



Aalto University

School of Engineering

Department of Engineering Design and Production

**Andrea Heredia del Castillo**

# **Rapid prototyping as a tool for learning product development.**

Final Project

Espoo April 29nd, 2015

Supervisor: Kalevi Ekman

<b>Author</b>	Andrea Heredia del Castillo
<b>School</b>	School of Engineering
<b>Department</b>	Department of Engineering Design and Production
<b>Professorship</b>	Kon-41-Product development
<b>Title</b>	Rapid prototyping as a tool for learning product development.
<b>Supervisor</b>	Professor Kalevi Ekman
<p><b>Abstract</b></p> <p>Recently, 3D printing as a tool for rapid prototyping is becoming a trendy topic in the society. It's usage is being widespread from the industry to the educational contexts. The success of a product is increasingly related to the performance of prototypes in Product Development Processes. In particular, in the first stages of these processes, rapid prototyping covers the lack of knowledge typical of the early phases. 3D printing enhances the diverger style of the experiential learning method required in the early phases of product development. In addition, learning environments where to enhance the use of rapid prototyping tools, such as 3D printers, are another key factor for a competent Product Development Process.</p> <p>This study aims to provide a learning environment that promotes creativity by using 3D printers. The work presents a qualitative and quantitative research. To gain an in-depth understanding of the needs and requirements of the case questionnaires and interviews have been done. Furthermore, this thesis suggests a comparative study of the feasibility of the use of low-end 3D printers in first stages of Product Development Process Variables are analysed in three experiments using different technologies. Lastly, an example of a learning environment supporting rapid prototyping in product development has been created.</p> <p>Based on the findings, it can be assumed that the creation of a learning environment that supports rapid prototyping fosters creativity in their users. The placement of the low-end 3D printer is economically viable and technically feasible. In addition, the space proposed promotes this technology.</p>	
<b>Key words:</b> rapid prototyping, product development process, learning environments, 3D printing.	<b>Date:</b> 29.04.2015 <b>Number of pages:</b> 75 <b>Language:</b> English

## *ACKNOWLEDGEMENTS*

First of all, thanks Eetu for giving me the chance to come to Finland and join ADF family. George, Joel, Maria, Heidi, Tiina, Miko and Ville thanks for the huge amount of advices you gave me. To all the DFers, thanks for the feedbacks, support, the hugs and smiles. Without you I couldn't finish this work and it has been wonderful to meet you all. For these unforgettable months, Kiitos paljon!

To all my friends, the olds and the new ones. Thanks. The ones who live far, you are always in my heart. The ones who share my daily life, thanks for making it easier. And especially Clara and Ruth, you beauties are the family I have chosen.

Andrea, you are my sun every morning, my lover, my soulmate and my best friend. With you each day is even better than the previous one. Thanks for supporting me through this thesis and your constant constructive reviews. I want to go with you until the end of the world because now my home is where you are.

To my family, you are the best treasure I have. Especially to my beloved parents. Mom, dad, you are the most marvellous people I know, honest, positive and brave. Thanks for educating me and pushing me to live the life, not always has been easy and you never give up. I will always be grateful for believing in me. Os quiero!

Thanks to all of you for making me feel the luckiest person in this world.

*A mis padres,  
la luz en mi camino*

# 1. TABLE OF CONTENTS

<b>ABBREVIATIONS.....</b>	<b>8</b>
<b>LIST OF FIGURES.....</b>	<b>9</b>
<b>LIST OF TABLES.....</b>	<b>9</b>
<b>1. INTRODUCTION.....</b>	<b>11</b>
1.1. Motivation.....	11
1.2. Background for research.....	12
1.3. Objectives and scope.....	14
1.4. Thesis structure.....	15
<b>2. THEORETICAL RESEARCH .....</b>	<b>16</b>
2.1. Product development process .....	16
2.1.1. Product .....	16
2.1.2. Product Development.....	16
2.1.3. Product Development Process .....	17
2.1.4. Prototyping in the first stages of the PDP .....	21
2.2. Advanced fabrication techniques.....	23
2.2.1. State of art in additive manufacturing.....	23
2.2.2. Impact of 3D printing.....	26
2.2.3. Benefits of Rapid Prototyping in first stages of PDP.....	28
2.3. Learning environments.....	29
2.3.1. Designing physical environments. ....	31
<b>3. METHODOLOGY OF THE RESEARCH.....</b>	<b>33</b>
3.1. Data collection from questionnaires and interviews.....	33
3.1.1. Questionnaires .....	34
3.1.2. Interviews .....	34
3.2. Comparison between CNC and 3d printing technologies.....	35
3.2.1. Variables analysed .....	36
3.2.2. Geometry of the study .....	38
3.3. 3D printer in Aalto design factory. ....	40
3.3.1. Market analysis.....	41
3.4. Building the physical space.....	43
3.4.1. Layout .....	44
3.4.2. Main characteristics that define the space .....	45
3.4.3. Means to access and act in the space .....	46

<b>4. RESULTS OF THE RESEARCH .....</b>	<b>48</b>
<b>4.1. Analysis questionnaires and interviews .....</b>	<b>48</b>
4.1.1. Questionnaires .....	48
4.1.2. Interviews .....	50
<b>4.2. What benefits come from using 3d printing instead of cnc technology at first stages of product development?.....</b>	<b>51</b>
4.2.1. Cnc experiment.....	52
4.2.2. U-print printer experiment.....	54
4.2.3. Object 30 printer experiment.....	55
4.2.4. Summary.....	56
<b>4.3. Selection of the printer.....</b>	<b>58</b>
<b>4.4. What kind of learning environments support rapid prototyping in product development?.....</b>	<b>62</b>
4.4.1. Learning environment enhancing rapid prototyping .....	63
<b>5. DISCUSSION .....</b>	<b>64</b>
<b>5.1. Limitations of study.....</b>	<b>67</b>
<b>5.2. Future work .....</b>	<b>67</b>
<b>REFERENCES.....</b>	<b>68</b>
<b>APPENDIX 1.....</b>	<b>74</b>

## *ABBREVIATIONS*

ADF	Aalto Design Factory
Addlab	Aalto University Digital Design Laboratory
PdP	Product development Project
PDP	Product Development Process
FFE	Fuzzy Front End
AM	Additive Manufacturing
ASTM	Association Society for Testing Materials
CNC	Control Numeric Computer
CAD	Computer Aided Design
STL	Stereolithography file
FDM	Fused Deposition Modelling
ABS	Acrylonitrile Butadiene Styrene
PLA	PolyLactic Acid
FFF	Fused Filament Fabrication



## *LIST OF FIGURES*

Figure 1 Generic Product Development Process. (Ulrich & Eppinger, 2012).....	18
Figure 2 Spiral Product Development Process. (Ulrich & Eppinger, 2012) .....	18
Figure 3 Design Process Paradox. (Ullman, 2003).....	19
Figure 4 Front End activities comprising the concept development phase. (Ulrich & Eppinger, 2012).....	20
Figure 5 Development phase in Product Development Process. (Burt & Pinkerton, 1996).....	20
Figure 6 Conceptual representation of rapid prototyping process (Prinz, 1997). .....	24
Figure 7 Industrial additive processes (Kruth, et al., 1998) .....	25
Figure 8 Forecast of AM industry (Terry Wohlers, 2013).....	26
Figure 9 Uses of industrial AM systems (Terry Wohlers, 2013) .....	27
Figure 10 Experiential learning cycle of Kolb. Adapted by (Smulders, 2004) .....	30
Figure 11 Geometry of the prototype .....	39
Figure 12 Build envelope dimensions.....	39
Figure 13 New distribution of the space. Designed by George Atanassov. ....	43
Figure 14 Render of the layout. Designed by George Atanassov .....	44
Figure 15 Backgrounds of the team members .....	49
Figure 16 Range of prototypes done by the team members.....	49
Figure 17 Workflow of CNC process .....	52
Figure 18 Workflow of U-print process.....	54
Figure 19 Workflow of Object 30 process.....	55
Figure 20 Results of market analysis.....	58
Figure 21 Parts of NUNU printer examples of prints.....	61
Figure 22 Evolution of the space.....	62
Figure 23 Results of the new space .....	63

## *LIST OF TABLES*

Table 1 Machines used for the comparison of CNC and AM technologies .....	36
Table 2 Variables selected for the comparison of CNC and AM technologies. ....	36
Table 3 Commercial printers comparison .....	41
Table 4 Commercial printers comparison (2).....	41
Table 5 Matrix printers/functions comparison .....	42
Table 6 Prototyping facilities division .....	43
Table 7 Workshops organized by Print staff.....	46
Table 8 Role of each interviewee.....	50
Table 9 Technical specifications of the materials used in the comparison of CNC and AM technologies.....	56

Table 10 Times for each process. ....	56
Table 11 Costs of each process. ....	57
Table 12 Perception of quality according uses. ....	57
Table 13 Technical specifications of the printer. ....	60
Table 14 Mechanical properties of the materials ....	64

# 1. INTRODUCTION

## 1.1. MOTIVATION

*“I cannot teach anyone anything; I can only make them think” — Socrates.*

In the last years, technology has been one of the main drivers of innovation. New tools, such as 3D printing are revolutionizing the industry but still a lot of study has to be done to better investigate this phenomenon. In particular, the uses of 3D printers as a complement for learning are not deeply studied. However, it is a hot topic in the educational contexts.

*“I hear and I forget. I see and I remember. I do and I understand.” — Confucius.*

This thesis focuses on 3D printers as technological tools for improving experiential learning. From the educational perspective, the inclusion of such tools as 3D printers may increase the level of motivation of the student. These tools can also promote the creativity; designs can be reformulated several times until building the final prototype. Simultaneously, opportunities for improvement are increased, since errors are displayed in shorter time.

This thesis studies the benefits of rapid prototyping when using 3D printing technology. In addition, it presents the renovation and adequacy of one of the spaces located in Aalto Design Factory (ADF), supporting rapid prototyping. The aim of this study is to find a 3D printer that fits to the requirements of the ADF, as well as to prepare the environment for the future users by providing handbooks, conducting test usage and making samples.

The purpose of this work is to give the students a facility, which to motivates their creativity, imagination and inspire for finding new ways of working.

## 1.2. BACKGROUND FOR RESEARCH

Aalto University is composed of six Schools, which have around 20.000 registered students in three different campuses. The research is focused to the Otaniemi campus, where Aalto Design Factory (ADF) is located.

Aalto Design Factory is an experimental co-creation platform that brings together researchers, businesses and students from many disciplines (Aalto Design Factory, s.f.). Visitors from different parties are also welcome to develop their ideas under the same aim of hard work passion-based. The spaces and facilities are designed to encourage teaching and learning in a more problem-based and hands-on way. ADF offers multifunctional spaces for teamwork as well as individual work. It has workshops utilities, as well as areas for taking a break, which all stimulate creativity. All the spaces are free to use for the university faculty and students. Some equipment, e.g cameras, can be loaned, with a promise of responsible usage of them and help is always available.

ADF follows Open innovation Policy (Aalto Design Factory, s.f.). This policy is a model that follows the concept of using external and internal ideas for the organization benefit. The combination of these ideas adds value in knowledge-intensive processes (Chesbrough, 2003). This policy is integrated at ADF as a way of sharing information between ADF community and visitors. The ideas and environments of ADF are hoped to inspire others and vice versa. Knowledge of outsiders is suitable to be implemented in ADF.

ADF hosts several lectures from courses that belong to the different Schools of Aalto University. In addition, ADF also organizes interdisciplinary courses in collaboration with partner universities from all over the world. The goal of these interdisciplinary courses is to introduce the students to the challenges of real work life, provide a direct contact with the companies as well as to learn team work and to solve complex problems.

Product development project (PdP) is an interdisciplinary course for which most of the students come from engineering, industrial design or business studies. For a whole academic year the students work with a project proposed by a company,

which is looking for innovative solutions for a particular theme or problem (PdP, s.f.). This is the largest course hosted by ADF and in which the majority of projects are based on performing physical prototypes. For that reason, the study on this thesis is based on PdP course.

In all the courses in which ADF is involved, the research project typically includes the following stages: *phases of planning, searching for information, creation of concepts, decision making and detailed computer aided development. The project phases of manufacture, assembly, and testing are strongly related to the most valuable learning experience* (Aalto University, s.f.). One of the crucial phases in these projects is the prototyping. Among the variety of tools available to quickly test a product, prototyping conducted by using 3D printers is one of the most innovative and interesting ones.

By the end of April 2015, Aalto University has fourteen 3D printers available for students and researchers. In addition, four new 3D printers planned to be added in the next couple months. The printers are located in the Aalto University Digital Design Laboratory (addlab). In order to teach the students how to use the equipment, addlab offers two workshops in each month. This one day-courses introduce the students to the principles of additive manufacturing, the basics of 3D modelling tools as well as 3D printing (addlab, s.f.). All Aalto students that have attended this course are free to use the basic 3D printers. The advanced ones are reserved for research use. In particular cases, files from thesis projects are studied to be executed with these advanced machines. Moreover, students from the courses hosted by ADF have special arrangements; the usage of the advanced printers by the students is recorded and the final costs are sent to the ADF afterwards.

ADF is intensively researching in the use of 3D printers as a tool for enhancing learning and promoting experimentation. This thesis aims to advance the state of the art in this field, proposing a learning environment that supports rapid prototyping with 3D printing. The next sections describe in details the objective and scope of this research.

### 1.3. OBJECTIVES AND SCOPE

The main objective of this thesis is to respond to the current needs of the students attending the different courses in the ADF, by offering them a space where to create and develop their projects with the help of rapid prototyping.

In particular, this study has been focused on one of the largest courses operating at the ADF, Product Development Project. PdP course is offered to students from all the six schools of Aalto. Above all, the course is addressed to students who are interested in product development of investment and customer products.

Each year, around 200 students are divided into 14 to 18 teams. Most of the students are from Aalto University and the rest work as remote members at the partner universities. The students work from September to May for an industrial company and at the end of the course they present a functional prototype. The main goal of the course is to solve adversities and to learn how to work in teams (Aalto University, s.f.).

One of the main problems encountered during the first stages of the course is insufficient prototyping. The reason is the absence of rapid prototyping tools, which are easy, cheap and fast to use. The amount of prototypes that the participants of the course develop is quite little. They usually use expensive technologies for testing out ideas, even though those are usually meant for final products. To address this situation, our purpose is to provide the students with a new workshop, in which they are assisted to use rapid prototypes for their projects.

The following research questions have been selected in order to solve the problem exposed above.

*RQ1: What benefits come from using 3D printing instead of CNC technology at first stages of product development?*

*RQ2: How to build a facility that supports rapid prototyping in learning environments?*

The first question is answered in the fourth chapter of this paper, with an empirical comparison between additive manufacturing and subtractive manufacturing. This

comparison has been made to prove the feasibility of a 3D printer in educational environments.

The answer to the second question is presented as series of steps showing the creation of the Printshop in ADF. In addition, both responses are supported by the theoretical research conducted in the second chapter of this thesis.

#### 1.4. THESIS STRUCTURE

This thesis is divided into three topics: benefits of rapid prototyping, the investigation of the 3D printer that will be placed at the ADF and the learning environment that enhances the uses of rapid prototyping. In every chapter each one of these three topics are analysed.

The first chapter introduces the reader to the context of the topics and provides motivations for the study. Furthermore, It presents the objectives and research questions.

The second chapter presents the state of the art of the three topics analysed. In first instance, it reviews the literature about Product Development Process and how prototyping improves the first stages of the projects. Secondly, the chapter explores the benefits that 3D printing brings as a rapid prototyping tool. Finally, it describes the variables that need to be taken under consideration when building a learning environment than enhances creativity and awareness.

The empirical research is presented in the third chapter. It exposes the methodology that has followed in the study. This chapter is divided in four sections that present the data collection of the different analysis. The results of this empirical research are presented in the fourth chapter according to the methodology followed in the four sections explained.

Finally, the discussion analyses the results and link them with the states of art studied in the second chapter. It concludes with the limitation of study and proposals for future work.

## 2. THEORETICAL RESEARCH

### 2.1. PRODUCT DEVELOPMENT PROCESS

To provide a better understanding about the concept of Product Development Process (PDP) the words product, development and process are explained separately, as well as the meaning they take when they are used together.

#### 2.1.1. PRODUCT

Cambridge International Dictionary (Cambridge , s.f.) gives three different definitions for a product. Selecting the one that best fit the context of this thesis, a product is “*something that is made to be sold, usually something that is produced by an industrial process or, less commonly, something that is grown or obtained through farming*”. This definition approximates to the theory of distinguishing goods and services as different items (Rathmell, 1966). However, over the years, many authors define that a product is any good that can be sold, even tangible and intangible attributes, namely, physical products and services (Kotler & Armstrong, 1980). Researchers also refer to product as something sold by an enterprise to its customers (Ulrich & Eppinger, 2012). Currently, it is still followed the concept of Kotler, father of the modern marketing. Nevertheless, it is common keep finding the terms product and service used separately in many articles or books. In this document the concept of product will be limited to physical products, as all the research used for the understanding of this thesis.

