |
| **Average** | | **33%** | | **22%** |
| **ST.DEV** | | **0.33** | | **0.19** |
| **Males** | | | | |
| 15-20 (3) | 1 | 33% | 1 | 33% |
| 20-30 (3) | 3 | 100% | 0 | 0% |
| 30-40 (0) | 0 | 0% | 0 | 0% |
| 40-50 (0) | 0 | 0% | 0 | 0% |
| 50-60 (0) | 0 | 0% | 0 | 0% |
| **Total** | **4** | **67%** | **1** | **17%** |
| **Average** | | **67%** | | **17%** |
| **ST.DEV** | | **0.47** | | **0.24** |
| **Females** | | | | |
| 15-20 (0) | 0 | 0% | 0 | 0% |
| 20-30 (3) | 1 | 33% | 2 | 67% |
| 30-40 (1) | 0 | 0% | 0 | 0% |
| 40-50 (0) | 0 | 0% | 0 | 0% |
| 50-60 (0) | 0 | 0% | 0 | 0% |
| **Total** | **1** | **25%** | **2** | **50%** |
| **Average** | | **17%** | | **33%** |
| **ST.DEV** | | **0.24** | | **0.47** |

## Table 3.5D12 – Breaks – Type of 3DP ('None' – 'Customize Only') - Age Range.

| Age Range - General | S | S% | C | C% |
|---|---|---|---|---|
| 15-20 (1) | 1 | 100% | 1 | 100% |
| 20-30 (9) | 7 | 78% | 2 | 22% |
| 30-40 (7) | 7 | 100% | 5 | 71% |
| 40-50 (0) | 0 | 0% | 0 | 0% |
| 50-60 (0) | 0 | 0% | 0 | 0% |
| **Total** | **15** | **88%** | **8** | **47%** |
| **Average** | | **93%** | | **65%** |
| **ST.DEV** | | **0.13** | | **0.39** |
| **Males** | | | | |
| 15-20 (0) | 0 | 0% | 0 | 0% |
| 20-30 (6) | 6 | 100% | 2 | 33% |
| 30-40 (3) | 3 | 100% | 3 | 100% |
| 40-50 (0) | 0 | 0% | 0 | 0% |
| 50-60 (0) | 0 | 0% | 0 | 0% |
| **Total** | **9** | **100%** | **5** | **56%** |
| **Average** | | **100%** | | **67%** |
| **ST.DEV** | | **0.00** | | **0.47** |
| **Females** | | | | |
| 15-20 (1) | 1 | 100% | 1 | 100% |
| 20-30 (3) | 1 | 33% | 0 | 0% |
| 30-40 (4) | 4 | 100% | 2 | 50% |
| 40-50 (0) | 0 | 0% | 0 | 0% |
| 50-60 (0) | 0 | 0% | 0 | 0% |
| **Total** | **6** | **75%** | **3** | **38%** |
| **Average** | | **78%** | | **50%** |
| **ST.DEV** | | **0.38** | | **0.50** |

## Appendix 3.5E – Statistics of the third page

## Enhancers

### Table 3.5E1 – Lights – Type of 3DP and Customizers

| Type of 3DP - General | S | S% | C | C% |
|---|---|---|---|---|
| 'Makers' (43) | 21 | 49% | 17 | 40% |
| 'Common' (40) | 25 | 63% | 22 | 55% |
| 'None' – C&A (10) | 4 | 40% | 2 | 20% |
| 'None' – CO (17) | 9 | 53% | 10 | 59% |
| **Total** | **59** | **54%** | **51** | **46%** |
| **Average** | | **51%** | | **43%** |
| **ST.DEV** | | **0.09** | | **0.18** |
| **Males** | | | | |
| 'Makers' (35) | 19 | 54% | 12 | 34% |
| 'Common' (35) | 24 | 69% | 21 | 60% |
| 'None' – C&A (6) | 3 | 50% | 1 | 17% |
| 'None' – CO (10) | 3 | 30% | 5 | 50% |
| **Total** | **49** | **57%** | **39** | **45%** |
| **Average** | | **51%** | | **40%** |
| **ST.DEV** | | **0.16** | | **0.19** |
| **Females** | | | | |
| 'Makers' (8) | 2 | 25% | 5 | 63% |
| 'Common' (5) | 1 | 20% | 1 | 20% |
| 'None' – C&A (4) | 1 | 25% | 1 | 25% |
| 'None' – CO (7) | 6 | 86% | 5 | 71% |
| **Total** | **10** | **42%** | **12** | **50%** |
| **Average** | | **39%** | | **45%** |
| **ST.DEV** | | **0.31** | | **0.26** |

