Mestrado Design de Produto M.D.P.

The Importance of Physical Prototyping in an Iterative Product Design Process

A Practical Experience in a Professional Environment

Estágio Académico de Natureza Profissional na Área de Design de Produto

Academic Internship of Professional Nature in the Area of Product Design

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Entidade de Acolhimento/Host Entity

INNGAGE

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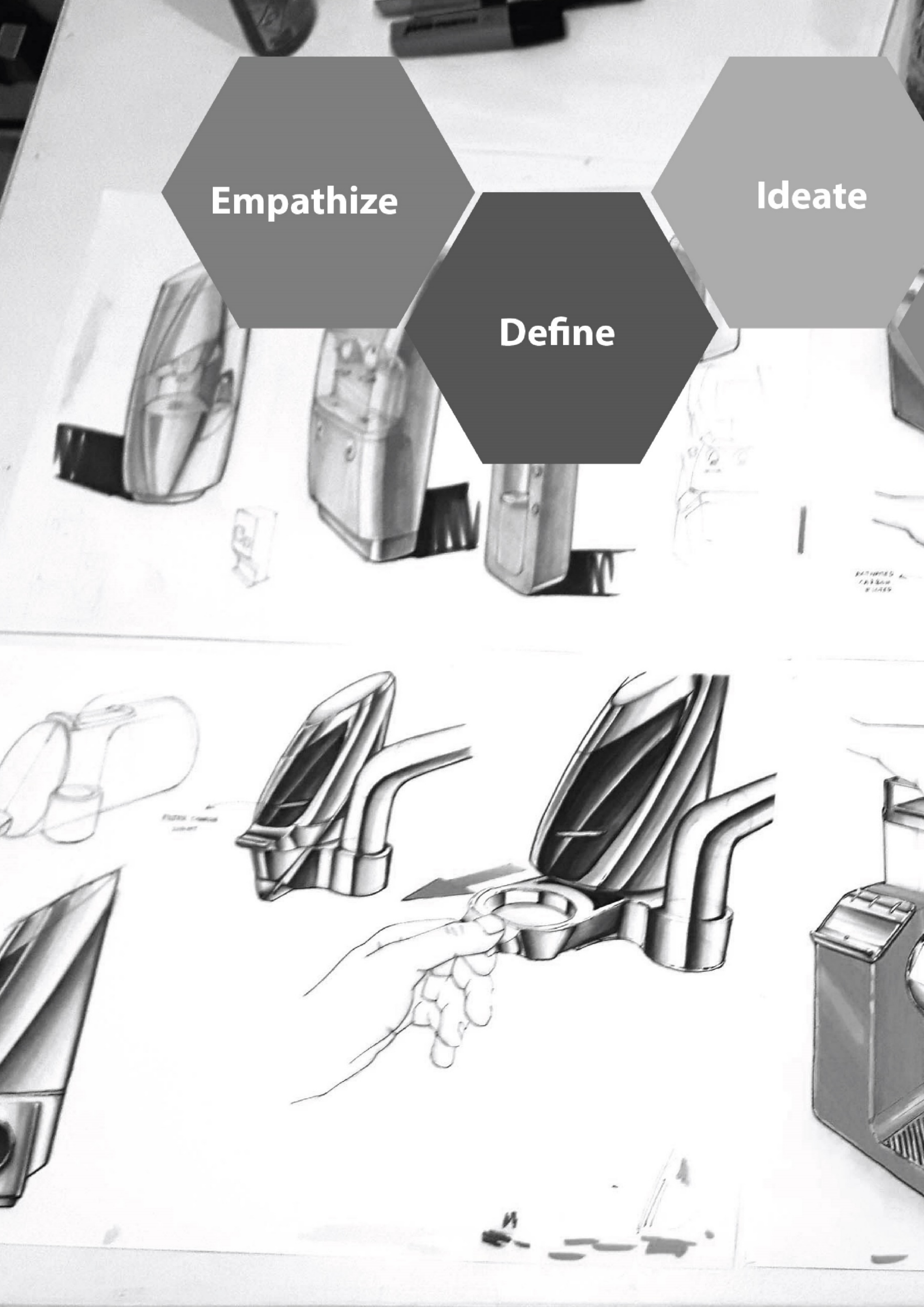
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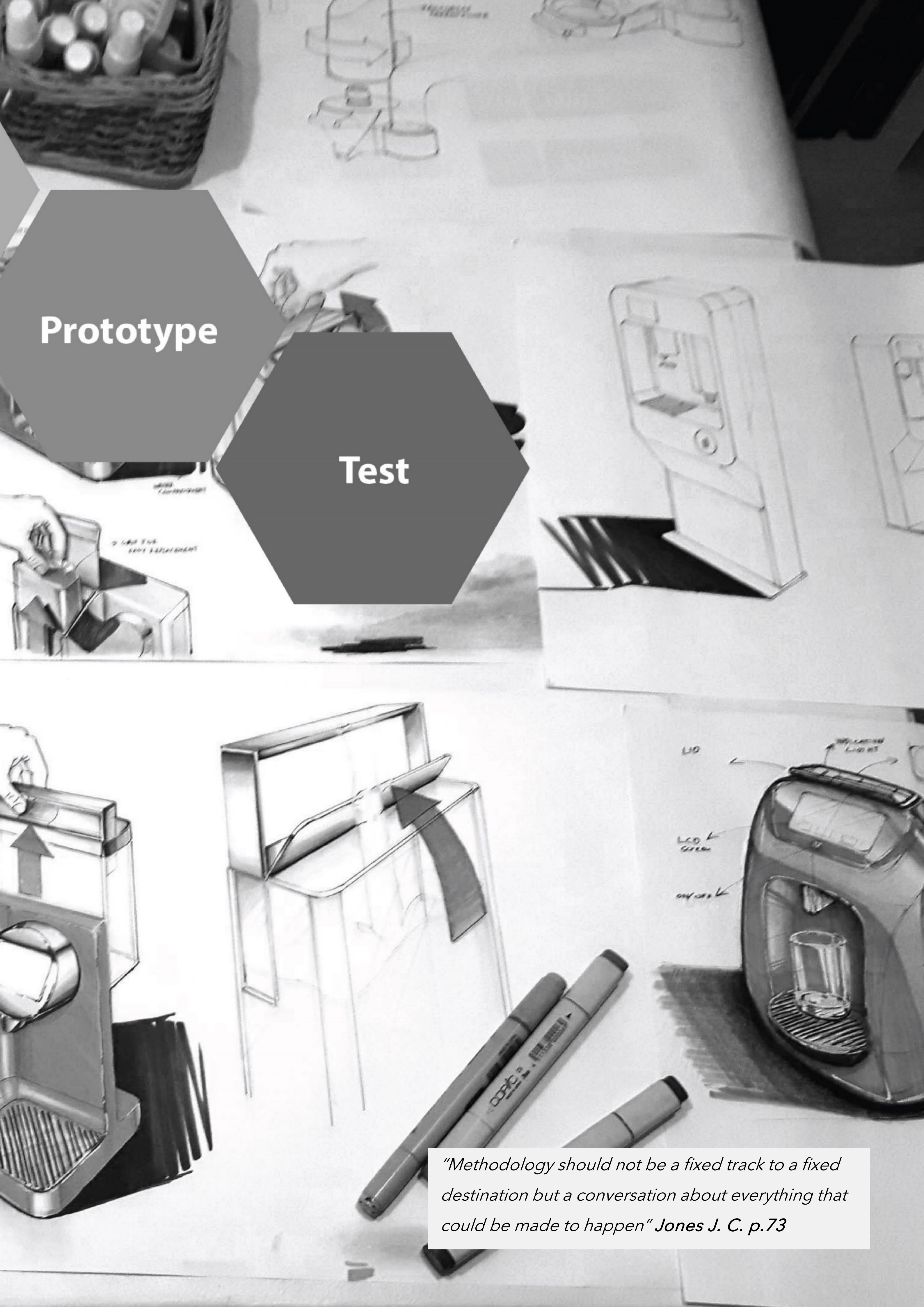