#### 2.1.2. PRODUCT DEVELOPMENT

Development is described with four definitions in the Cambridge International Dictionary (Cambridge , s.f.). According to this research, the two that resemble more to it are following. The first is “*The process in which someone or something grows or changes and becomes more advanced*”. The second is “*the process of developing something new*”. The link between product and development leads to the concept of



product development. Product development refers to the sequence of actions that bring an idea to the store. The literature on product development continues to increase. As Mintel firm estimates in its Global New Product Database, around 12000 new products are launched every month covering 49 of the world's major economies. (Mintel, s.f.) However, there are high differences between successful or unsuccessful product development efforts. Thus, to understand what makes a product successful is crucial to provide management insights (Cooper, 2000). Studies define five main variables that assess how successful a product is. The first two variables refer to the product itself and they are the quality and cost of the product. The remaining variables refer to the development of the product and they are time, cost and capability of the development (Ulrich & Eppinger, 2012). More in-depth studies add other key factors. Robert G. Cooper suggested the following categories: uniqueness, customer focus and market orientation, pre-development work, sharp and early product definition, execution of activities, organizational structure and climate, planning and resourcing the launch and speed without compromising quality (Cooper, 2013). In addition, other studies consider the factor of innovativeness as an important component in sustainable competitive advantage (Wessel, 2008). Although all the approaches describe factors for product development performance, there is not an agreement on a universal definition of successful new product development.

### *2.1.3. PRODUCT DEVELOPMENT PROCESS*

According to the three definitions given by Cambridge International Dictionary (Cambridge, s.f.), a process is “*a series of actions that you take in order to achieve a result*”, “*a series of changes that happen naturally*”, “*a method of producing goods in a factory by treating natural substances*”. The three definitions are helpful to better understand the concept of Product Development Process.

Product Development Process is a combination of steps or tasks of creating and understanding, testing and commercializing a product. These activities are intellectual and organizational rather than physical (Ulrich & Eppinger, 2012). There are many product development processes, each one tailored to the product itself and the culture where it is produced. In general, any product development process

is composed of three phases. The first is to *understand the opportunity*; namely, transform vision into a successful realization. The second is to *develop a concept*, which involves design the concept, have the functional model and the concept engineering. The last phase of the process is to *implement the concept*, which mostly is embodiment engineering. (Otto & Wood, 2001). Nonetheless, there are more in detail approaches of what phases compose the Product Development Process. The *generic product development process* proposed by Karl Ulrich and Steven Eppinger suggest six phases as showed in Figure 1.

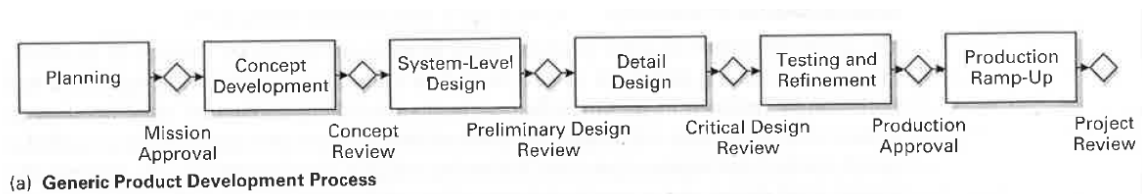


Figure 1 Generic Product Development Process. (Ulrich & Eppinger, 2012)

K.Otto and K.Wood propose a similar linear model called *Stage Gate process*, which was previously defined by Cooper in 1998 in his book “product leadership” (Marxt & Hacklin, 2005). Both approaches comprise activities and tasks, stages, in the development work. During these stages ideas are transformed into products offerings. Review points, gates, evaluate the previous phase and ensure the next stage is worth to be executed (Schmidt & Calantone, 2002).

The *generic product development process* is focused on generic products, that is to say, market-pull, but several variants of product process types are common. Therefore, the generic process is adapted in accordance to the process type. Ulrich introduces a process flow called *spiral product development process* as showed in Figure 2.

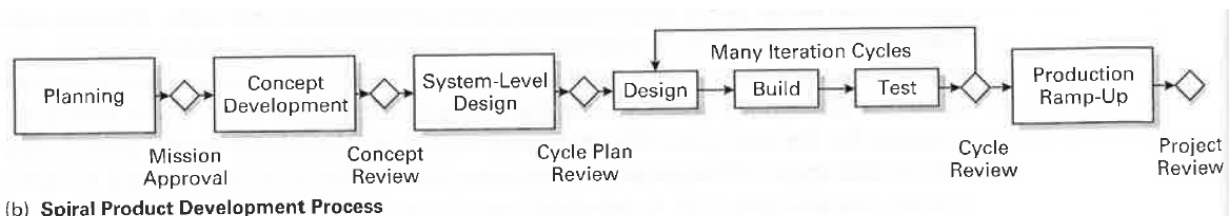


Figure 2 Spiral Product Development Process. (Ulrich & Eppinger, 2012)

In linear processes, the projects proceed sequentially phase by phase, however, it is common that different activities overlaps. Indeed, the concept development phase is

considered the most challenging stage of the projects due to the fact that it has the highest impact in the whole process. The early phases are called *Front-End* process (Ulrich & Eppinger, 2012). The term *Fuzzy Front-End* (FFE) process is also used to highlight the unstructured nature of the Front-end concept A.Khwarana & R. Rosenthal (1997) (Koen, et al., 2002). FFE is the first area of a innovation process, where the new product development process is also included (Koen, et al., 2002). In addition, it is also considered a prior phase of the well structured product development process. However, the term FFE can be confusing because some authors consider this phase part of the PDP - the early stages of the process (Brun, et al., 2009).

To avoid confusion, in this thesis, the early stages of the new product development process are called *Front-End* process or concept development phase, which is the focus of this study.

The Front-End process acquire high importance because decisions taken at these stages will affect to the result of the product. However, these phases are particularly problematic because of the lack of knowledge. Ullman labels this situation by the design process paradox, as showed in the figure below. An effective study is to learn as much as possible in the early phases about the evolving product. (Ullman, 2003)

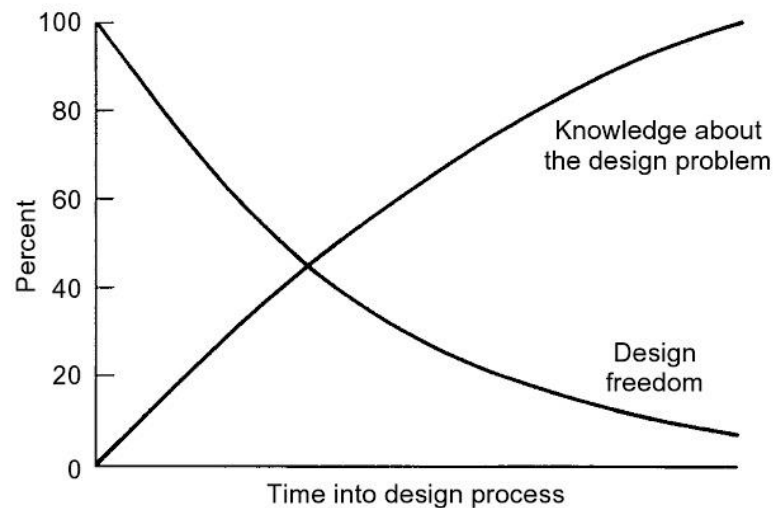


Figure 3 Design Process Paradox. (Ullman, 2003)

According to Ulrich and Eppinger, the *Front-End* process includes 10 distinct activities: *Identifying customer needs, establishing target specifications, concept generation, concept selection, concept testing, setting final specifications, project planning, economic analysis, benchmarking of competitive products, modeling and prototyping*. Figure 4 depicts activities. The dashed arrows represent the repetition that is sometimes necessary of previous steps before proceeding (Ulrich & Eppinger, 2012).

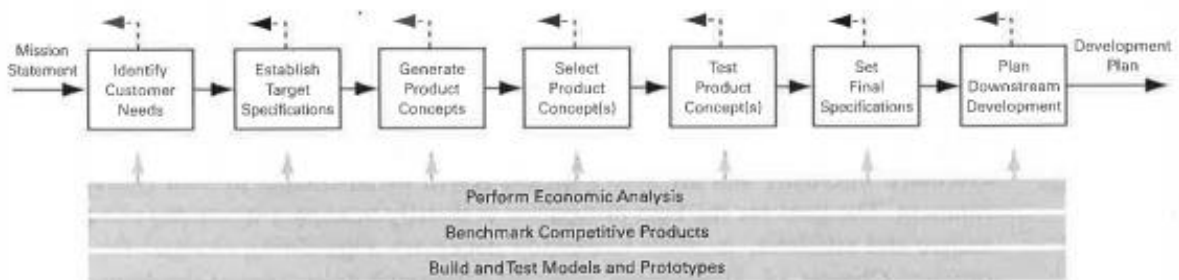


Figure 4 Front End activities comprising the concept development phase. (Ulrich & Eppinger, 2012)

As can be seen in Figure 4, models and prototypes are developed along all the concept development phase, but is not only in this phase where prototypes are created. From Figure 5 it is showed all the moments where prototyping is evolved during the Product Development Process.

The next section is focused in the prototyping activities inside the concept development phase.

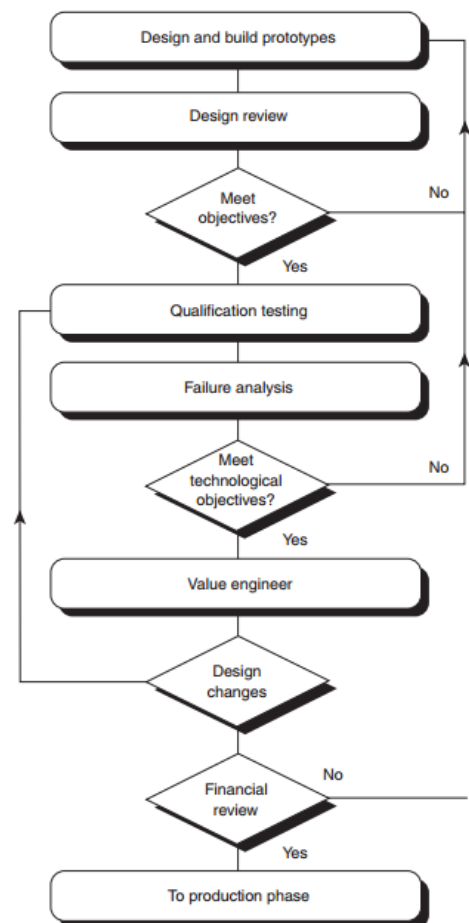


Figure 5 Development phase in Product Development Process. (Burt & Pinkerton, 1996)

#### 2.1.4. *PROTOTYPING IN THE FIRST STAGES OF THE PDP*

*Prototyping is a dance.* Sometimes the music doesn't move you or your steps fail. But not reason to stop (Kelley, 2004). With this powerful comparison the author shows the purpose of prototyping: to test, experiment, get an approximation of the final product. For that reason, the higher the number of developed prototypes, the better will be the understanding of it to find and eliminate errors and to consider different solutions (Houde & Hill, 1997). As can be observed in Figure 4, there are various feedbacks returning to the realization of a new prototype, until the objectives are accomplished.

There are hundreds of ways of defining a prototype. Each scientific research gives a different definition, making the term likely to be ambiguous. Ulrich and Eppinger define a prototype as an approximation of the product along one or more dimensions of interest (Ulrich & Eppinger, 2012). Other authors describe prototypes as filters intended to traverse and sift through a design space and as manifestations of design ideas that concretize and externalize conceptual ideas (Lim, et al., 2008). The different approaches of what a prototype is, imply different classifications.

Ulrich and Eppinger classify the prototypes along two dimensions. *Physical/analytical, comprehensive/focused* (Ulrich & Eppinger, 2012). Other researches classify the prototypes according to their uses in the industry. The proposed category is: *proof-of-concept models, industrial design prototypes, DOE experimental prototypes, alpha prototypes, beta prototypes, preproduction prototypes* (Otto & Wood, 2001). Other work classifies the prototypes between high-quality and low-quality (Walker, et al., 2002).

The empirical part of this thesis refers to the term prototype as physical and focused prototype. The former is characterized to be tangible. The latter is made for "work-like" and "looks-like" a final product. In other words it is a proof-of-concept developed to obtain insights about the product. Related to the quality, both high and low quality respond to the definition of the prototype because the approximation to the low or high quality it will differ on the project.

Prototyping is a very beneficial tool used for many purposes. The most appropriated purpose for the types of prototypes presented in the thesis is learning and communication. As a learning tool, prototypes cover the lack of knowledge typical in the early stages of the projects, to discover problems and arrange solutions. Prototyping as a communication tool of two kinds; external and internal. Internal because improve the communication between the members of the team work. External, needed to obtain feedback from customers, vendors, suppliers and management (Ulrich & Eppinger, 2012). The purposes are not mutually exclusive; a prototype can be used for more than one purpose at the time. Taking in consideration these uses of prototypes, the benefits generated are:

- Reduction of time operation and costs. Early prototypes identify design errors that have a low cost to fix in early phases. In addition, as soon as the errors are found, less time the process would take (Ulrich & Eppinger, 2012).
- Flexible choice of products. Evaluating variety of ideas with the customer, improves the communication and the sort of outcomes (Campbell & de Beer, 2007).
- Greater freedom and care in allocating resources (Otto & Wood, 2001).

Even these benefits are taken as a general features, the medium in which the prototypes are formed will determinate its specific profit (Walker, et al., 2002). This thesis does not argue the validity of the multiple definitions for a prototype. Nonetheless, among all the medium, physical prototypes are considered more helpful, as a learning and communication tool rather than the virtual. In fact, virtual models hide many details of how products will actually perform.

The production of hands-on product is crucial in many fabrication processes in order to perform them. The difference between the processes falls into two categories: hand working methods and advanced fabrication techniques (Otto & Wood, 2001). Both types of processes are equally important, although it is tend to think the advanced precision equipment provide a better prototype. Instead, even prototypes made of cardboard are very useful for testing (Ehn & Kyng, 1991). The technique selected will depend on the purpose and accuracy to obtain from the prototype. Within the advanced fabrication techniques, three main groups can be identified. These manufacturing methods are known as subtractive, formative and additive methods.

## 2.2. ADVANCED FABRICATION TECHNIQUES

Advanced fabrication techniques for prototyping are divided in three groups.

This first group is defined as subtractive method. This method is defined as the process of removing layers from a block of material to produce an object. The models either come from 3-D model data, 2-D CAD data or G-Code. Conventional subtractive method techniques include cutting, drilling, milling and micro-machining.

The second group is known as the formative method. This method builds the part by means of external forces or topological constraints imposed by cavities, molds or tooling. Formative methods techniques include casting, injection molding and forging.

The last group encompasses additive manufacturing (AM). This method consists in to build a part by adding or binding material layer by layer. The use of AM in Product development is commonly known as RP. This technique is commonly known as rapid prototyping (RP) and includes several technologies such as extrusion based and powder based systems among others (Gibson, et al., 2010).

The main difference between the three methods is that the first two are meant for mass production. Additive manufacturing, instead, is beneficial for the projects in their first stages. This method, in fact, is able to develop almost any geometry; a crucial advantage in the first phases of a project.

### *2.2.1. STATE OF ART IN ADDITIVE MANUFACTURING*

ASTM, American Society for Testing Materials, (ASTM, F2792-12a), define additive manufacturing as the process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies. However, the variety of synonyms used to describe this technology can lead to confusion. One of the most commonly used terms is rapid prototyping (RP). Researches propose many definitions about the concept of rapid prototyping. All of them, with different words describe this process as the range of technologies for rapidly creating a physical model from computer aided design (CAD) data (Mahindru & Mahendru, 2013).

However, some authors explain a different relationship between AM and RP. AM is a large set of techniques for product manufacturing, while RP may use additive manufacturing or subtractive manufacturing technologies (Mellor, et al., 2014) (Pham & Gault, 1998). Nonetheless, this categorization is not widely adopted. RP techniques are usually cheaper and used to develop a prototype meant for testing purposes and not the final products. The additive manufacturing techniques used for the production of end-use parts are categorized as Rapid Manufacturing (Campbell, et al., 2011). RP has limitations to manufacture production parts in large volumes while rapid manufacturing would solve these drawbacks (Dickens, 2001). In this thesis, the term RP is used regardless the finality of the part so rapid manufacturing term is not studied.

Any RP technology follows the general process represented in Figure 6. The process begins by taking a virtual design from modelling or computer aided design (CAD) software. The file is converted to STL, which is file format native to the stereolithography CAD software. Then the file is sent to the AM machine. The machine reads the data from the file and lays down successive layers of material, building up the physical model from a series of cross sections (Gibson & Stucker, 2010).