### Table 3.5E2 – Lights – Age Range.

| Age Range - General | S | S% | C | C% |
|---|---|---|---|---|
| 15-20 (18) | 9 | 50% | 9 | 50% |
| 20-30 (58) | 29 | 50% | 27 | 47% |
| 30-40 (26) | 15 | 58% | 11 | 42% |
| 40-50 (7) | 4 | 57% | 3 | 43% |
| 50-60 (1) | 1 | 100% | 1 | 100% |
| **Total** | **58** | **53%** | **51** | **46%** |
| **Average** | | **54%** | | **45%** |
| **ST.DEV** | | **0.04** | | **0.04** |
| **Males** | | | | |
| 15-20 (14) | 7 | 50% | 7 | 50% |
| 20-30 (44) | 24 | 55% | 20 | 45% |
| 30-40 (19) | 12 | 63% | 8 | 42% |
| 40-50 (7) | 4 | 57% | 3 | 43% |
| 50-60 (1) | 1 | 100% | 1 | 100% |
| **Total** | **48** | **56%** | **39** | **46%** |
| **Average** | | **56%** | | **45%** |
| **ST.DEV** | | **0.05** | | **0.04** |
| **Females** | | | | |
| 15-20 (4) | 2 | 50% | 2 | 50% |
| 20-30 (14) | 5 | 36% | 7 | 50% |
| 30-40 (7) | 3 | 43% | 3 | 43% |
| 40-50 (0) | 0 | 0% | 0 | 0% |
| 50-60 (0) | 0 | 0% | 0 | 0% |
| **Total** | **10** | **40%** | **12** | **48%** |
| **Average** | | **32%** | | **36%** |
| **ST.DEV** | | **0.07** | | **0.04** |

## Table 3.5E3 – Lights – Type of 3DP ('Makers') - Age Range.

| Age Range - General | S | S% | C | C% |
|---|---|---|---|---|
| 15-20 (9) | 4 | 44% | 3 | 33% |
| 20-30 (22) | 10 | 45% | 8 | 36% |
| 30-40 (11) | 6 | 55% | 5 | 45% |
| 40-50 (0) | 0 | 0% | 0 | 0% |
| 50-60 (1) | 1 | 100% | 1 | 100% |
| Total | 21 | 49% | 17 | 40% |
| Average | | 48% | | 38% |
| ST.DEV | | 0.06 | | 0.06 |
| Males | | | | |
| 15-20 (7) | 3 | 43% | 2 | 29% |
| 20-30 (17) | 9 | 53% | 4 | 24% |
| 30-40 (10) | 6 | 60% | 5 | 50% |
| 40-50 (0) | 0 | 0% | 0 | 0% |
| 50-60 (1) | 1 | 100% | 1 | 100% |
| Total | 19 | 54% | 12 | 34% |
| Average | | 52% | | 34% |
| ST.DEV | | 0.09 | | 0.14 |
| Females | | | | |
| 15-20 (2) | 1 | 50% | 1 | 50% |
| 20-30 (5) | 1 | 20% | 4 | 80% |
| 30-40 (1) | 0 | 0% | 0 | 0% |
| 40-50 (0) | 0 | 0% | 0 | 0% |
| 50-60 (0) | 0 | 0% | 0 | 0% |
| Total | 2 | 25% | 5 | 63% |
| Average | | 23% | | 43% |
| ST.DEV | | 0.25 | | 0.40 |