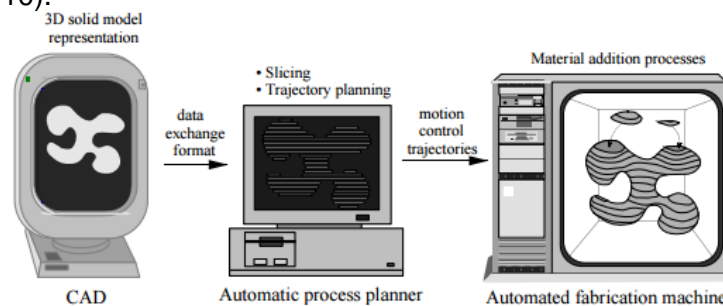


Figure 6 Conceptual representation of rapid prototyping process (Prinz, 1997).

There are many ways to classify AM technologies. Selecting the wrong variables to classify them may produce odd combinations, or may separate process with same results (Gibson, et al., 2010). D.T Pham proposes a two dimensions method which encompasses a more divided classification. A dimension, refers to how the layers are created and another dimension relates to which raw material is used. However, the majority of the works done about the classification of the AM technologies use classification based on material addition. Kruth gives a good overview of the



different material addition processes in the Figure 7. Gibson gives more detailed information about each process (Gibson, et al., 2010).

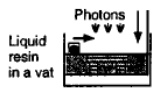
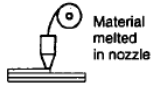
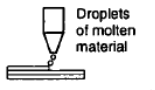
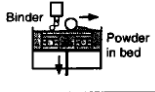
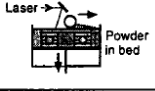
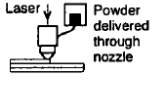
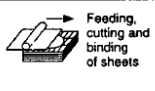
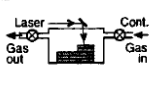
Supply	Process	Lay-out	Layer creation technique	Phase Change during layer solidification	Materials	Variants /Laser based	Systems
LIQUID	Stereo-Lithography (SL)	 Photons Liquid resin in a vat	Liquid layer deposition	Photo-polymerization	Photo-polymers: - acrylates - epoxies - filled resins (glass, ceramic, metal,...) - colorable resins	Laser illumination	3D System - SLA (US) NTT Data CMET-SOUP (J) D-MEC/Sony - SCS (J) [EOS - Stereos (D)] <sup>2</sup> MEIKO-Cclamm (J) Teijin Seiki (Dupont)-Soliform (J) Aaroflex (Dupont) - Solid Imager Denken - SLP (J) (US) Fockele & Schwarze (D) Ushio - Unirapid (J)
	Fused Deposition Modeling (FDM)	 Material melted in nozzle	Continuous extrusion and deposition	Solidification by cooling	Polymers: (ABS, PA,...) Wax Filled polymers (glass,...)	FDM	Stratasys - FDM (US) Stratasys - Genisys (US)
					Metals with binder	MJS	Development [IFAM (D)]
Ceramics with binder	FDC	Development [Austin, Rutgers]					
LIQUID	Ink Jet Printing (IJP)	 Droplets of molten material	Drop-on-demand deposition	Solidification by cooling	Polymers Wax	milling layers	3D System - Actua (US) Sanders - ModelMaker (US)
						5-axis milling layer +contour	Development [Stanford]
POWDER	Three Dimensional Printing (3D-P)	 Binder Powder in bed	Layer of powder + Drop-on-demand binder printing	No phase change	Ceramics with binder		Soligen-DSPC (US)
					Metals with binder		Extruhone-3DP (US)
					Polymer with binder		Z-corp.-3DP (US)
POWDER	Selective Laser Sintering (SLS)	 Laser Powder in bed	Layer of powder	Laser sintering / Laser melting & resolidification by cooling	Polymers (PC, PA,...) Filled polymers (glass,...) Metals with binder Metals (pure) Sand, ceramics	Laser-based	DTM - Sinterstation (US) EOS - EOSint (D)
	Laser Cladding	 Laser Powder delivered through nozzle	Continuous injection of powder	Laser melting & solidification by cooling	Metals	Laser + milling layer and contour Laser-based	Röders - CMB (D) Development: - LENS [Sandia] - LAPS-J [IPK (D)]
SOLID	Laminated Object Manufactur. (LOM)	 Feeding, cutting and binding of sheets	Deposition of sheet material	No phase change	Paper	Laser cutting	Helisys-LOM (US) Kinergy-ZIPPY (Sing.)
						Knife cutting	Kira - SAHP (J)
					Polymer	Knife cutting	[SPARX-(Sweden)] <sup>2</sup>
					Polymer foam	Heated wire cutting	Development [Utah]
					Composites	Laser cutting	Helisys-LOM (US)
					Ceramics	Laser cutting	Development [Dayton]
Metals	Laser cutting	Semi-industrial [U. Tokyo, U. Erlangen (D), CRIF(B)]					
GAS	Selective Laser Chem. Vapour Deposition	 Laser Gas out Gas in	Condensation of gas	Forming solid from gas by chemical reaction	Metals (Al, FeNi,...) Ceramics (SiC,...)	Laser-based	Development: - LCDV [M. Planck-(D)] - SALD [Connect., Texas, Renssel.]

Figure 7 Industrial additive processes (Kruth, et al., 1998)

Another term commonly used to refer to additive manufacturing is 3D printing, interchangeably used for rapid prototyping. 3D printing is becoming more popular than AM. (Terry Wohlers, 2013). The ASTM defines 3D printing as the fabrication of objects through the deposition of a material using a print head, nozzle or other printer technology (ASTM, F2792-12a). However, this is also a grey terminology because the same term is also used to mention one specific AM technology, belonging to powder based group, as is represented in Figure 7.

Among all the definitions given in this chapter, this thesis follows Wohlers report published in 2013, that is using 3D printing and additive manufacturing as synonyms. The connection between AM and RP is explained conceiving AM as a technique of RP. At the end of the 2.1.4 section it is explained the different prototyping categories; however, RP is generally identified as an AM process (Kruth, et al., 1998)

### 2.2.2. IMPACT OF 3D PRINTING.

Additive manufacturing is gaining more importance every day disrupting the way to run product development. Forbes magazine mentioned according to Wohlers Associates that additive manufacturing is a \$2.2 billion industry today and sales – both products and services – could exceed \$6 billion by 2017 (Bagley, 2014). Figure 8 maps the worldwide forecast of the sales of AM products. It is expected to reach 10.8\$ billion by 2021.

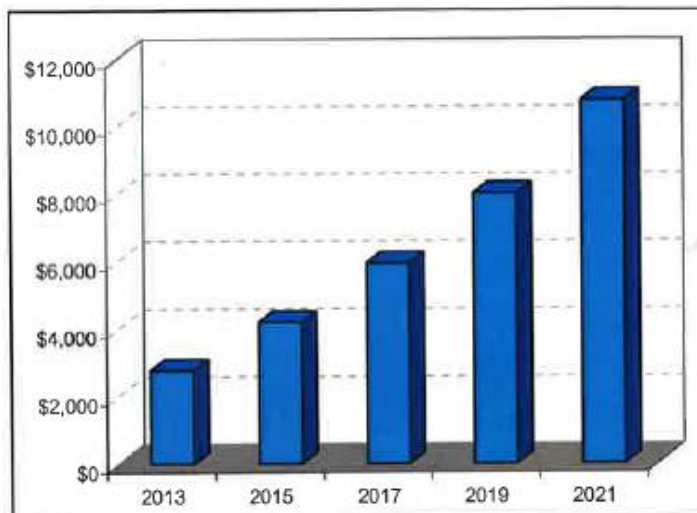


Figure 8 Forecast of AM industry (Terry Wohlers, 2013)

AM industry has two segments. Industrial machines are those that sell for \$5000 or more, and 3D personal printers are those above \$5000. This new category of AM systems has been purchased mostly by hobbyists, young engineers and educational institutions in the early years. Sales of personal 3D printers are growing massively; the average is a growth of 346% each year from 2008 through 2011 and 46.3% in 2012. Nonetheless, they are still representing the 6.5% of the total market of AM systems sales. In the last years, this growth trend is becoming to saturate the market. This level of saturation is produced by the improvements of the personal 3D printers in terms of quality and capability. This leads to a transition into the professional market space. That transition suggests the emergence of a new mid-level segment of printers. (Terry Wohlers, 2013)

However, the lack of awareness about the importance of AM technologies is still a key point to improve. A survey conducted by Wohlers association shows in a chart the percentages about how customers are using the parts obtained with industrial AM technologies.

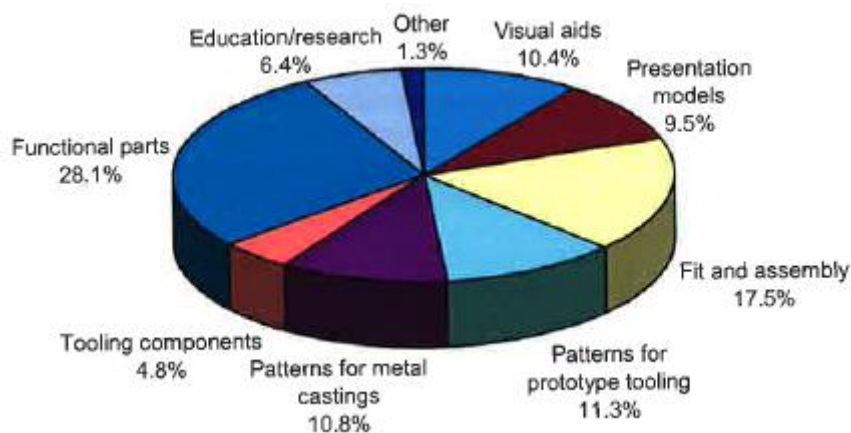


Figure 9 Uses of industrial AM systems (Terry Wohlers, 2013)

Figure 9 depicts the results of the survey. An interesting finding is that education and research is one of the lowest areas. The next chapters present the benefits that rapid prototyping provides in educational environments and it gives insights on how to apply it in product development projects.

### *2.2.3. BENEFITS OF RAPID PROTOTYPING IN FIRST STAGES OF PDP*

As its name refers, rapid prototyping is an easier and quicker tool to build prototypes than numerically controlled machines (Kostakis, et al., 2015). Easier because 3D printers do not use tool-path calculations as cutting machines. Quicker because this tool-path calculation requires time to run the machine.

Researchers often mention in details the advantages that using 3D printing as a rapid method provides. 3D printers produce highly complicated geometries. The geometrical freedom is practically infinite in engineering design. This design opportunity is one of the main benefits rapid prototyping offers. The creativity is a feature that is developed in its specially in the first stages of the projects. Greater is the design, greater are the possibilities to obtain innovative products and quicker are potential profits. In contrast the shapes obtained with conventional manufacturing methods are limited. It is extremely difficult to compute the paths that the cutting tools have to follow in order to make that shape automatically (Bradshaw, et al., 2010).

In the first stages of the projects, a prototype generates constant feedback between the product development team and the customer. Prototypes reduce design cycles, allowing the team to show the client mock-ups instead of manufacturing the final product. Physical prototypes reduce the uncertainty and permit the product development team to react more quickly. This advantage often leads to substantial savings and lower liability (Cohen, 2014). According to United States consumer product safety commission, the flexibility of prototyping is highlighted by the cost of customer product safety incidents, which amounts to \$ 1 trillion in United States per year (Cohen, 2014). In addition, rapid prototyping improves long distance communication with remote team workers or customers. In fact, can be sent and can provide clearer information about the product than videoconferences or 2D sketches.

Concept selection is an integral of the Product Development Process. To select a concept vary of methods may be applied including rapid prototyping. As a tool, prototypes enhance internal communication in the product development team. The organization builds and test prototypes of each concept. Having a physical model

makes easier for the team to detect pros and cons of the product and it helps to make a better choice (Ulrich & Eppinger, 2012).

Another advantage is that a prototype may reduce the risk of costly iterations. Quick identification of problems decreases the time and cost of the project. The process speeds up by repeating early development phases until obtaining a desired outcome and then proceeding to the next phase avoiding iterations (Ulrich & Eppinger, 2012). 3D printing combine features in single-piece parts. With fewer parts to assembly, cost and time are reduced. To summarize, among others, rapid prototyping benefits in the following areas. (CHUA, et al., 2003)

- Experimentation and learning.
- Testing and proofing.
- Communication and interaction.
- Synthesis and integration.
- Scheduling and makers.

### 2.3. LEARNING ENVIRONMENTS

Learning in the area of product development is a process that goes beyond the classroom. Especially the early phases of product development start with an abstract knowledge creation to a concrete knowledge application. This process of learning is the combination of experience, perception, cognition and behaviour (Kolb, 1984).

The theories that focus on the experience as the centre of the learning process are grouped under the name of Experiential learning theories. Experiential learning is a process of constructing knowledge based in life experiences, where the students are in an active role. In this student-centred process they have more freedom and responsibility over their own learning. Consequently, the teacher takes the role of a facilitator. This experiential learning process involves creative hands-on. It is believed that the best way of learning is through the experience. (Dewey, 2007).

The main characteristics of the experiential learning process are the following: Learning is not conceived as the result of the process, but the process itself.

Learning is based on experiences so it is a continuous process. Since process of learning involves experience, perception, cognition, and behaviour; all life experiences are potential for learning. Learning is the process of creating knowledge. Learning involves transactions between the person and the environment because each factor influences in the other one. (Kolb, 1984).

Kolb enlarges the experiential learning theory explaining the cycle from abstract concepts to concrete implications through four stages. The learning process starts with a *concrete experience*, which is *reflectively observed*. When the concrete experience is understood, *abstract concepts* are created, to later be transformed through *active experimentation* in new experiences, and like this the cycle starts again. In each of the four stages are characterized by different learning styles. *Diverging* is the first style of the process. The diverger person has a tendency to develop new ideas. *Assimilating* is the second learning style. This requires the understanding and ordering in a logical form the ideas proposed by the diverger. Assimilating style or thinker comes with abstract concepts of the concrete experience. The *converging* style finds practical uses of these abstract concepts. The *accommodating* style, or do-er has the ability to learn from the hands-on experience. (Kolb & Kolb, 2005).

Figure 10 represents the cycle of the experiential learning process explained above.

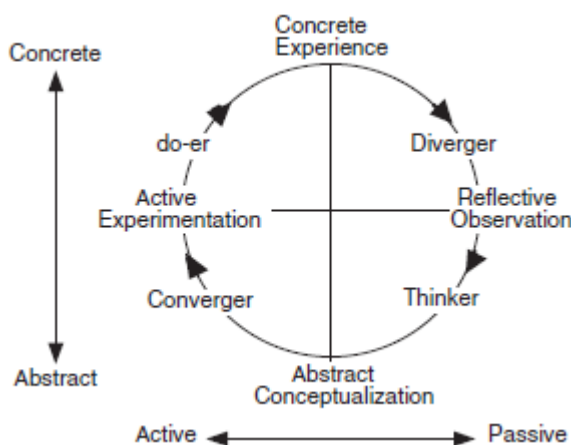


Figure 10 Experiential learning cycle of Kolb. Adapted by (Smulders, 2004)

In the ideal learning process all four abilities would be equally developed by the learner. However, in practice, people emphasize some abilities more than others. Concerning to the Product Development Process, in each stage of this process a learning style is the dominant. In this thesis the assumption taken is the following. For the planning phase it is needed a dominant diverger style. The phase of concept development is emphasized by the diverger and assimilating style. Assimilating style is also important in the system-level design. For the detail design phase a converger is needed. Finally in the testing and refinement and production ramp-up phases are characterized by an accommodating style.

This thesis is focused on the concept development phase of the Product Development Process. Hence, it is focused the first quarter of the cycle, where the diverger style is the dominant. This learning style requires the development of creativity to generate new perspectives and conceptual ideas of a product (Smulders, 2004).

### *2.3.1. DESIGNING PHYSICAL ENVIRONMENTS.*

To enhance learning in an early phase of a product development process, a well-designed physical space is needed. Different researches point out different variables to define a learning environment. The variables are selected based on social behaviour impact, fostering creativity and teaching and learning needs among others.

An effective Product Development Process requires creativity, especially in first stages of the process. For that reason, it is considered an important characteristic to base the design of the learning environment.

Several parameters are defined to evaluate the physical spaces in order to foster creativity. To design a good physical work environment, both social and physical variables have to be taken in consideration. *Natural elements* resemble to natural environments to enhance creativity potential because they capture one's attention and reduce the fatigue. *Freedom* is another variable to look at when creating a learning environment. The flexibility to decide how things are being done and the responsibility over your own learning also promotes creativity. But freedom has to be

combined with *support*. Finding help easily is crucial for any process. Facilitators, supervisors or people in charge of the space play the supportive role. *Challenges* are viewed as a way to increment the creativity. A physical space that gives the possibility to carry out challenging task enhances the users to develop greater ideas. *Coherence* is supported by a collaborative and cooperative atmosphere. An adequate social behaviour enhances the interaction between the user and the space. (Evans & McCoy, 2002).

Despite extensive studies have been done regarding the design of an effective working environment, in some cases the proposed parameters cannot be easily developed. Depending on the limitation of the space, cost or learning purposes some are prioritized. The combination of all the different approaches exposed will define the learning environment created for Design Factory presented in the third chapter of this thesis.