## Table 3.5E4 – Lights – Type of 3DP ('Common') - Age Range.

| Age Range - General | S | S% | C | C% |
|---|---|---|---|---|
| 15-20 (5) | 3 | 60% | 4 | 80% |
| 20-30 (21) | 12 | 57% | 13 | 62% |
| 30-40 (7) | 5 | 71% | 2 | 29% |
| 40-50 (7) | 4 | 57% | 3 | 43% |
| 50-60 (0) | 0 | 0% | 0 | 0% |
| Total | 24 | 60% | 22 | 55% |
| Average | | 61% | | 53% |
| ST.DEV | | 0.07 | | 0.22 |
| Males | | | | |
| 15-20 (4) | 3 | 75% | 4 | 100% |
| 20-30 (18) | 11 | 61% | 12 | 67% |
| 30-40 (6) | 5 | 83% | 2 | 33% |
| 40-50 (7) | 4 | 57% | 3 | 43% |
| 50-60 (0) | 0 | 0% | 0 | 0% |
| Total | 23 | 66% | 21 | 60% |
| Average | | 69% | | 61% |
| ST.DEV | | 0.12 | | 0.30 |
| Females | | | | |
| 15-20 (1) | 0 | 0% | 0 | 0% |
| 20-30 (3) | 1 | 33% | 1 | 33% |
| 30-40 (1) | 0 | 0% | 0 | 0% |
| 40-50 (7) | 0 | 0% | 0 | 0% |
| 50-60 (0) | 0 | 0% | 0 | 0% |
| Total | 1 | 20% | 1 | 20% |
| Average | | 11% | | 11% |
| ST.DEV | | 0.19 | | 0.19 |

## Table 3.5E5 – Lights – Type of 3DP ('None' – Customize & Assemble) - Age Range.

| Age Range - General | S | S% | C | C% |
|---|---|---|---|---|
| 15-20 (3) | 1 | 33% | 1 | 33% |
| 20-30 (6) | 3 | 50% | 1 | 17% |
| 30-40 (1) | 0 | 0% | 0 | 0% |
| 40-50 (0) | 0 | 0% | 0 | 0% |
| 50-60 (0) | 0 | 0% | 0 | 0% |
| **Total** | **4** | **40%** | **2** | **20%** |
| **Average** | | **28%** | | **17%** |
| **ST.DEV** | | **0.25** | | **0.17** |
| **Males** | | | | |
| 15-20 (3) | 1 | 33% | 1 | 33% |
| 20-30 (3) | 2 | 67% | 0 | 0% |
| 30-40 (0) | 0 | 0% | 0 | 0% |
| 40-50 (0) | 0 | 0% | 0 | 0% |
| 50-60 (0) | 0 | 0% | 0 | 0% |
| **Total** | **3** | **50%** | **1** | **17%** |
| **Average** | | **50%** | | **17%** |
| **ST.DEV** | | **0.24** | | **0.24** |
| **Females** | | | | |
| 15-20 (0) | 0 | 0% | 0 | 0% |
| 20-30 (3) | 1 | 33% | 1 | 33% |
| 30-40 (1) | 0 | 0% | 0 | 0% |
| 40-50 (0) | 0 | 0% | 0 | 0% |
| 50-60 (0) | 0 | 0% | 0 | 0% |
| **Total** | **1** | **25%** | **1** | **25%** |
| **Average** | | **17%** | | **17%** |
| **ST.DEV** | | **0.24** | | **0.24** |

## Table 3.5E6 – Lights – Type of 3DP ('None' – 'Customize Only') - Age Range.

| Age Range - General | S | S% | C | C% |
|---|---|---|---|---|
| 15-20 (1) | 1 | 100% | 1 | 100% |
| 20-30 (9) | 4 | 44% | 5 | 56% |
| 30-40 (7) | 4 | 57% | 4 | 57% |
| 40-50 (0) | 0 | 0% | 0 | 0% |
| 50-60 (0) | 0 | 0% | 0 | 0% |
| **Total** | **9** | **53%** | **10** | **59%** |
| **Average** | | **67%** | | **71%** |
| **ST.DEV** | | **0.29** | | **0.25** |
| **Males** | | | | |
| 15-20 (0) | 0 | 0% | 0 | 0% |
| 20-30 (6) | 2 | 33% | 4 | 67% |
| 30-40 (3) | 1 | 33% | 1 | 33% |
| 40-50 (0) | 0 | 0% | 0 | 0% |
| 50-60 (0) | 0 | 0% | 0 | 0% |
| **Total** | **3** | **33%** | **5** | **56%** |
| **Average** | | **33%** | | **50%** |
| **ST.DEV** | | **0.00** | | **0.24** |
| **Females** | | | | |
| 15-20 (1) | 1 | 100% | 1 | 100% |
| 20-30 (3) | 2 | 67% | 1 | 33% |
| 30-40 (4) | 3 | 75% | 3 | 75% |
| 40-50 (0) | 0 | 0% | 0 | 0% |
| 50-60 (0) | 0 | 0% | 0 | 0% |
| **Total** | **6** | **75%** | **5** | **63%** |
| **Average** | | **81%** | | **69%** |
| **ST.DEV** | | **0.17** | | **0.34** |