### 3. METHODOLOGY OF THE RESEARCH

This chapter describes the empirical part of the thesis. In order to respond to the different research questions, the chapter is divided in three sections. The first section presents the data collection from questionnaires in contemplation of how the students focus their projects. Furthermore, non-structured interviews are realized to better understand the actual situation and the perceptions of the people in the ADF about PdP projects. These interviews are designed to check the interest of the students in their projects. The second section describes an experiment conducted for understanding the benefits of 3D printing in the first stages of projects. Finally, the last section explains the methodology followed to select the 3D printer that best fits with the necessities of the ADF.

#### 3.1. DATA COLLECTION FROM QUESTIONNAIRES AND INTERVIEWS

Sample surveys are an empirical research technique widely used in the last 50 years. It is one of the most widespread methods to collect data. (Peter H. Rossi, 2013) Surveys are quantitative or qualitative. Both methods involve the process of collecting, analysing, interpreting and writing the results of a study. Quantitative research is a more logical and data-led approach. It provides a measure of what people think from a statistical and numerical point of view. Qualitative approaches are designed for exploring and understanding the meaning individuals ascribe to a problem (Creswell, 2014). The combinations of both methods in this thesis will contribute to understand the actual situation of the PdP courses in the ADF, followed by the motivation of the ADF of placing a 3D printer in the building.

In particular, the questionnaires and interviews help to understand which technologies are the most used by the students when developing prototypes for their projects. Eventually, after the data is analysed, it is possible to proceed with a depth study of finding the possible benefits that 3D printing would provide the students in the first stages of their projects.

### *3.1.1. QUESTIONNAIRES*

Quantitative methods provide reliable and objective outcome data and normally the results can be generalised to a larger population (A Steckler, 1992).

For the questionnaires, data has been collected from students from PdP courses as representative sample. The reasons why these students have been chosen are the following. First, PdP is the largest course with more students developing their projects in situ at ADF. Second, the majority of the projects involve production of physical products (Section 1.3).

The study is conducted in the form of a survey, under the name of “Prototype experiences in PdP course”. The data of the survey was gathered via an online form (Survey Monkey, s.f.) and sent to the project managers of each group that attended the course in the last 3 years. Returned surveys from 40 project managers yielded a 32,5% response rate. Appendix 1 lists with the answers.

The form has been divided into three main categories, starting from broader-based questions and then moving to narrower in scope. In the questionnaires have been used different types of questions, both closed and open ended questions.

More specifically, the questions were formulated as follows.

Questions 1-3 are designed to have an overview about the teams and their products. Questions 4-8 analyses how involved they are with rapid prototyping in their projects. Questions 9-10 are focused on personal opinions about the prototypes and further considerations.

### *3.1.2. INTERVIEWS*

Interviews, as a qualitative method, are the most common way to investigate a social reality. This method allows collecting information about events and subjective aspects of people: beliefs and attitudes, values or knowledge. A research interview is a conversation with a purpose (Bingham & Moore, 1931). Other authors define interview as the transaction of information between two people (Norman M.

Bradburn, 2004). Conversely, another approach defines interview as an interchange of views between two or more people (Kvale, 2007). This thesis follows Bradburn theory.

There are different types of interviews including structure interviews, semi-structured interviews, unstructured interviews and non-directive interviews (Kajornboon, 2005). The interviews conducted in this thesis pursue the unstructured model. The strengths of an unstructured interview are non-restrictions and flexible method. The interviewee is able to express opinion and share experiences. However, it is harder to obtain relevant information and to drive the interview. Despite the drawbacks, unstructured interview are widely used and they are a good approach to get honest answers.

The data collection consists in six interviews conducted during the months of September and October in 2014. In addition, information has been extracted from informal talks during the whole research project. The interviews are focused on people contributing to ADF, such as students, course assistants, ADF staff and model makers. Despite the informality, that is the absence of pre-defined questions, the purposes are:

- Personal opinions about prototypes made in the projects.
- General feelings about the idea of placing a Printshop in ADF.

### 3.2. COMPARISON BETWEEN CNC AND 3D PRINTING TECHNOLOGIES

To respond to the first research question of this thesis:

*What are the benefits of using 3D printing at first stages of the projects?* A comparison has been conducted between CNC technology and 3D printing. The comparison of 3D printing with CNC is due to the fact that they are opposite technologies, and the most used in PdP projects.

The first technology exposed is subtractive manufacturing, obtained with a Computer numerical control (CNC), machine located in ADF. The second technology explained and compared with the prior is additive manufacturing.

Additive manufacturing has been studied under two perspectives. The first one is FDM, using the printer model called U-print by Stratasys, located in addlab. The second one, is Polyjet technology, using the 3D printer Obect30 from Stratasys, which is also located in addlab.

The experiments have some limitations. They are realized in an academic environment, which means that the machines used are not as professional as the ones that are used in the industry. For that reason, the measurements of the variables taken are bounded to an educational field.

Table 1 Machines used for the comparison of CNC and AM technologies

<b>MACHINE</b>	<b>M1</b>	CNC
	<b>M2</b>	3D PRINTER 1: U-print
	<b>M3</b>	3D PRINTER 2: Obect30

### 3.2.1. VARIABLES ANALYSED

The variables selected in this study aimed to evaluate what are the most common trade-offs in the manufacturing of part using CNC and AM technologies.

The key aspects to be compared are listed in the next table.

Table 2 Variables selected for the comparison of CNC and AM technologies.

<b>VARIABLES</b>	<b>V1</b>	Material
	<b>V2</b>	Timing
	<b>V3</b>	Total costs
	<b>V4</b>	Surface quality

Each of the three experiments has been executed with different materials (**V1**) because of the nature of each technology used. They are considered the most suitable for rapid prototyping.

**V1-M1** uses SikaBlock® M960. The areas of application are manufacture of foundry models, match plates and core boxes, various moulds and tools, manufacture of master models and mouldings for high quality demands. The benefits of the

SikaBlock M960 are its excellent milling properties, high mechanical strength and impact resistance among others. (Sika, 2013).

**V1-M2** uses ABS plus. The U-print is a printer that operates with FDM technology. Among the different materials that are acceptable to use with this technology, ABS plus is thermoplastic so durable that is ideal for conceptual modelling and functional prototyping to perform much like the final product. It offers good tensile, flexural strength and low cost.

**V1-M3** uses Veroblack material. It is a photopolymer adequate for finished products with a detailed visualization, good durability and high strength.

For **V2** the global time for each process has been divided as follows.

$T_o$  = time of the mechanical operations, the ones done by the machine.

$T_m$  = time of manual operations, those hand working ones, where a model maker is needed.

$T_t$  = time tool changes (is considered an average time per change).

$T_p$  = time of the global process.  $T_p = T_o + T_m + T_t$

**V3** represents the total cost of the process. The total cost comprises: cost of material used, cost that each machine generates during the operating time and cost of the worker. It has to be noticed that for printing methods the cost of the operator is not relevant due to the fact these processes are practically automatic. The process can be run by almost any person without need of high printing knowledge.

The cost of the materials for the three processes depends on the vendors.

The cost for the milling process, **M1**, with CNC includes four main operations: *Part break up*, in this operation is calculated the time consumed to know which position is the most appropriate to build the part. *Milling path calculations*, CNC requires a code that needs to be configured for each different prototype. *CNC operations* require time and consequently a cost. *Possible rework*, in some prototypes a post process as casting or painting is needed. The electricity that the machine consumes per hour and the cost of the time of a worker needed are included in these operations.

The cost of **M2** process is obtained with the following formulas.

$$\text{Material usage} = \text{cm}^3 \times 0.33 \text{ cents}$$

$$\text{Timing cost} = \text{time} \times 3 \text{ €/h}$$

For the cost of the last process, **M3**, addlab staff does not have data available for it. However, they assume approximately timing cost of 2€/h.

**V4** is surface quality and conformity of the prototype. The methodology used to evaluate this variable is unstructured interviews. Ten people who do not know which method has followed each prototype are asked to answer the following questions.

- Which of the three prototypes do you think it has higher quality? (in meanings of finished, strength, etc.)
- Which prototype would you use for rapid prototyping?

### *3.2.2. GEOMETRY OF THE STUDY*

The geometry used for the experiment is a prototype designed by a professional model maker working at ADF. The prototype models an example of consumer electronic device, a remote control. In this approach, the time and cost needed to get the CAD design are not taken in consideration. The study starts from the STL file.

This geometry was selected for the experiment due to its complexity. In some parts the border thickness is very low. Since this geometry was designed for a subtractive manufacturing process, it will be a good example to prove how resistant are this parts with an additive manufacturing method. The dimensions of the prototype are presented in Figure 12. As it can be seen, the part is irregular, but the main dimensions length\*width\*height, to know the build envelope, that evolves the prototype, are necessary because the printers accept a maximum size of the print. These build envelope dimensions are: 208.3\*75.7\*12.4 mm.

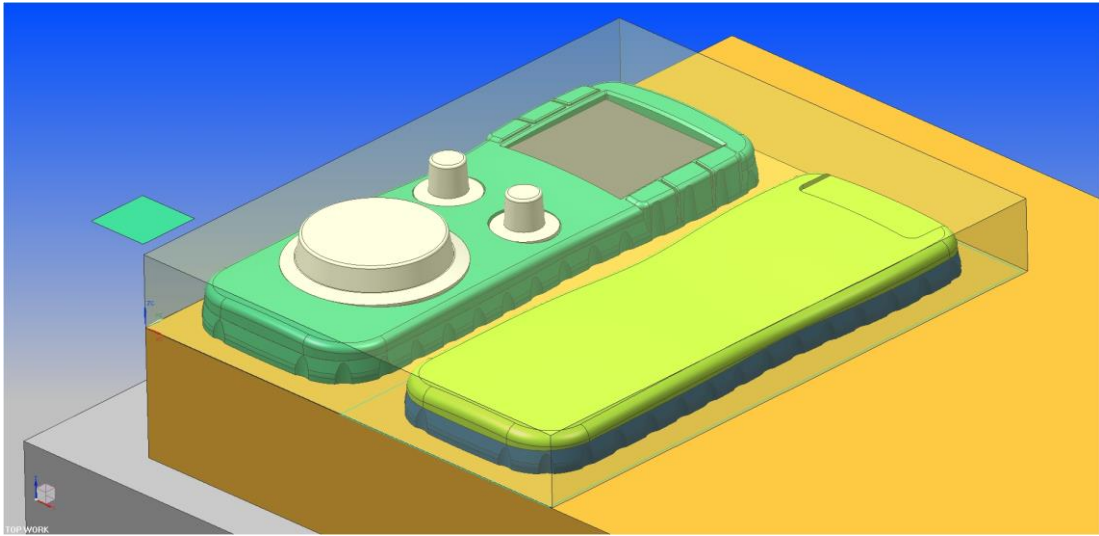


Figure 11 Geometry of the prototype

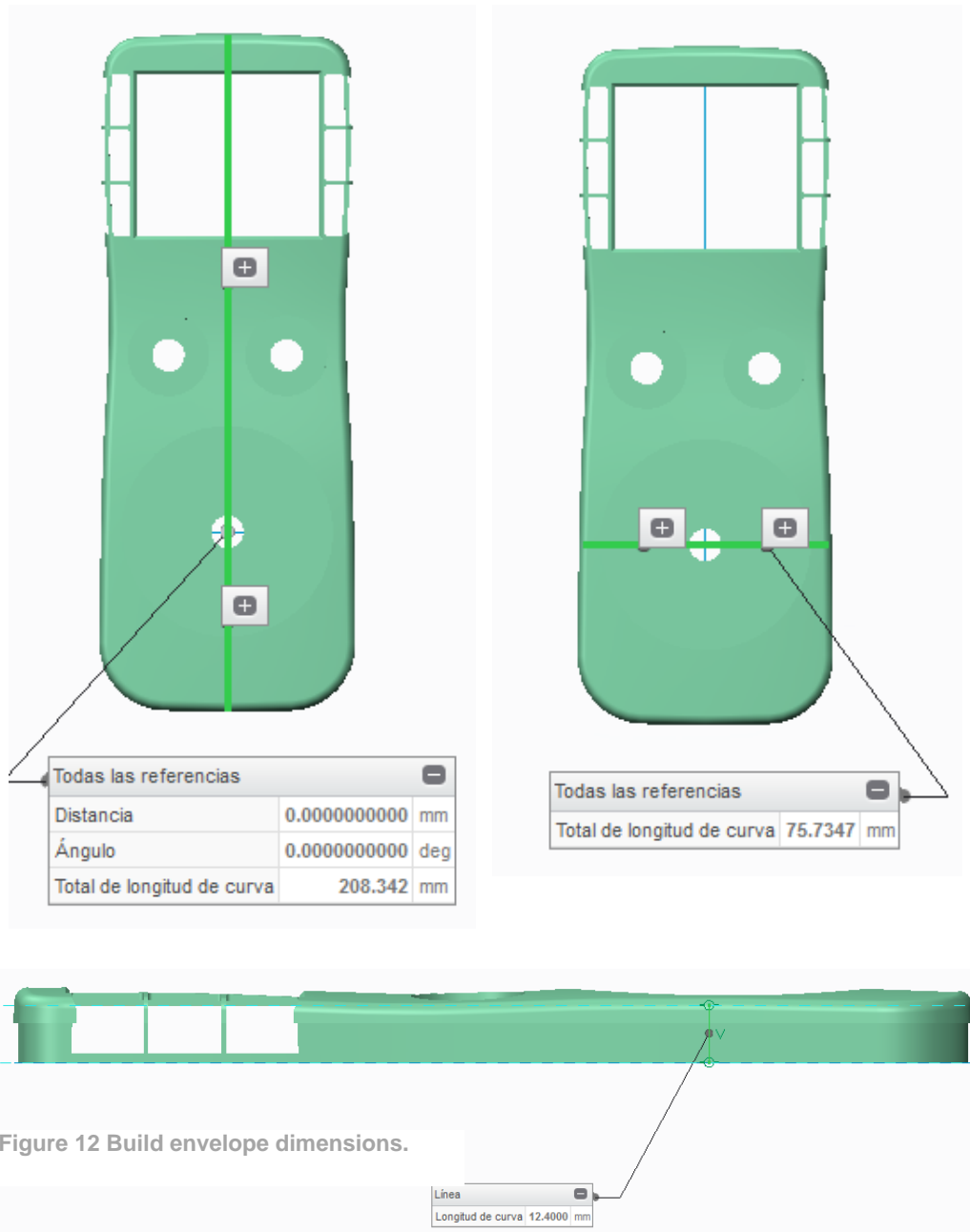


Figure 12 Build envelope dimensions.

### 3.3. 3D PRINTER IN AALTO DESIGN FACTORY.

Aalto Design Factory is characterized by a philosophy of creativity and experimentation. For that reason, arises the possibility of having a 3D printer. The idea is based in the benefits exposed in the second chapter of this thesis.

This section narrows the search of the printer which best fits in ADF according to its required needs. The placement of a 3D printer in an environment that supports the creative and experimental learning will help the students to cover the lack of prototyping in the first stages of their projects.

To address the problem, two possibilities have been compared. The first option is to buy commercial 3D printer, the second option a RepRap. RepRap 3D printers run open software and open hardware. For this reason they are self-replicating, namely, from one it is possible to build the components of another one.

In order to choose the most suitable 3D printer, it is performed a research about all the devices that are already in the market, their properties, their uses and all the different technologies available for them. Between all the market offer and attending to ADF needs, the study is only based in low-end printers.

A systematic approach identifies and compares 17 products according to the main characteristics that the users frequently demand in this kind of devices. The analysis evaluates which functions are the most common and therefore must be considered when selecting the printer for the ADF. The main objective is to find a printer that complies the basic specifications required from this range of printers and adds value to ADF.

A technical specifications table and function-competition matrix are presented below. In this last one, boxes checked with (1) are the ones where the printer includes the function.



### 3.3.1. MARKET ANALYSIS

Table 3 Commercial printers comparison

		COMPETITION								
		stratasys Mojo	Stratasys uprint SE	Stratasys uprint SE plus	3Dsystems Cube 3	3Dsystems Cube X	3Dsystems Cube Pro	3Dsystems Projet 1200	Mass Portal MP Delta	Bq Witbox
SPECIFICATIONS	Size (mm)	630x450x530	635x660x787	653x660x787	n/a	515x515x598	275x275x177	n/a	320x630x310	505x450x388
	Weight (kg)	27	76	76	n/a	36	36	n/a	15	28
	Model size (mm)	127x127x127	203x152x152	203x203x152	152,4x152,4x152,4	275x265x240	285.4 x 230 x 270.4	43x27x150	150x186x150	297X200X210
	layer thickness (mm)	0,178	0,254	0,33	0,07	0,1	0,07	0,03	0,05	0,06
	model material	ABSplus	ABSplus	ABSplus	PLA/ABS	PLA/ABS	PLA/ABS/Nylon	VisiJet	PLA, ABS Nylon, PET...	PLA

Table 4 Commercial printers comparison (2)

		Bq Prusa i3 Hephastos	Ultimaker original+	Ultimaker Ultimaker 2	Formlabs Form1	markerbot Replicator z18	markerbot Replicator 2x	Kühling&Kühling	Leapfrog Creatr Dual
SPECIFICATIONS	Size (mm)	408 x 425 x 233	357 x 342 x 388	357 x 342 x 388	300X280X450	493 x 565 x 854	490 x 320 x 531	800 x 600 x 800	600X500X500
	Weight (kg)	9,7	n/a	n/a	8	41	12,9	49	n/a
	Model size (mm)	215 x 210 x 180	210 x 210 x 205	230 x 225 x 205	125x125x165	305x457x305	152x155x285	200x180x290	200X227X200
	layer thickness (mm)	0,06	0,02	0,02	0,025	0,1	0,1	n/a	0,05
	model material	PLA	ABS/PLA	ABS/PLA	LIQUID RESIN	PLA	ABS/Dissolable filament	ABS/PLA	ABS/PLA/PVA

Table 5 Matrix printers/functions comparison

1 Printer includes the function

		COMPETITION																		
FUNCTIONS		strataysys -Mojo	Strataysys - uprint SE	Strataysys - uprint SE plus	3Dsystems - Cube 3	3Dsystems -Cube X	3Dsystems -Cube Pro	3Dsystems -Projet 1200	Mass Portal - MP Delta	Bq - Witbox	Bq- Prusa i3 Hephestos	Ultimaker- Ultimaker original+	Ultimaker-Ultimaker 2	Formlabs - Form1	markerbot-Replicator z18	markerbot-Replicator 2x	Kühling&Kühling	Leapfrog Creatr Dual	TOTAL	
	FDM	1	1	1	1	1	1		1	1	1	1	1		1	1	1	1	1	15
	polyJet																			0
	SLA							1						1						2
	€ material/kg<100														1	1	1	1		4
	€ > 5000€	1	1	1				1							1		1			6
	Support extruder	1	1	1			1									1	1	1	1	7
	max. Part size > 10dm <sup>3</sup>					1	1			1			1		1			1		6
	prototype isolate	1	1	1			1	1		1				1	1			1		9
	software opensource								1	1	1	1	1					1	1	7
hardware opensource									1	1	1	1					1		5	

The matrix shows that no market impositions are introduced. Market impositions are features common to all the products analysed. Some examples include the variety of colours of the materials. In addition, features as other additive manufacturing methods are not taken in consideration, due to the fact that as is known in advance which devices are used in a higher level with costs that exceed the budget.

### 3.4. BUILDING THE PHYSICAL SPACE

Prototyping facilities have high importance inside of the 3200 m<sup>2</sup> of ADF, being 1/3 of the total usable floor area. Table 6 represents the space used for each prototyping facility, how the usable floor is currently divided.

Table 6 Prototyping facilities division

PROTOTYPING FACILITY M <sup>2</sup> BY SEPTEMBER 2014	
PUUHABUNKKERI	114
MACHINESHOP	104
ELECTROSHOP	26
CUT & INK	15
MODELSHOP	22
KNITTINGSHOP	58
PAINTSHOP	26
WOODSHOP	19
SUPPLY CAVE	22
AC DC	25
THE CAGE	77
<b>TOTAL</b>	<b>508</b>

The proposed improvement is to add a new rapid prototyping facility besides the Cut & Ink space. The new space is called Printshop. Cut & Ink area will increase to 20m<sup>2</sup> and 3D printing area will occupy 24,5m<sup>2</sup>. Due to this change, prototyping facilities will increase from 508m<sup>2</sup> to 537,5m<sup>2</sup>.

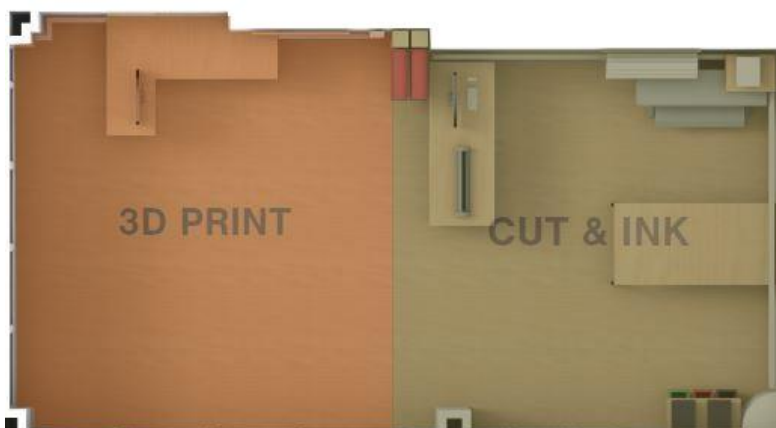


Figure 13 New distribution of the space. Designed by George Atanassov.

This chapter is divided in three parts to explain the different steps proposed to build the space.

### 3.4.1. LAYOUT

The first step is creating the layout, which facilitates the goal of obtaining a successful facility. The objectives for designing a good layout are the following.

- Facilitate production process. Organize machines, equipment and work areas so that the flow of materials is as smooth as possible, avoiding crosses and interferences.
- Minimize movement of material. Make the material accessible from the work place.
- Maximize the flexibility. Anticipate the changes in the products and productive capabilities.
- Reduce equipment investment. Together with the design process, its arrangement can contribute to minimize the necessary equipment.
- Promote safety, hygiene and comfort. Ergonomics of workspace, protection, lighting, ventilation, cleaning, noise etc.

Figure 14 shows a 3D rendering of the layout proposed. It has to be noticed that the left space is also renovated. It is an open space of computers available for everybody. However, in this thesis this space is not analysed.

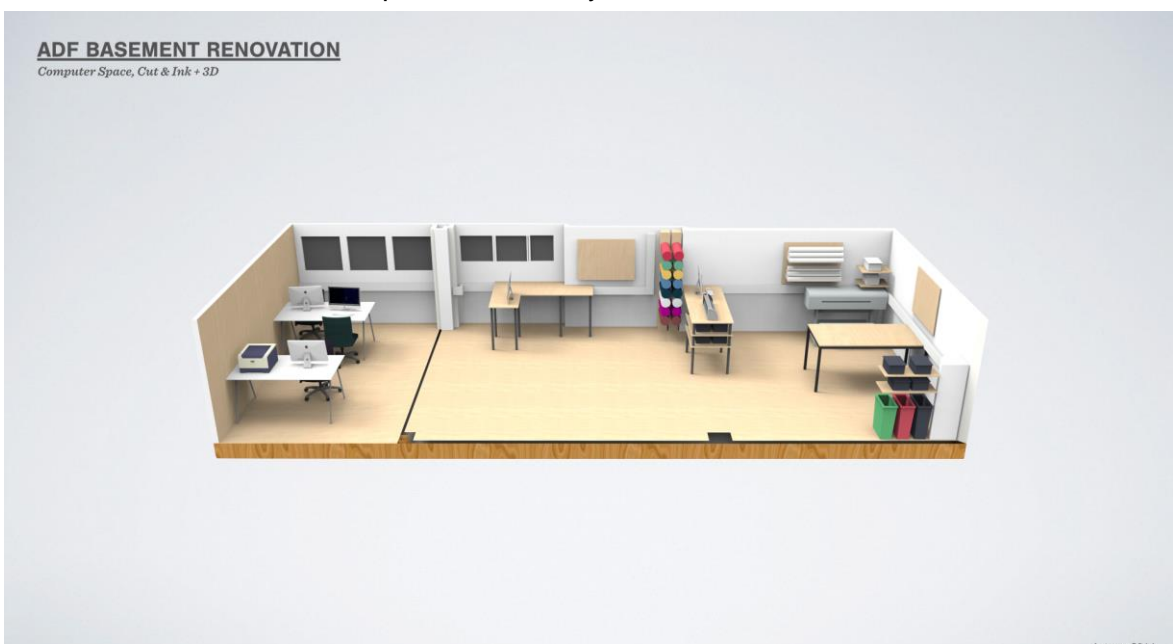


Figure 14 Render of the layout. Designed by George Atanassov

### *3.4.2. MAIN CHARACTERISTICS THAT DEFINE THE SPACE*

To design a successful space, physical characteristics have to be implemented, considering the impact that these produce in social behaviour. In this section we will present all the aspects studied to build the space based on the previous experience of other facilities of the ADF.

The idea of combining a 3D printer with Cut & Ink space comes from the aim to put together hands-on work in the same space. In addition, the new position of the machines enables an easier use of the plotter compared to the old Cut & Ink facility (See Figure 22.1). This is the result of the more spacious environment.

The spatial form of the room is a rectangle, large enough to accommodate several people. Furthermore, it promotes the informal interaction between the two ambient areas. The 3D printer is placed up of a table with wheels, to enable flexible movement and educational activities. At the same time, the space is also large enough to virtually divide the room in the two areas. The virtual division is made with the vinyl rolls and a computer table for plotting and vinyl cutting (See Figure 22.4). With this visual separation, the space dictates location based on activity but does not hinder social interaction.

Windows provide natural views and light that resembles to a natural environment. Natural environments reduce the fatigue and foster the creativity. However, the space is located in the basement of the building, where windows are small and natural light is low. This absence is compensated with natural materials in the furniture. The main material used for the floor and the furniture is light wood (See Figure 22.5). Furthermore, wood materials are conceived as a hands-on material. Wood also reflects a warm light resembling skin colour and enhances the organic atmosphere. The intention to use wood is to remove some of the technical complexity associated with the equipment of the room. The organic feel of the wood contrasts the complexity of the machines and makes the space more approachable.

The room is half-private. The two of the walls that connect with the corridor and computer space are made with glass (See Figure 22.6). Glass is a material that transmits transparency. High visibility is reciprocal form outside and inside. On the one

side, people from outside can see what activities are being conducted in the moment and enhance their curiosity of learning from them. On the other side, the glass is a form of privacy, giving information from outside about the movement of inside without interrupting the activity. Another aspect that promotes privacy is the accessibility to the room. The only access is a locked door. To enter in the room a key or code is needed. To obtain that code or key there are conditions explained in next section.

The high height of the tables has the purpose to condition the work of the people (See Figure 22.7). The height is beneficial for precise hands work, which both 3D printing and vinyl cutting require. Another aspect is if people cannot sit comfortable for a long time, it reduces the time of using the space for other activities not related with the Printshop. The different shelves are organized in order to storage all the items needed. Shelves are all transparent without any doors so that users can clearly see how much material is left and what is where. Supplies that are stored in boxes are clearly labelled. There is one box per material in order to reduce clutter. There is no public storage in the room and all projects should be stored on display or elsewhere.

### 3.4.3. MEANS TO ACCESS AND ACT IN THE SPACE

As mentioned in the previous section, the access to the space is restricted. To get the access, it is necessary to participate to a workshop. This workshop teaches users to use the machines and the space. ADF staff holds the workshops. It will be mandatory to sign up to confirm the assistance. The information about the different workshops, contact information of the print staff and other relevant issues will be showed in a screen located in the glass wall to the corridor (See Figure 22.8). The duration of each workshop and its frequency is estimated bellow.

Table 7 Workshops organized by Print staff

ACTIVITY	DURATION	FREQUENCY	HOURS PER MONTH
3D printing	3h	2times/month	6
Plotting	1h	1time/month	1
Vinyl cutting	3h	2times/month	6
<b>Total</b>			13h/month

After attending to the workshop, the person will get access to the room and will be added to a mail list. The mail list is used to inform users with updates of the space and inform in case a machine is broken.

The workshops are meant to improve the skills of the users and teach them how to operate the machines autonomously. Nevertheless, the print staff can help with the prints. The staff will be available 6h/week, 24hours per week. 13 hours out of 24 will be designated to teach the workshops. The rest of the time the staff will be available for any consultation. However, not everybody of Aalto University is allowed to use of the Printshop. This facility is reserved for people in ADF, such as course teams and research studies. A list of places where to 3D print, vinyl cut and plot will be suggested for people not related with ADF.

After using the facility, it will be essential to annotate the amount of material used and the purpose of the work (See Figure 22.9). For the future, this data base will help to obtain statistics about the job conducted. The used material is updated automatically on the Printshop info screen. This promotes transparency and awareness. For the sake of transparency and awareness it is important to show tangible metrics of the input vs. output of the space for the current academic year.

Instructions for the use of the different machines are available in the room in order to help the operators (See Figure 22.10). These rules for accessing the machine has been decided to provide a good experience for the users. Learning how to use the machine, in particular, is crucial to limit the incidents and increase the effectiveness of the environment. The incidences will be written in a message board, so every user of the room is informed of the state of the machine.

All the proposals have been agreed by the print staff. However, they can be modified according to the needs that arise once operating the room.

## 4. RESULTS OF THE RESEARCH

This chapter presents the results of data analysis. The data is collected and processed in response to the problems posed in chapter 1 of this thesis. Two fundamental goals drive the collection of the data and the subsequent data analysis. The goals consist in developing a base of knowledge about the organization of Aalto Design Factory and product development in an educational level related with rapid prototyping. The findings presented in this chapter demonstrate the potential for merging theory and practice.

### 4.1. ANALYSIS QUESTIONNAIRES AND INTERVIEWS

#### 4.1.1. QUESTIONNAIRES

The questionnaire proposed to PdP course students is meant to understand whether rapid prototyping is used successfully. Questions 1 to 3 are designed to retrieve information about the teams and their products. All the teams have at least one engineer and one designer. Therefore, every team has combination of knowledge needed for rapid prototyping using 3D printing: the design part needed to create models and the technological background of machines settings provided by the engineers. In addition, most of the projects were conducted for industry or consumers which are directly related with the prototyping benefits. (Bagley, 2014). Figure 15 shows a pie chart representing the backgrounds of the students. From the 13 responses, it has been obtained that the total number of participants is 137.



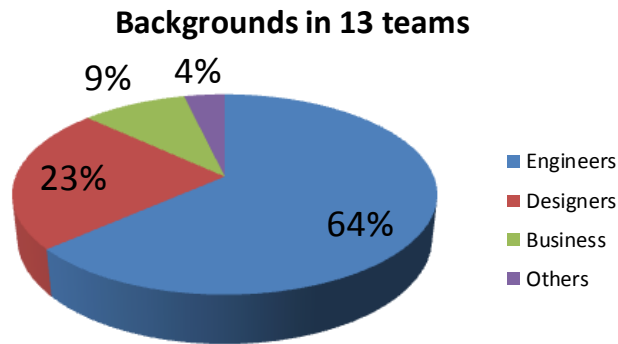


Figure 15 Backgrounds of the team members

Questions 4 to 8 relate the utilization of rapid prototyping in the projects of the students. One interesting finding is that few prototypes are implemented. Figure 16 depicts the results. Another finding is that only two out of the thirteen used the 3D printing method. The majority of the other groups answered that they didn't need to 3D print but as shown in the previous questions they used CNC in the most cases. CNC is a more expensive technology and it needs an operator during all the process. The resulting prototype might be more similar to a finished product, even if the intention is just to test the design. The most interesting finding of this group of questions is that almost the 85% of the groups had at least one of the members with enough knowledge to print. Despite that fact, only four of the seven 3D printed prototypes were made by themselves.

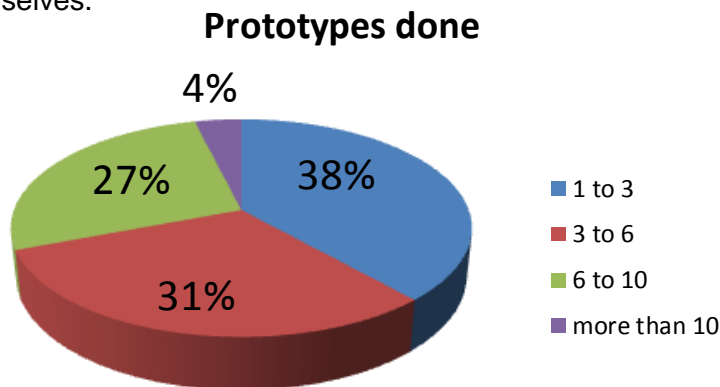


Figure 16 Range of prototypes done by the team members

Questions 9-10 regards personal opinions about the prototypes and further considerations. These questions are asked to the team that build a prototype with 3D printing method. The results point out that the students are satisfied with the accuracy and shape obtained but not both aesthetics and material used. There is a positive

correlation between the grade of satisfaction that the students show in their responses for the different variables and what it wants to achieve with the new printer in ADF. Because printer will be a tool in the first stages of the projects, getting an approximate shape of what is wanted will be more important than the quality of the surface or aesthetics which is related with the characteristics of the material.

#### 4.1.2. INTERVIEWS

In this thesis, interviews are used as retrieve baseline data about the status of rapid prototyping at ADF. The five interviewees are employees from ADF and all of them have had relation with PdP course in the previous years. The first interviewee, student of Aalto, did her PdP course as project manager in the academic year 2013-2014. The second interviewee was also project manager from a PdP team in 2012-2013 and later assistant of the same course. The third interviewee is model maker of ADF, responsible for making prototypes of students by conventional technologies. The fourth respondent is the coach of ADF. The last respondent is an IT manager of ADF. The interviewees and their roles in ADF are presented in Table 8.