## Table 3.5E7 – Mud flaps – Type of 3DP and Customizers

| Type of 3DP - General | S | S% | C | C% |
|---|---|---|---|---|
| 'Makers' (43) | 17 | 40% | 14 | 33% |
| 'Common' (40) | 24 | 60% | 20 | 50% |
| 'None' – C&A (10) | 4 | 40% | 4 | 40% |
| 'None' – CO (17) | 11 | 65% | 7 | 41% |
| **Total** | **56** | **51%** | **45** | **41%** |
| **Average** | | **51%** | | **41%** |
| **ST.DEV** | | **0.13** | | **0.07** |
| **Males** | | | | |
| 'Makers' (35) | 15 | 43% | 10 | 29% |
| 'Common' (35) | 23 | 66% | 19 | 54% |
| 'None' – C&A (6) | 3 | 50% | 2 | 33% |
| 'None' – CO (10) | 8 | 80% | 4 | 40% |
| **Total** | **49** | **57%** | **35** | **41%** |
| **Average** | | **60%** | | **39%** |
| **ST.DEV** | | **0.17** | | **0.11** |
| **Females** | | | | |
| 'Makers' (8) | 2 | 25% | 4 | 50% |
| 'Common' (5) | 1 | 20% | 1 | 20% |
| 'None' – C&A (4) | 1 | 25% | 2 | 50% |
| 'None' – CO (7) | 3 | 43% | 3 | 43% |
| **Total** | **7** | **29%** | **10** | **42%** |
| **Average** | | **28%** | | **41%** |
| **ST.DEV** | | **0.10** | | **0.14** |

## Table 3.5E8 – Mud flaps – Age Range.

| Age Range - General | S | S% | C | C% |
|---|---|---|---|---|
| 15-20 (18) | 6 | 33% | 6 | 33% |
| 20-30 (58) | 33 | 57% | 24 | 41% |
| 30-40 (26) | 11 | 42% | 12 | 46% |
| 40-50 (7) | 5 | 71% | 3 | 43% |
| 50-60 (1) | 1 | 100% | 0 | 0% |
| **Total** | **56** | **51%** | **45** | **41%** |
| **Average** | | **51%** | | **41%** |
| **ST.DEV** | | **0.17** | | **0.05** |
| **Males** | | | | |
| 15-20 (14) | 5 | 36% | 4 | 29% |
| 20-30 (44) | 29 | 66% | 19 | 43% |
| 30-40 (19) | 9 | 47% | 9 | 47% |
| 40-50 (7) | 5 | 71% | 3 | 43% |
| 50-60 (1) | 1 | 100% | 0 | 0% |
| **Total** | **49** | **58%** | **35** | **41%** |
| **Average** | | **55%** | | **40%** |
| **ST.DEV** | | **0.17** | | **0.08** |
| **Females** | | | | |
| 15-20 (4) | 1 | 25% | 2 | 50% |
| 20-30 (14) | 4 | 29% | 5 | 36% |
| 30-40 (7) | 2 | 29% | 3 | 43% |
| 40-50 (0) | 0 | 0% | 0 | 0% |
| 50-60 (0) | 0 | 0% | 0 | 0% |
| **Total** | **7** | **28%** | **10** | **40%** |
| **Average** | | **21%** | | **32%** |
| **ST.DEV** | | **0.02** | | **0.07** |

## Table 3.5E9 – Mud flaps – Type of 3DP ('Makers') - Age Range.

| Age Range - General | S | S% | C | C% |
|---|---|---|---|---|
| 15-20 (9) | 2 | 22% | 2 | 22% |
| 20-30 (22) | 10 | 45% | 7 | 32% |
| 30-40 (11) | 4 | 36% | 5 | 45% |
| 40-50 (0) | 0 | 0% | 0 | 0% |
| 50-60 (1) | 1 | 100% | 0 | 0% |
| **Total** | **17** | **40%** | **14** | **33%** |
| **Average** | | **35%** | | **33%** |
| **ST.DEV** | | **0.12** | | **0.12** |
| **Males** | | | | |
| 15-20 (7) | 2 | 29% | 1 | 14% |
| 20-30 (17) | 8 | 47% | 4 | 24% |
| 30-40 (10) | 4 | 40% | 5 | 50% |
| 40-50 (0) | 0 | 0% | 0 | 0% |
| 50-60 (1) | 1 | 100% | 0 | 0% |
| **Total** | **15** | **43%** | **10** | **29%** |
| **Average** | | **39%** | | **29%** |
| **ST.DEV** | | **0.09** | | **0.19** |
| **Females** | | | | |
| 15-20 (2) | 0 | 0% | 1 | 50% |
| 20-30 (5) | 2 | 40% | 3 | 60% |
| 30-40 (1) | 0 | 0% | 0 | 0% |
| 40-50 (0) | 0 | 0% | 0 | 0% |
| 50-60 (0) | 0 | 0% | 0 | 0% |
| **Total** | **2** | **25%** | **4** | **50%** |
| **Average** | | **13%** | | **37%** |
| **ST.DEV** | | **0.23** | | **0.32** |

## Table 3.5E10 – Mud flaps – Type of 3DP ('Common') - Age Range.

| Age Range - General | S | S% | C | C% |
|---|---|---|---|---|
| 15-20 (5) | 2 | 40% | 2 | 40% |
| 20-30 (21) | 14 | 67% | 12 | 57% |
| 30-40 (7) | 3 | 43% | 3 | 43% |
| 40-50 (7) | 5 | 71% | 3 | 43% |
| 50-60 (0) | 0 | 0% | 0 | 0% |
| **Total** | **24** | **60%** | **20** | **50%** |
| **Average** | | **55%** | | **46%** |
| **ST.DEV** | | **0.16** | | **0.08** |
| **Males** | | | | |
| 15-20 (4) | 2 | 50% | 2 | 50% |
| 20-30 (18) | 13 | 72% | 12 | 67% |
| 30-40 (6) | 3 | 50% | 2 | 33% |
| 40-50 (7) | 5 | 71% | 3 | 43% |
| 50-60 (0) | 0 | 0% | 0 | 0% |
| **Total** | **23** | **66%** | **19** | **54%** |
| **Average** | | **61%** | | **48%** |
| **ST.DEV** | | **0.13** | | **0.14** |
| **Females** | | | | |
| 15-20 (1) | 0 | 0% | 0 | 0% |
| 20-30 (3) | 1 | 33% | 0 | 0% |
| 30-40 (1) | 0 | 0% | 1 | 100% |
| 40-50 (7) | 0 | 0% | 0 | 0% |
| 50-60 (0) | 0 | 0% | 0 | 0% |
| **Total** | **1** | **20%** | **1** | **20%** |
| **Average** | | **11%** | | **33%** |
| **ST.DEV** | | **0.19** | | **0.58** |