Table 8 Role of each interviewee

Interviewee 1	Interviewee 2	Interviewee 3	Interviewee 4	Interviewee 5
Student PdP	PdP assistant	Model Maker	coach	IT manager

The interviews tell personal opinions about prototypes developed in the projects and general feelings about the idea of placing a Printshop in ADF. Three major outcomes emerged from the data.

- **Importance of the PdP course.** All the respondents stated the significance of the course and the positive consequences that this brings the students to focus the rest of their studies and real-life problems.

*“The course animates the students t think greater, to think further”.*

*“Working in something real makes the students motivated”.*

- **Lack of prototyping.** Several respondents admitted that the students do not test enough in the first stages of their projects. The lack of prototyping it can be

caused because of the lack of time. The only 3D printers accessible in the campus are the ones in addlab and most of the times they are overbooked.

*“CAD models are not enough to evaluate the quality, shape or dimensions, so ADF ends up wasting time and money manufacturing parts without utility”.*

*“They go directly to the final product, and at the end they realize irreparable mistakes”*

- **Utility of a 3D printer.** The majority of the participants said that a 3D printer it would be a useful tool to make the students test more. However, one of the respondents point out that it would be only worth if the printer would produce accurate pieces.

*“Rapid prototyping would reduce the amount of prototypes in the Machine shop”*

*“With a 3D printer it could be tested the ergonomics and aesthetics of the prototypes before final decisions”*

*“if it is not going to be a high quality printer, I would use the space for another purpose, because the students do not have enough space to work in ADF”.*

Based on the interviews and questionnaires data, it is believed the feasibility of a 3D printer. The next section proves the utility of putting a 3D printer as a tool in the ADF.

## 4.2. WHAT BENEFITS COME FROM USING 3D PRINTING INSTEAD OF CNC TECHNOLOGY AT FIRST STAGES OF PRODUCT DEVELOPMENT?

In this section the results of the three experiments are presented. To understand each process, Figures 17, 18 and 19 illustrate all the steps needed to build the prototype. In each image is shown the time spent for that step and below it, description of the procedure. The text above the images explains the operation executed between steps. The section is divided in four sub-sections. The three first ones report the results of the variables analysed for each technology used. The last sub-section summarises the results of the three models, combining them in tables according to each variable.

The section 4.2.1 presents the CNC technology, 4.2.2 the U-print and 4.2.3 the Object 30.

### 4.2.1. CNC EXPERIMENT



Figure 17 Workflow of CNC process

The cost of the materials used is the following.

The cost of one Sika M 960 block with dimensions 1000\*500\*30 mm is 202,00€. Adding 24% of VAT (Finland) gives the final cost of the block 250,48 €. The block used for this experiment is 275\*150\*30 mm what means that the cost of it is 20.66€. The cost of the resins Sika 26a/b are approximately 10€/kg. For the creation of the mold it has been used 200gr of each one, so the total cost for the resins is 4€. The total cost of the materials used is 24.66€.

The times taken in the process are:

- Time CNC operations,  $T_o = 239$  minutes.
- Time hand working operations (there are not included the tools changes and turns and replacements of the part),  $T_m = 34$  minutes.
- Time tool changes (is considered an average time per change of one minute)  $T_t = 8$  minutes.

Time of the global process;  **$V2-M1 = T_p = T_o + T_m + T_t = 281$  minutes = 4.6833hours.**

The cost of the process is 125€/h taxes included \* 4.6833h = 585.41€.

The total cost of making the prototype in a CNC machine is;  **$V3-M1 = 24.66€ + 585.41€ = 610€.$**

#### 4.2.2. U-PRINT PRINTER EXPERIMENT

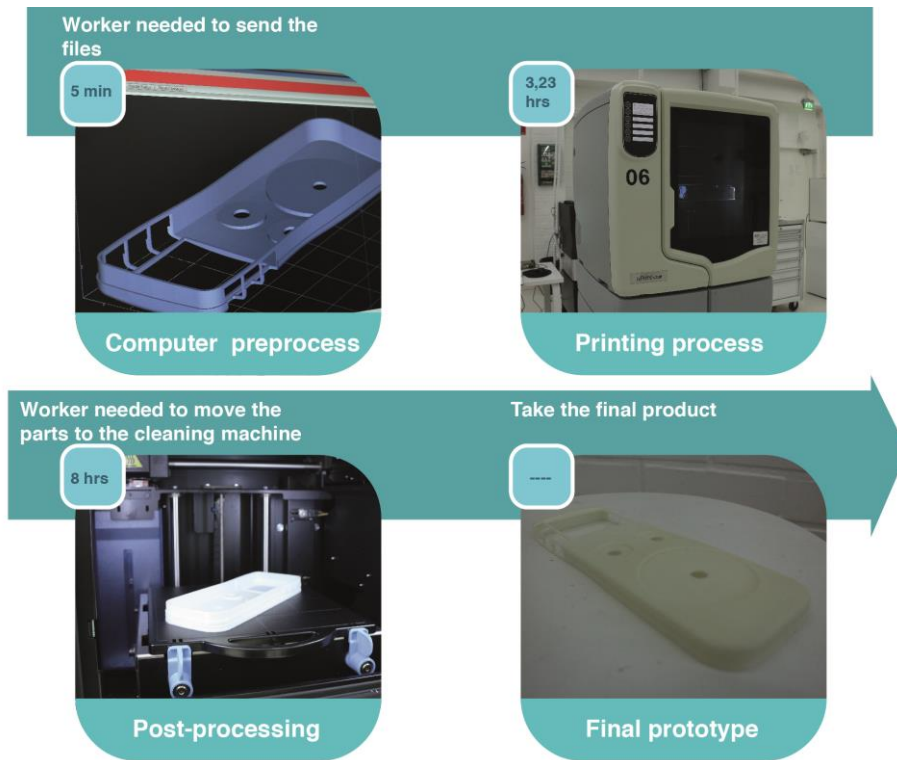


Figure 18 Workflow of U-print process

The cost of the ABS plus for addlab is 675€ per 10kg of material. In this case, the prototype weighs 56gr, both model and support. The cost will be 3.78€. However, addlab staff uses a formula that measure the material usage, including the material itself, the investment of the machines, maintenance, cost of the build plate and washing material among others.

The times taken in the process are:

- Time machine operations,  $T_o = 683$  minutes.
- Time hand working operations  $T_m = 5$  minutes.
- Time tool changes (is considered an average time per change of one minute)  
 $T_t = 1$  minute.

**Time of the global process;  $V2-M2 = T_p = T_o + T_m + T_t = 689$  minutes = 11.48 hours.**

The cost of the process is calculated with the two formulas. *Material usage* =  $cm^3 \times 0.33 \text{ cents} = (29.49 \text{ cm}^3 + 27.12 \text{ cm}^3) \times 0.33 \text{ cents} = 18.68\text{€}$ .  $29.49 \text{ cm}^3$  belongs to the model material.  $27.12 \text{ cm}^3$  belongs to the support material. Both are ABS plus.

$Timing\ cost = time \times 3\ \text{€}/h = 11.48h \times 3\text{€}/h = 34.44\text{€}$ . An important remark to notice is that in this process the cost of the operator is not relevant due to the fact that printing technologies are practically automatic. The process can be run by almost any person without need of high printing knowledge. Factors as electricity and cost of the machine are included.

The total cost of making the prototype with the U-print is; **V3-M2 = 18.68€ + 34.44€ = 53€**.

#### 4.2.3. OBJECT 30 PRINTER EXPERIMENT



Figure 19 Workflow of Object 30 process

The cost of the Veroblack and the support material that uses this technology are 205€/litre. Considering both materials with a density of  $1.17\text{g}/\text{cm}^3$  and a total weight of 123gr, the volume of the prototype is:  $\rho = m/V$  ;  $V = 105\text{cm}^3$ . The cost of both materials for the measurements of the prototype is 26.25€.

The times taken in the process are:

- Time machine operations,  $T_o = 261$  minutes.

- Time hand working operations  $T_m = 15$  minutes.
- Time tool changes (is considered an average time per change of one minute)  
 $T_t = 2$  minutes.

**Time of the global process.  $T_p = T_o + T_m + T_t = 278$  minutes = 4.63 hours.**

To obtain the cost of the process, there are not stimulated same formulas as the ones used for the U-print. An approximation to obtain the cost of the process would be  
*Material usage* =  $cm^3 \times 2\text{€} = 105cm^3 * 2\text{€} = 210\text{€}$ . *Timing cost* =  $time \times 3 \text{€}/h = 4.63h * 3\text{€}/h = 13.89\text{€}$

The total of for making the prototype with Object 30;  **$V3-M3 = 210\text{€} + 13.89 = 224\text{€}$**

#### 4.2.4. SUMMARY

Table 9 Technical specifications of the materials used in the comparison of CNC and AM technologies.

MECHANICAL PROPERTIES	ASTM test method	MATERIALS		
		Sika M960	ABS plus	VeroBlackPlus RGD875
Tensile modulus	ISO604-D638	2200MPa-n/a	n/a-2200MPa	n/a-2000-3000MPa
Flexural modulus	D790	n/a	2100MPa	2200-3200MPa
Hardness	Shore D-Rockwell R	78D-n/a	n/a	83-86D-n/a
Impacte resistance	ISO179-D256	30kJ/m <sup>2</sup> -n/a	n/a-106J/m	n/a-20-30J/m

Table 10 Times for each process.

TIMING	M1	M2	M3
Automatic (min)	239	683	261
Human ( min)	42	6	17
<b>Total</b>	4,683 h	11,48 h	4,63 h



Table 11 Costs of each process.

<b>COST</b>	<b>M1</b>	<b>M2</b>	<b>M3</b>
<b>Material (€)</b>	24,66	3,78	26,25
<b>Process (€)</b>	585,41	34,44 + 18,68	210 + 13,89
<b>Total</b>	610 €	53 €	224 €

Table 12 Perception of quality according uses.

<b>QUALITY</b>	<b>M1</b>	<b>M2</b>	<b>M3</b>
<b>Higher</b>	8	2	0
<b>Rapid prototyping</b>	2	5	3

### 4.3. SELECTION OF THE PRINTER

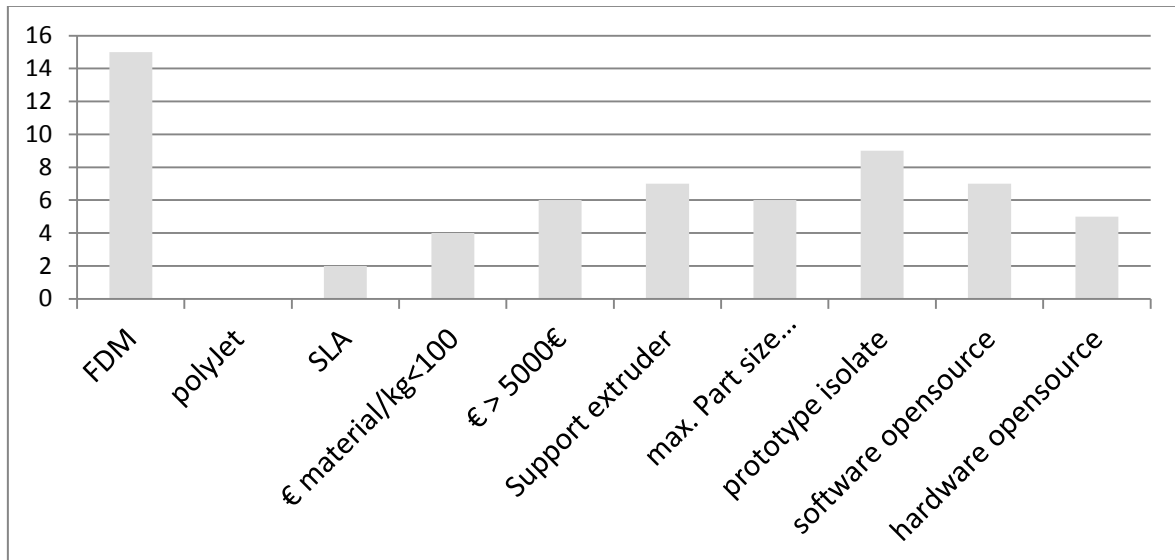


Figure 20 Results of market analysis

In comparing different 3D printers, the first consideration to take in account is the difference between the commercial printers and the RepRap, which are the ones running open source. Open source software means that the code is available to be studied and manipulated. Open hardware refers to the possibility to assembly a 3D printer, taking the parts from different suppliers, or 3D printing the parts from a previous 3D printer. These two concepts encompass the rigorous definition of a RepRap printer. However, in this paper, the term “RepRap” is used in a broader sense referring to some of the brands analysed above, such as Ultimaker, bq and Kühling&Kühling. Although these companies sell the product already assembled, they follow the open source philosophy, giving the possibility of changing the code and the physical design of the machine.

The majority of the printers from this category utilize Fused Deposition Modeling (FDM) technology, called also Fused Filament Fabrication (FFF). FFF and FDM are similar; however the latter is a Stratasys trademark. This technology is the most accessible according to quality-price and it uses mainly thermoplastic materials as ABS and PLA. The materials used for FDM technology are commonly more affordable than materials used in other methods. However, trademark ABS reach 68€/kg In contrast, for RepRap

ABS is around 22€/kg. In addition, the cost of a RepRap printer is usually never above 5000€.

Another consideration is the importance of support material. Support material is crucial in many structures with large overhangs or unsupported areas. Many printers use the same structure material to generate the support using the same extruder.

However, there are certain drawbacks associated with the use of the same material for the support. On the one side, parts can have features not accessible by hand or machine. On the other side, even in many cases support can be removed, the support has to be broken by hand and sanded eventually and it can cause dimensional inaccuracies. Thus, the use of a dissolvable support material, such as HIPS for FDM technology, allows higher accuracy and more complex geometries. Moreover, it leads no signs of support left after the removal. The dissolvable material requires a second extruder, increasing the price of the printer. As it is shown in the matrix only one of the RepRap printers includes the function of dual extruder, concurring with being the one with a cost over 5000€.

Finally, the last function to take in consideration is the isolation of the prototype. The enclosure of the printer avoids the heat loss, fumes emission and mitigates the noise.

The main objective is to find a printer that complies the basic specifications required from this range of printers and adds value to ADF giving the most benefits as possible and the lower cost as possible. Following this premises, taken together, these results suggest that the Kühling and Kühling is the best choice. Nevertheless, instead of buying this printer, it has been decided to build one following Kühling and Kühling characteristics. The reasons to build a 3D printer instead of taking one from the market are the following.

First of all, building 3D printers fits the value of ADF. In fact, it promotes hands-on approach in working. Learning by doing is one of the major highlights of this open community. This is the main reason to take the decision of assembling the printer. In addition, building a printer internally adds value to rapid prototyping. The member of ADF in charge of building the tool will develop deep technical knowledge about the machine. He/She will be able to help the students, to fix the machine, or to enhance the performance in the future.

From the technical point of view, as mentioned, an open source system allows code manipulation. The advantage consists in the possibility of highly customizable settings. Conversely, with the commercial printer the settings are fixed and the interaction of the worker with the process is reduced. The materials used are the same on RepRap and commercial 3D printers with the advantage of the low cost of the RepRaps. Another feature to consider is the support extruder. Figure 20 shows that only seven printers have the function of the second extruder (support extruder) five out of seven are commercial printers. It will be a challenge to incorporate the function to the 3D printer in the ADF without exceeding 5000€.

Building a 3D printer requires a high knowledge in the field. For that reason, it has been selected an experienced student to conduct this job coming from the School of Engineering and a passionate of 3D printers. The result is the following.

The time since ordering the parts to finalising the printer it has been 96 hours of work. The estimation is computed calculating the work of one person, three times per week, 8 hours per day. The code has been modified by 5% and the physical design by a 10%, to obtain more accuracy and a build model of 10800 cm<sup>3</sup>, remarkably higher than the average. The support extruder is included, using HIPS material and the prototype is isolated. The ordering of the components has been done from different companies getting the most competitive prices. Each roll of ABS is composed by 2.3 kg of material and each roll of HIPS by 1kg. The name has been called Nunu.

Table 13 Technical specifications of the printer

<b>NUNU SPECIFICATIONS</b>	
<b>Technology</b>	FDM
<b>Size (mm)</b>	600*600*800
<b>Weight (kg)</b>	40
<b>Model size (mm)</b>	200*180*300
<b>Layer thickness (mm)</b>	0,25-0,05
<b>Structure material; €/kg</b>	ABS 21,74 €/kg
<b>Support material; €/kg</b>	HIPS 33 €/kg
<b>Isolated prototype</b>	YES
<b>Duration of assembly</b>	96 h
<b>Total cost</b>	3.834 €

While this thesis has been completed, the 3D printer has been built and the space becomes operational. Figure 21 shows some examples of the prints obtained with the prints.