**Table 3.5E11 – Mud flaps – Type of 3DP ('None' – Customize & Assemble) - Age Range.**

| Age Range - General | S | S% | C | C% |
|---|---|---|---|---|
| 15-20 (3) | 1 | 33% | 1 | 33% |
| 20-30 (6) | 3 | 50% | 3 | 50% |
| 30-40 (1) | 0 | 0% | 0 | 0% |
| 40-50 (0) | 0 | 0% | 0 | 0% |
| 50-60 (0) | 0 | 0% | 0 | 0% |
| Total | 4 | 40% | 4 | 40% |
| Average | | 28% | | 28% |
| ST.DEV | | 0.25 | | 0.25 |
| Males | | | | |
| 15-20 (3) | 1 | 33% | 1 | 33% |
| 20-30 (3) | 2 | 67% | 1 | 33% |
| 30-40 (0) | 0 | 0% | 0 | 0% |
| 40-50 (0) | 0 | 0% | 0 | 0% |
| 50-60 (0) | 0 | 0% | 0 | 0% |
| Total | 3 | 50% | 2 | 33% |
| Average | | 50% | | 33% |
| ST.DEV | | 0.24 | | 0.00 |
| Females | | | | |
| 15-20 (0) | 0 | 0% | 0 | 0% |
| 20-30 (3) | 1 | 33% | 2 | 67% |
| 30-40 (1) | 0 | 0% | 0 | 0% |
| 40-50 (0) | 0 | 0% | 0 | 0% |
| 50-60 (0) | 0 | 0% | 0 | 0% |
| Total | 1 | 25% | 2 | 50% |
| Average | | 17% | | 33% |
| ST.DEV | | 0.24 | | 0.47 |

**Table 3.5E12 – Mud flaps – Type of 3DP ('None' – 'Customize Only') - Age Range.**

| Age Range - General | S | S% | C | C% |
|---|---|---|---|---|
| 15-20 (1) | 1 | 100% | 1 | 100% |
| 20-30 (9) | 6 | 67% | 2 | 22% |
| 30-40 (7) | 4 | 57% | 4 | 57% |
| 40-50 (0) | 0 | 0% | 0 | 0% |
| 50-60 (0) | 0 | 0% | 0 | 0% |
| Total | 11 | 65% | 7 | 41% |
| Average | | 75% | | 60% |
| ST.DEV | | 0.23 | | 0.39 |
| Males | | | | |
| 15-20 (0) | 0 | 0% | 0 | 0% |
| 20-30 (6) | 6 | 100% | 2 | 33% |
| 30-40 (3) | 2 | 67% | 2 | 67% |
| 40-50 (0) | 0 | 0% | 0 | 0% |
| 50-60 (0) | 0 | 0% | 0 | 0% |
| Total | 8 | 89% | 4 | 44% |
| Average | | 83% | | 50% |
| ST.DEV | | 0.24 | | 0.24 |
| Females | | | | |
| 15-20 (1) | 1 | 100% | 1 | 100% |
| 20-30 (3) | 0 | 0% | 0 | 0% |
| 30-40 (4) | 2 | 50% | 2 | 50% |
| 40-50 (0) | 0 | 0% | 0 | 0% |
| 50-60 (0) | 0 | 0% | 0 | 0% |
| Total | 3 | 38% | 3 | 38% |
| Average | | 50% | | 50% |
| ST.DEV | | 0.50 | | 0.50 |

## Appendix 3.5F – Statistics of the fourth page

### Table 3.5F1 – Perception of P3DP - Gender

| | Total | Total% | Males | Males% | Females | Females% |
|---|---|---|---|---|---|---|
| Inkjet Printer | 60 | 47% | 43 | 45% | 17 | 53% |
| Smartphone | 39 | 31% | 28 | 30% | 11 | 34% |
| Digital Camera | 28 | 22% | 24 | 25% | 4 | 13% |
| Total | 127 | 100% | 95 | 100% | 32 | 100% |