# NUNU

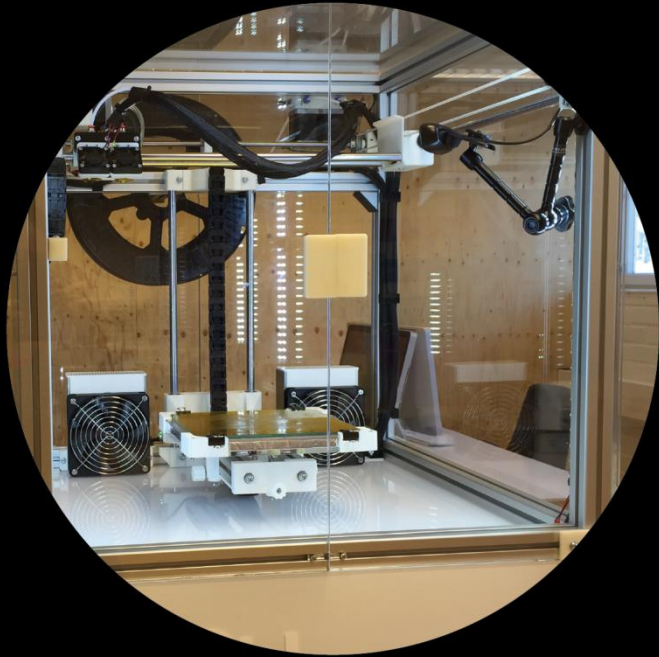


Figure 21 Parts of NUNU printer examples of prints

#### 4.4. WHAT KIND OF LEARNING ENVIRONMENTS SUPPORT RAPID PROTOTYPING IN PRODUCT DEVELOPMENT?

Despite this question has already answered in the methodology of the research, section 3.4, here with a sequence of images is shown the evolution of the creation of the new facility according to the literature reviewed. Below each image there is a summary of the feature implemented. These all features are explained in detail in the third chapter. In addition, some speculations will be done in the discussion.

**1. OLD CUT & INK**  
1. The old Cut & Ink does not have enough space to afford the task properly.

**2. NEW SPACE**  
2. New Cut & Ink will be located in the right side of the room.

**3. NEW SPACE**  
3. 3D printing will be located in the left side of the room.

**4. SPACE DIVISION**  
4. The vinyl rolls and the computer table divide the space but not hinder social interaction.

**5. MATERIALS**  
5. Wood provides an organic atmosphere that fosters creativity.

**6. GLASS**  
6. Glass walls provide transparency. They act as both as a mean of communication as well as privacy.

**7. FURNITURE**  
7. The furniture is designed to suit the activities performed.

**8. INFORMATION DISPLAY**  
8. The screen is used to post info that helps both the user and the staff.

**9. MATERIAL USAGE**  
9. In the iPad, the material usage is saved for each project. It is a useful tool for future studies.

**10. INSTRUCTIONS**  
10. The instructions to use the machines are a of steps to follow as a reminder.

**TRANSFORMATION STEPS**

Figure 22 Evolution of the space

4.4.1. LEARNING ENVIRONMENT ENHANCING RAPID PROTOTYPING



Figure 23 Results of the new space

## 5. DISCUSSION

The first part of this thesis tends to prove the benefits that using 3d printing in learning environments provides to the students in first stages of Product Development Processes.

This thesis analyses physical and focused prototypes. Physical means tangible and focused means that prototypes “works-like”, “looks-like” the final product (Ulrich & Eppinger, 2012). Based on the results obtained from the three experiments, they suggest the following conclusions.

The comparison of the materials used shows that all of them have suitable characteristics for being used in rapid prototypes. However, for a consumer electronic device as a final product, a suitable and common material is ABS injection molded. Table 14 shows the mechanical properties of these materials. The test methods used to measure the materials are different. Both standards are technically equal, but they do not offer comparable results. Some differences include forms of the samples and test speed. Hence, the comparison is made when possible.

Table 14 Mechanical properties of the materials

MECHANICAL PROPERTIES	ASTM test method	MATERIALS			
		Sika M960	ABS plus	VeroBlackPlus RGD875	ABS injection molded
Tensile modulus	ISO604-D638	2200MPa-n/a	n/a-2200MPa	n/a-2000-3000MPa	n/a-2340
Flexural modulus	D790	n/a	2100MPa	2200-3200MPa	2410MPa
Hardness	Shore D-Rockwell R	78D-n/a	n/a	83-86D-n/a	100R-n/a
Impact resistance	ISO179-D256	30kJ/m <sup>2</sup> -n/a	n/a-106J/m	n/a-20-30J/m	38,1kJ/m <sup>2</sup> -507J/m

The tensile modulus describes the elastic properties of a material when it is stretched or compressed. In other words, is the technique researching the tensions of the parts. This feature is obtained from the tensile testing. With this testing are achieved the majority of the mechanical properties of a material. For that reason, having a look on Table 14 the ABS injection molded material has better mechanical properties. Comparing the ABS injection molded with the rapid prototyping materials one to one, the former has a higher tensile modulus. However, the difference is not large. The most suitable materials to be used for rapid prototyping concerning to the tension modulus are SikaBlockM960 and ABS plus.



The flexural modulus, which is the capacity of an object to resist to the flexion when this is placed under tension, is also similar in the four materials of Table 13. However, Veroblack is the nearest approach to the consumer material.

Related to the hardness, for being the three of the rapid prototyping materials in different ASTM test method, is not taking in consideration.

Impact resistance is one of the main requirements for a consumer electronics device. It is the resistance that an object has when it is applied a punctual force on it. Comparing this feature, ABS plus and SikaBlock M960 are more accurate to the final product.

To summarize, according to the mechanical properties of each material, the three materials meet the requirements to be used for prototyping. However, taking in consideration that impact resistance is one of the most important mechanical properties of ABS, the most suitable materials are ABS plus and SikaBlock.

According to the times of processes the differences are clear. CNC process and 3D printing with Object 30 are much shorter than the print with U-print. U-print spends 60% more time to have the prototype ready. However, 3D printing methods require minimum human interaction. U-print and Object 30 require a 14% and 41% of the time needed for a CNC process respectively. In addition, the 42 minutes the model maker spends in CNC process are not totally real. This is because the 42 minutes are fractionated in small times of about two or five minutes in which the model maker has to change tool or do a hand working. These comings and goings difficult to carry out other work simultaneously. For that reason the cost of the worker is computed in the total price of the process, unlike the printing processes in which the human interaction is not taking in consideration for the total costs.

Regarding to economic aspects, both materials and processes are analysed. The difference in the prices of the materials itself is very high. It is proved that the most affordable material is the ABS plus, while the other two cost more than 6 times. But the most important is the cost of the whole process. The cost of the CNC technology is more than 11 times expensive than the printing method done with U-print.

The feasibility of a 3D printer as a rapid prototyping tool it has been proved with the direct variables analysed before. In addition, it has been demonstrated the feasibility of a printer in the category of the U-print. These types of printers use FDM technology and thermoplastics as base material. User level printers are the most accessible

according to quality-price. The reduction of time and cost of the process is a key benefit mentioned in the theoretical frame.

Prototyping at first stages of a project has an impact in the whole process. However, this cannot be measured in this thesis because the research is limited to the concept development phase in an educational context.

This thesis provides a concrete example of supporting experiential learning typical of the product development process with parameters of physical spaces fostering creativity. The focus is on the planning and concept development stages of product development as well as the divergent learning style typical of these stages. The findings emphasize the parameters of freedom and support in designing physical spaces supportive of rapid prototyping.

Freedom is manifested in the flexible spaces that motivate the users to develop their projects with greater challenges. Challenging tasks support the users in developing better ideas. Flexible spaces support the experiential divergent learning style. Freedom is also manifested in accessibility of the learning environment. In the case of the PrintShop, the accessibility is gradual. The locked door avoids the free entrance to the room. But after attending to the introductory workshops organized, the user has total freedom to use the machines by doing a responsible use of the space. This community freedom is feasible when involves a linear progression with the responsibility and social behaviour.

An adequate social behaviour enhances the interaction between the user and the space. Support from the staff members is needed to guide the students towards respectful, collaborative way of working. Support of the staff helping the users in their projects adds value to the facility. The variable of support has been a key factor in the selection of the printer. A person in charge of the printer will be able to help the students, to fix the machine or to enhance the performance in the future. In addition, it promotes the interest of others in performing rapid prototypes with the use this innovative tool.

Printshop provides a physical learning environment that supports divergent learning style in a rapid prototyping stage of a product development process. Based on the study, product development education could benefit from providing the students an access to the Printshop learning environment.

## 5.1. LIMITATIONS OF STUDY

This thesis focuses on an educational context. Concerning to the experiments realized, they are not comparable with industry studies. The results are limited to the machinery available so it is understood that the variables analysed can potentially differ using other machines. For that reason, the results obtained and the comparison with the state of art narrowed to the used tools. To have a better analysis, more experiments have to be conducted. A further remark is that small sample size of the experiment limits the result.

In relation to the environment supporting rapid prototyping, the main limitation is that the space is determined before the study. This drawback limits the successful accomplishment of all the variables that the literature review proposes as crucial to obtain a successful learning environment.

In addition, the entire thesis reflects an experimental work conducted at ADF. No other facilities include 3D printing as an available tool for the students. For that reason, the feasibility of this tool in PdP projects cannot be proved yet. However, many insights have been given and it is believed that they contributed to the literature reviewed.

## 5.2. FUTURE WORK

To prove the feasibility of this work, the projects of the students should be monitored. A useful tool to recollect data is the iPad already placed in the Printshop. After the academic year this data should be analysed. The results will show the number of prototypes done with 3D printing. If this quantity is higher than the data obtained from the questionnaires done, it can be said that the 3D printer plays an important role in the projects.

Another suggested experiment is to conduct interviews before and after the PdP course. The interviews will measure the expectations and the actual utilizations of 3D printing. In this way, it is possible to measure the effectiveness of the new environment.

The learning environment has been done, according to the knowledge of the staff and following key points obtained from previous researches in learning environments. However, the opinion of the users is important. Interviews to the users are always very helpful to improve the environment according to their needs.

## REFERENCES

- 3D systems, n.d. *3D systems*. [Online]  
Available at: <http://www.3dsystems.com/quickparts/prototyping-pre-production/selective-laser-sintering-sls>  
[Accessed 2 10 2014].
- A Steckler, K. M. R. G. S. B. L. M., 1992. Toward integrating qualitative and quantitative methods: an introduction. *Health Education Quarterly*, 18(1), p. 7.
- Aalto Design Factory, n.d. *Aalto Design Factory*. [Online]  
Available at: <http://www.aaltodesignfactory.fi/>  
[Accessed 9 2014].
- Aalto University, n.d. *Into*. [Online]  
Available at: <https://into.aalto.fi/display/enmech/Homepage>  
[Accessed 11 2014].
- Aalto University, n.d. *noppa-portaali*. [Online]  
Available at: <https://noppa.aalto.fi/noppa/kurssi/kon-41.4002/esite>  
[Accessed 10 2014].
- Aalto University, n.d. *weboodi*. [Online]  
Available at: <https://oodi.aalto.fi/a/frame.jsp?Kieli=6&valittuKieli=6>  
[Accessed 10 2014].
- addlab, n.d. *Aalto University Digital Design Laboratory*. [Online]  
Available at: <http://addlab.aalto.fi/>  
[Accessed 10 2014].
- ASTM, F2792-12a. *Standard Terminology for Additive Manufacturing*. s.l.:s.n.
- Bagley, R. O., 2014. How 3D Printing Can Transform Your Business. *Forbes*.
- Bingham, W. V. & Moore, B. V., 1931. *How to interview*. Oxford: Harpers.
- Bradshaw, S., Bowyer, A. & Haufe, P., 2010. THE INTELLECTUAL PROPERTY IMPLICATIONS OF LOW-COST 3D PRINTING. *ScriptEd*, 7(1), pp. 5-31.
- Brun, E., Harrison, J. R. & Sætre, A. S., 2009. *MANAGING AMBIGUITY IN NEW PRODUCT DEVELOPMENT. PROJECTS: A FORMAL MODEL AND SIMULATION OF AMBIGUITY MANAGEMENT STRATEGIES*, Norway: s.n.
- Burt, D. N. & Pinkerton, R. L., 1996. *A Purchasing Manager's Guide to Strategic Proactive*. 27 ed. New York: AMACOM.

Cambridge , n.d. *Cambridge International Dictionary*. [Online]  
Available at: <http://dictionary.cambridge.org/>  
[Accessed 3 2015].

Campbell, R. & de Beer, D. B. L. B. G. T. M. C. R. B., 2007. Design evolution through customer interaction with functional prototypes. *Journal of Engineering design*, 18(6), pp. 617-635.

Campbell, T., Williams, C., Ivanova, O. & Garrett, B., 2011. *Could 3D printing change the world. Technologies, Potential, and Implications of Additive Manufacturing*, s.l.: s.n.

Carrillo, R., n.d. *Kowork*. [Online]  
Available at: <http://www.kowork.net/category/design-thinking>  
[Accessed 4 3 2015].

Chesbrough, H., 2003. In: H. B. Press, ed. *Open innovation: The new imperative for creating and profiting from technology*. s.l.:s.n., p. 227.

CHUA, C. L., LIM, K. & Prototyping, C. R., 2003. *Principles and applications*. 3 ed. Singapore: World Scientific Publishing Co.

Cohen, D., 2014. Fostering Mainstream Adoption of Industrial 3D Printing: Understanding the Benefits and Promoting Organizational Readiness. *MARY ANN LIEBERT, INC.*, 1(2), pp. 62-69.

Cooper, R. G., 2000. New Product Performance: What distinguishes the star Products. *Australian Journal of Management*, 25(1).

Cooper, R. G., 2013. New products-What separates the winners from the losers and what drives success.. In: H. N. J. W. & S. K.B. Kahn, ed. *PDMA handbook of new product development*. s.l.:s.n.

Creswell, J. W., 2014. *Research Design*. 4 ed. s.l.:SAGE publications.

Custompart, n.d. *custompart.net*. [Online]  
Available at: <http://www.custompartnet.com/wu/fused-deposition-modeling>  
[Accessed 10 September 2014].

Dewey, J., 2007. *Experience And Education*. s.l.:Simon and Schuster.

Dickens, P., 2001. Rapid manufacturing. In: J. McDonald, C. Ryall & D. Wimpenny, eds. *Rapid Prototyping Casebook*. London: Professional Engineering Publishing, pp. 239-242.

digita2, n.d. *protorapido*. [Online]  
Available at: <http://www.protorapido.es/para.pdf>  
[Accessed 24 9 2014].

Ehn, P. & Kyng, M., 1991. Cardboard Computers: Mocking-it-up or Hands-on the Future. In: *Design at Work: Cooperative Design of Computer Systems*. s.l.:Lawrence Erlbaum Associates, pp. 169-195.

- Elfner, E. S., 2003. technical note five. *www.ateneonline.it*, p. 217.
- Evans, G. & McCoy, J., 2002. The Potential Role of the Physical Environment in Fostering Creativity. *Creativity Research Journal*, 14(3 and 4), pp. 409-416.
- Gibson, I. R. D. & Stucker, B., 2010. *Additive Manufacturing Technologies; Rapid Prototyping to Direct Digital Manufacturing*. London: Springer.
- Gibson, I., Rosen, D. & Stucker, B., 2010. *Additive Manufacturing Technologies; Rapid Prototyping to Direct Digital Manufacturing*. London: Springer.
- Graetz, K. & Goliber, M., 2002. Designing collaborative learning places: psychological foundations and new frontiers. In: D. J. B. Nancy Van Note Chism, ed. *The importance of physical space in creating supportive learning environments*. San Francisco: Jossey-Bass, pp. 13-22.
- Heredia, A., n.d. *Survey Monkey*. [Online]  
Available at: <https://www.surveymonkey.com/s/5TMWC37>  
[Accessed 2014].
- Herzberg, F., n.d. One More Time: How Do You Motivate Employees?. *Harvard Business Review*.
- Houde, S. & Hill, C., 1997. What do prototypes prototype?. In: T. L. P. M.G. Helander, ed. *Handbook of Human-Computer Interaction*. Amsterdam: Elsevier Science B,V, pp. 367-380.
- I. Gibson, D. W. R. B. S., 2010. *Additive Manufacturing Technologies, Rapid Prototyping to Direct Digital*. s.l.:Springer.
- JADCM123, n.d. *youtube*. [Online]  
Available at: <http://www.youtube.com/watch?v=4QAHBtBLE5g>  
[Accessed 18 9 2014].
- Kajornboon, A. B., 2005. Using interviews as research instruments. *E-journal for Research Teachers*, p. 10.
- Kelley, T., 2004. Prototyping is the shorthand of innovation. In: *The art of innovation*. London: Profile books LTD, pp. 101-118.
- Killbride, L., Phelan, A. & Vanbuel, M., 1998. *Classrooms for distance teaching and learning*. Leuven: Leuven University Press.
- Koen, P., Ajamian, G. M. & Scott Boyce, A. C. E. F. S. F. J. P. P. R. S., 2002. Fuzzy Front End: Effective Methods, Tools, and Techniques.. In: A. G. S. Paul Belliveau, ed. *The PDMA ToolBook 1 for New Product Development*. s.l.:pdma, pp. 5-36.
- Kolb, A. & Kolb, D., 2005. Learning Styles and Learning Spaces: Enhancing Experiential Learning in Higher Education. *Academy of Management Learning & Education*, 4(2), pp. 193-212.

- Kolb, D., 1984. *Experiential Learning: Experience as the Source of Learning and Development*. New Jersey: Prentice-Hall.
- Kostakis, V., Niaros, V. & Giotitsas, C., 2015. Open source 3D printing as a means of learning: An educational experiment in two high schools in Greece. *Telematics and informatics*, 32(1), pp. 118-128.
- Kotler, P. & Armstrong, G., 1980. 1st ed. s.l.:s.n.
- Kruth, J. P., Leu, M. C. & Nakagawa, 1998. Progress in Additive Manufacturing and Rapid Prototyping. *CIRP Annals-Manufacturing Technology*, 47(2), pp. 525-540.
- Kvale, S., 2007. In: U. Flick, ed. *Doing an interview*. s.l.:SAGE publications, p. 14.
- L, C. D., 2014. 3D Printing and Additive Manufacturing. *MARY ANN LIEBERT, INC*, 1(2), p. 64.
- Lim, Y.-k., Stolterman, E. & tenenberg, J., 2008. The Anatomy of Prototypes: Prototypes as Filters, Prototypes as Manifestations of Design Ideas. *ACM Transactions on Computer-Human Interaction*, 15(2), p. 27.
- Mahindru, D. & Mahendru, P., 2013. Review of Rapid Prototyping-Technology for the Future. *Global Journal of Computer Science and Technology Graphics & vision*, 13(4).
- Marxt, C. & Hacklin, F., 2005. DESIGN, PRODUCT DEVELOPMENT, INNOVATION: ALL THE SAME IN THE END?. *Journal of Engineering Design*, 16(4), p. 6.
- Mellor, S., Hao, L. & Zhang, D., 2014. Additive Manufacturing: A Framework for implementation. *International Journal production economics*, Volume 149, pp. 194-201.
- Mintel, n.d. *Mintel.GNPD*. [Online]  
Available at: <http://www.gnpd.com/sinatra/gnpd/frontpage/>  
[Accessed 11 2014].
- Nonaka, I. & Konno, N., 1998. Concept of "Ba": Building a foundation for knowledge creation. *California Management Review*, 40(3), pp. 40-54.
- Norman M. Bradburn, S. S. W., 2004. *Asking Questions*. s.l.:jossey-bass.
- Otto, K. & Wood, K., 2001. Journeys of product development. In: *Product Design*. s.l.:Prentice Hall, pp. 1-21.
- Partsnap, n.d. *PartSnap*. [Online]  
Available at: <http://www.partsnap.com/partsnap-faq/what-are-the-pros-and-cons-of-polyjet-and-fdm-3d-printing/>  
[Accessed 11 12 2014].
- PdP, n.d. *PdP*. [Online]  
Available at: <http://pdp.fi/>  
[Accessed 10 2014].

- PdP, n.d. *product development project*. [Online]  
Available at: <http://pdp.fi/course-overview/what-is-pdp/>  
[Accessed 13 3 2015].
- Peter H. Rossi, J. D. W. B. A., 2013. *Handbook of survey research*. 3 ed. s.l.:Academic Press.
- Pham, D. & Gault, R., 1998. A comparison of rapid prototyping technologies. *International Journal of Machine Tools & Manufacture*, Volume 38, pp. 1257-1287.
- Pozo, D. G. R., n.d. *Barcelona Institute of Packaging*. [Online]  
Available at: <http://www.eic.cat/gfe/docs/10585.pdf>  
[Accessed 16 9 2014].
- Prinz, F., 1997. JTEC/WTEC panel report on rapid prototyping in Europe and Japan. *Loyola College*, Volume I and II.
- Rathmell, J. M., 1966. What is meant by services?. *Journal of Marketing*, 30(4).
- Schmidt, J. B. & Calantone, R. J., 2002. Escalation of Commitment During New Product Development. *Journal of the Academy of Marketing Science*, 30(103), p. 17.
- Sika, 2013. *Sika*. [Online]  
Available at: [deu.sika.com/dms/.../SikaBlock\\_M960\\_eng.pdf](http://deu.sika.com/dms/.../SikaBlock_M960_eng.pdf)  
[Accessed 12 2014].
- Smulders, F. E., 2004. Co-operation in NPD: Coping with Different Learning Styles. *CREATIVITY AND INNOVATION MANAGEMENT*, 13(4).
- Solid concepts Inc., n.d. *Youtube*. [Online]  
Available at: <https://www.youtube.com/watch?v=Som3CddHfZE>  
[Accessed 11 12 2014].
- Solid concepts, n.d. *Solid concepts*. [Online]  
Available at: <https://www.solidconcepts.com/technologies/direct-metal-laser-sintering-dmls/>  
[Accessed 13 12 2014].
- Standord University, n.d. *Standford University*. [Online]  
Available at: [http://web.stanford.edu/group/me310/me310\\_2014/](http://web.stanford.edu/group/me310/me310_2014/)  
[Accessed 4 10 2014].
- Survey Monkey, n.d. *Survey Monkey*. [Online]  
Available at: <https://www.surveymonkey.com/s/5TMWC37>  
[Accessed 2014].
- Terry Wohlers, 2013. *Additives manufacturing and 3D printing state of the industry*. s.l.:Wohlers associates.
- Ullman, D. G., 2003. *The mechanical design process*. 3 ed. s.l.:s.n.



Ulrich & Eppinger, 2012. *Product Design and Development*. 5 ed. s.l.:McGraw Hill.

Ulrich, K. & Eppinger, S., 2012. *Product Design and Development*. 5 ed. s.l.:McGraw Hill.

Walker, M., TAKAYAMA, L. & LANDAY, J. A., 2002. HIGH-FIDELITY OR LOW-FIDELITY, PAPER OR COMPUTER? CHOOSING ATTRIBUTES WHEN TESTING WEB PROTOTYPES. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting.*, pp. 661-665.

Wessel, k., 2008. *New Product Development Performance*. s.l.:VDM Verlag Dr. Müller.

wikipedia, n.d. *wikipedia*. [Online]

Available at: <http://en.wikipedia.org/wiki/Stereolithography>

[Accessed 18 9 2014].

# APPENDIX 1

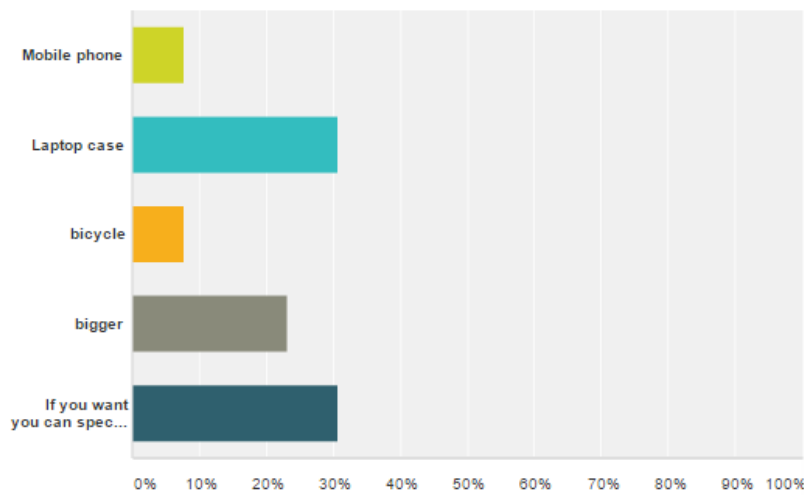
## How many people of each field were in your team?

Answered: 13 Skipped: 0

Answer Choices	Responses
Engineers	100.00% 13
Designers	100.00% 13
Business	76.92% 10
Others	38.46% 5

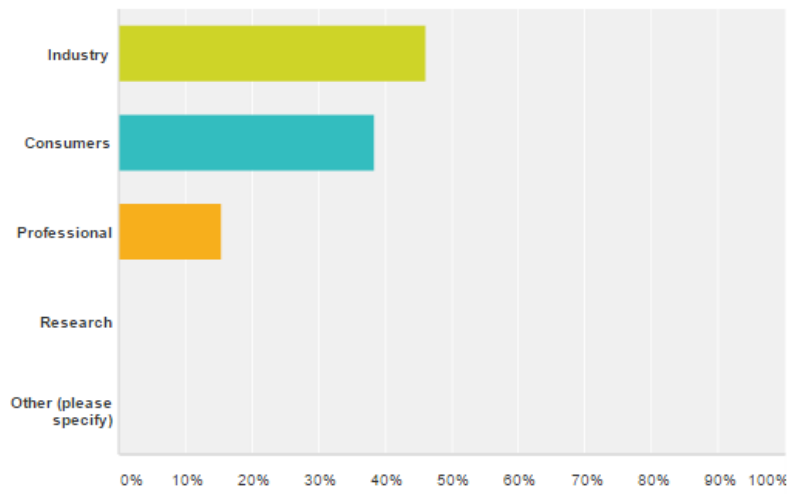
## How handholdable was your product?(sizes are approximated)

Answered: 13 Skipped: 0



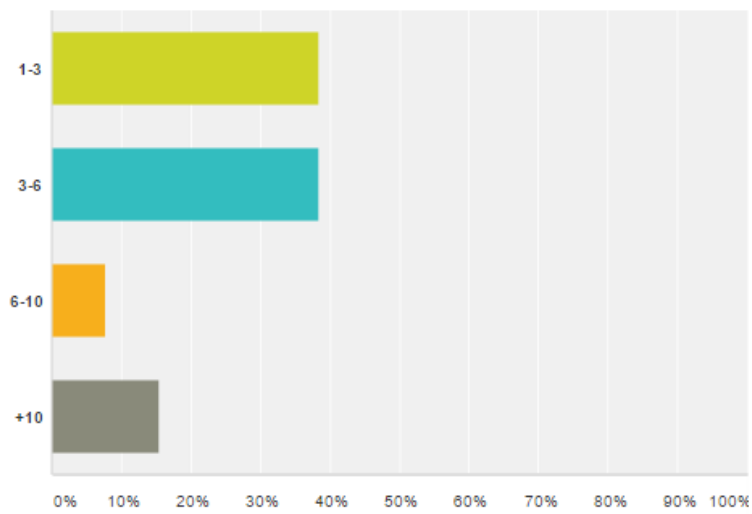
### Who was the product for?

Answered: 13 Skipped: 0



### How many prototypes did you developed during the course?

Answered: 13 Skipped: 0



## If in the 5th question you answered that the amount of prototypes made with 3D printing was 0, could you please specify why?

Answered: 9 Skipped: 4

● Responses (9)   Text Analysis   My Categories

**PRO FEATURE**  
Use text analysis to search and categorize responses; see frequently-used words and phrases. To use Text Analysis, upgrade to a GOLD or PLATINUM plan.  
[Upgrade](#)   [Learn more »](#)

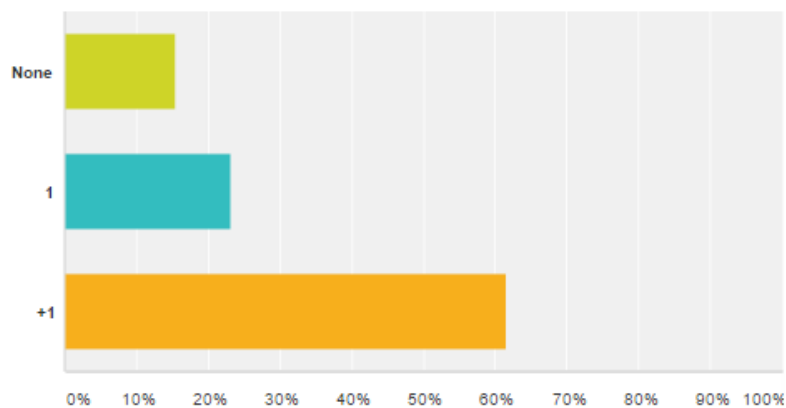
Categorize as...   Filter by Category   Search responses

Showing 9 responses

We made prototypes that had all of the elements above.	11/25/2014 9:19 AM	<a href="#">View respondent's answers</a>
Protos where assemblies of existing, cheap products that needed only small amounts of modification. No need for 3D printing.	11/24/2014 6:41 PM	<a href="#">View respondent's answers</a>
No need for 3D printing in our case	11/24/2014 4:54 PM	<a href="#">View respondent's answers</a>
The sponsoring company had a plastic moulding factory.	11/23/2014 5:34 PM	<a href="#">View respondent's answers</a>
CNC was more practical for our solution	11/23/2014 11:23 AM	<a href="#">View respondent's answers</a>
No need for them.	11/23/2014 12:01 AM	<a href="#">View respondent's answers</a>
Too big	11/22/2014 8:53 PM	<a href="#">View respondent's answers</a>

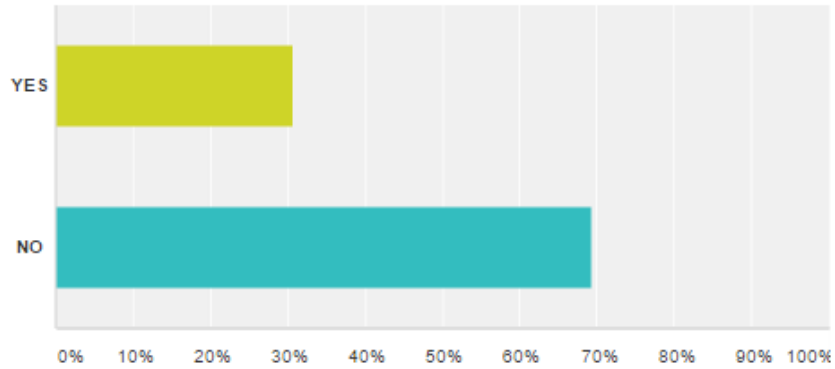
## How many members of your team had enough skills to build 3D printing prototypes by their own?

Answered: 13 Skipped: 0



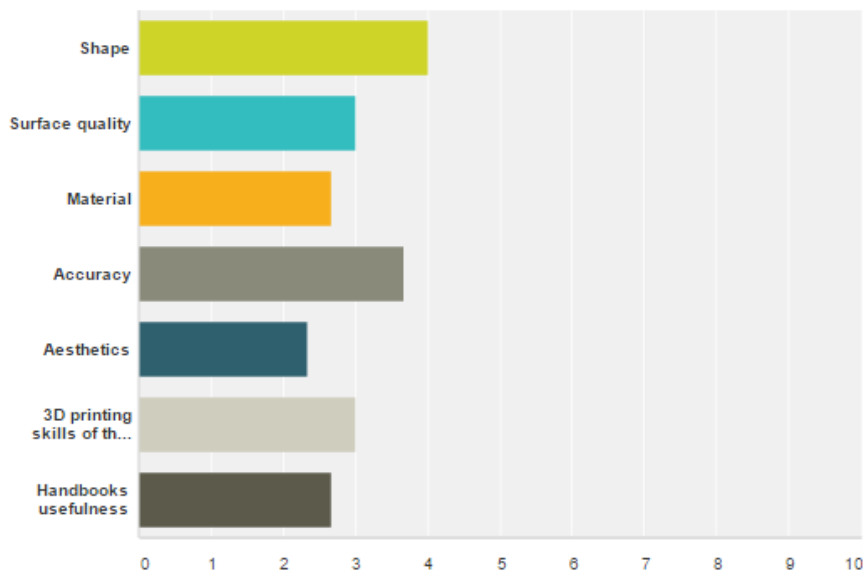
### Did you do (as a team) any 3D prototype by your own?

Answered: 13 Skipped: 0



### If your answer was YES in the 8th question, please specify the grade of satisfaction with the variables presented below.

Answered: 3 Skipped: 10



**If there is something that has not been asked in this survey and you consider important related with the use of hand working, CNC or 3D printing methods used in your project, please let us know your opinion.**

Answered: 2 Skipped: 11

● Responses (2)   Text Analysis   My Categories

**PRO FEATURE**  
Use text analysis to search and categorize responses; see frequently-used words and phrases. To use Text Analysis, upgrade to a GOLD or PLATINUM plan.  
[Upgrade](#)   [Learn more »](#)

Categorize as...   Filter by Category   Search responses

Showing 2 responses

---

Maybe you should ask the percentages of prototype mass or hours put in instead of "did you do a 3D printed prototype". You simply cannot manufacture anything complex by just 3D-printing if you want to call it anything else but a very rude mock-up. Our prototype had CNC-machined parts, Casted plastic, Hand worked details and 3d-printed parts. I think this questionnaire provides biased data due to the method of asking questions and almost 0 conclusions can be withdrawn  
11/25/2014 9:19 AM   [View respondent's answers](#)

---

Sorry. Can't remember all the facts anymore. :)  
11/23/2014 12:01 AM   [View respondent's answers](#)