### Table 3.5F2 – Perception of P3DP – Age Range

| General | Inkjet Printer | Inkjet Printer% | Smartphone | Smartphone% | Digital Camera | Digital Camera% |
|---|---|---|---|---|---|---|
| 15-20 (19) | 8 | 42% | 8 | 42% | 3 | 16% |
| 20-30 (61) | 28 | 46% | 20 | 33% | 13 | 21% |
| 30-40 (29) | 18 | 62% | 4 | 14% | 7 | 24% |
| 40-50 (15) | 5 | 33% | 6 | 40% | 4 | 27% |
| 50-60 (2) | 1 | 50% | 1 | 50% | 0 | 0% |
| 60-70 (1) | 0 | 0% | 0 | 0% | 1 | 100% |
| Males | | | | | | |
| 15-20 (15) | 6 | 40% | 6 | 40% | 3 | 20% |
| 20-30 (45) | 21 | 47% | 13 | 29% | 11 | 24% |
| 30-40 (21) | 11 | 52% | 3 | 15% | 7 | 33% |
| 40-50 (11) | 4 | 36% | 5 | 46% | 2 | 18% |
| 50-60 (2) | 1 | 50% | 1 | 50% | 0 | 0% |
| 60-70 (1) | 0 | 0% | 0 | 0% | 1 | 100% |
| Females | | | | | | |
| 15-20 (4) | 2 | 50% | 2 | 50% | 0 | 0% |
| 20-30 (16) | 7 | 44% | 7 | 44% | 2 | 12% |
| 30-40 (8) | 7 | 88% | 1 | 12% | 0 | 0% |
| 40-50 (4) | 1 | 25% | 1 | 25% | 2 | 50% |
| 50-60 (0) | 0 | 0% | 0 | 0% | 0 | 0% |
| 60-70 (0) | 0 | 0% | 0 | 0% | 0 | 0% |

## Table 3.5F3 – Type of P3DP – Perception of P3DP - Gender

| General | Inkjet Printer | Inkjet Printer% | Smartphone | Smartphone% | Digital Camera | Digital Camera% |
|---|---|---|---|---|---|---|
| Makers (43) | 15 | 35% | 17 | 40% | 11 | 25% |
| Common (40) | 25 | 63% | 12 | 30% | 3 | 7% |
| None (44) | 20 | 45% | 10 | 23% | 14 | 32% |
| Males | | | | | | |
| Makers (35) | 12 | 34% | 12 | 34% | 11 | 32% |
| Common (35) | 21 | 60% | 11 | 32% | 3 | 8% |
| None (25) | 10 | 40% | 5 | 20% | 10 | 40% |
| Females | | | | | | |
| Makers (8) | 3 | 38% | 5 | 62% | 0 | 0% |
| Common (5) | 4 | 80% | 1 | 20% | 0 | 0% |
| None (19) | 10 | 53% | 5 | 26% | 4 | 21% |

## Table 3.5F4 – Willingness to Pay - Gender

| | Total | Total% | Males | Males% | Females | Females% |
|---|---|---|---|---|---|---|
| Less than 100 | 20 | 16% | 14 | 15% | 6 | 19% |
| 100-200 | 38 | 30% | 29 | 31% | 9 | 28% |
| 200-300 | 22 | 17% | 16 | 17% | 6 | 19% |
| 300-400 | 17 | 13% | 15 | 16% | 2 | 6% |
| 400-500 | 13 | 10% | 8 | 8% | 5 | 16% |
| 500-1000 | 9 | 7% | 6 | 6% | 3 | 9% |
| More than 1000 | 8 | 7% | 7 | 7% | 1 | 3% |

## Table 3.5F5 – Willingness to Pay – Age Range - Gender

| General | 15-20 (19) | | 20-30 (61) | | 30-40 (29) | | 40-50 (15) | | 50-60 (2) | | 60-70 (1) | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Less than 100 (19) | 2 | 11% | 13 | 21% | 1 | 3% | 3 | 20% | 1 | 50% | 0 | 0% |
| 100-200 (37) | 9 | 48% | 21 | 34% | 6 | 21% | 1 | 7% | 0 | 0% | 1 | 100% |
| 200-300 (22) | 1 | 5% | 13 | 21% | 6 | 21% | 2 | 13% | 0 | 0% | 0 | 0% |
| 300-400 (17) | 4 | 21% | 5 | 8% | 7 | 24% | 1 | 7% | 0 | 0% | 0 | 0% |
| 400-500 (13) | 1 | 5% | 4 | 7% | 5 | 17% | 3 | 20% | 0 | 0% | 0 | 0% |
| 500-1000 (9) | 1 | 5% | 3 | 5% | 2 | 7% | 3 | 20% | 0 | 0% | 0 | 0% |
| More than 1000 (7) | 1 | 5% | 2 | 4% | 2 | 7% | 2 | 13% | 1 | 50% | 0 | 0% |
| **Males (92)** | | | | | | | | | | | | |
| Less than 100 (13) | 2 | 13% | 9 | 20% | 0 | 0% | 2 | 18% | | | | |
| 100-200 (28) | 7 | 46% | 19 | 42% | 2 | 10% | 0 | 0% | | | | |
| 200-300 (16) | 1 | 7% | 7 | 16% | 6 | 28% | 2 | 18% | | | | |
| 300-400 (15) | 4 | 27% | 4 | 9% | 6 | 28% | 1 | 9% | | | | |
| 400-500 (8) | 0 | 0% | 2 | 4.3% | 3 | 14% | 3 | 28% | | | | |
| 500-1000 (6) | 1 | 7% | 2 | 4.3% | 2 | 10% | 1 | 9% | | | | |
| More than 1000 (6) | 0 | 0% | 2 | 4.3% | 2 | 10% | 2 | 18% | | | | |
| Total | **15** | **100%** | **45** | **100%** | **21** | **100%** | **11** | **100%** | | | | |
| **Females (32)** | | | | | | | | | | | | |
| Less than 100 (6) | 0 | 0% | 4 | 25% | 1 | 12.5% | 1 | 25% | | | | |
| 100-200 (9) | 2 | 50% | 2 | 12.5% | 4 | 50% | 1 | 25% | | | | |
| 200-300 (6) | 0 | 0% | 6 | 37.5% | 0 | 0% | 0 | 0% | | | | |
| 300-400 (2) | 0 | 0% | 1 | 6.25% | 1 | 12.5% | 0 | 0% | | | | |
| 400-500 (5) | 1 | 25% | 2 | 12.5% | 2 | 25% | 0 | 0% | | | | |
| 500-1000 (3) | 0 | 0% | 1 | 6.25% | 0 | 0% | 2 | 50% | | | | |
| More than 1000 (1) | 1 | 25% | 0 | 0% | 0 | 0% | 0 | 0% | | | | |
| Total | **4** | **100%** | **16** | **100%** | **8** | **100%** | **4** | **100%** | | | | |

## Table 3.5F6 – Type of P3DP – Willingness to Pay - Gender

| General | Less Than 100 (20) | | 100-200 (38) | | 200-300 (22) | | 300-400 (17) | | 400-500 (13) | | 500-1000 (9) | | More than 1000 (8) | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Makers (43)** | 7 | 16% | 7 | 16% | 7 | 16% | 12 | 28% | 4 | 9% | 3 | 7.5% | 3 | 7.5% |
| **Common (40)** | 2 | 5% | 18 | 45% | 5 | 12.5% | 1 | 2.5 | 6 | 15% | 3 | 7.5% | 5 | 12.5% |
| **None (44)** | 11 | 25% | 13 | 30% | 10 | 23% | 4 | 9% | 3 | 6.5% | 3 | 6.5% | 0 | 0% |
| **Males** | | | | | | | | | | | | | | |
| **Makers (35)** | 5 | 14% | 5 | 14% | 7 | 20% | 11 | 31% | 2 | 6% | 2 | 6% | 3 | 9% |
| **Common (35)** | 1 | 3% | 18 | 51% | 4 | 12% | 0 | 0% | 5 | 14% | 3 | 9% | 4 | 11% |
| **None (25)** | 8 | 32% | 6 | 24% | 5 | 20% | 4 | 16% | 1 | 4% | 1 | 4% | 0 | 0% |
| **Total** | **14** | | **29** | | **16** | | **15** | | **8** | | **6** | | **7** | |
| **Females** | | | | | | | | | | | | | | |
| **Makers (8)** | 2 | 25% | 2 | 25% | 0 | 0% | 1 | 12.5% | 2 | 25% | 1 | 12.5% | 0 | 0% |
| **Common (5)** | 1 | 20% | 0 | 0% | 1 | 20% | 1 | 20% | 1 | 20% | 0 | 0% | 1 | 20% |
| **None (19)** | 3 | 16% | 7 | 37% | 5 | 26% | 0 | 0% | 2 | 10.5% | 2 | 10.5% | 0 | 0% |
| **Total** | **6** | | **9** | | **6** | | **2** | | **5** | | **3** | | **1** | |