"Methodology should not be a fixed track to a fixed destination but a conversation about everything that could be made to happen" Jones J. C. p.73

Acknowledgements

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Table of Contents

Figures Index

Table Index

Resumo

Toda a teoria deve ser suportada por factos e experiências práticas para que sejam eficazes, por isso foi escolhido o estágio acadêmico como trabalho final de graduação do Mestrado em Design de Produto.

O Design de Produto é um processo complexo de resolução de problemas que evidenciam as habilidades cognitivas do designer. As ferramentas como a prototipagem e os métodos de design são utilizadas como auxiliares no processo de design.

Durante cinco meses foi realizado um estágio de design na "INNGAGE", empresa especializada em design de produtos de consumo, por forma a obter uma melhor compreensão das ferramentas e aplicabilidade destas no processo de design real. O foco deste trabalho é o uso da Prototipagem Física como abordagem sistemática para o desenvolvimento de produtos. Numa primeira abordagem foi utilizada a literatura com o objetivo de adquirir uma dimensão técnica e crítica nos campos em estudo. Posteriormente e durante o estágio, foi aplicada uma metodologia qualitativa intervencionista, onde a principal actividade foi o desenvolvimento de protótipos por forma a suportar este processo.

A bem-sucedida realização desta experiência no campo do design de produto, levou ao desenvolvimento dos conhecimentos em ferramentas de prototipagem e métodos de design, bem como a capacidade de trabalhar em ambiente profissional. Com este estágio a empresa também beneficiou de um aumento do número de projectos em portfolio, com abordagens de design mais estruturadas e uma utilização de métodos de prototipagem mais avançados.

Palavras- Chave

Design de produto, Prototipagem física, Processo de design, Metodologia de design, Estágio

Abstract

Theory must be backed up by practical experience, to be more effective. For this reason an academic internship was selected as a graduation final project of the Master's degree in Product Design.

Product design is a complex problem-solving process that stresses the finite cognitive abilities of the designer. Designers use tools such as prototyping and design methods to help them during the design process to arrive to a reliable solution.

To get a better understanding of these tools and how they are applied in the real-world design process, an academic internship was conducted in the design studio INNGAGE, specialized in consumer product design. The focus of this work was the use of Physical Prototyping in a systematic design approach to product development. First, literature review was conducted, with the aim of acquiring a theoretical and critical dimension on the fields under study. During the internship a qualitative interventionist methodology was applied. The main activity was product development and fabrication of physical prototypes to support this process.

The successful realization of this experience resulted in the considerable enrichment of knowledge for the student in the fields of product design, prototyping tools and design methods, along with the gain of practical experience working in a professional environment. This internship also benefited the company by expanding the portfolio of projects with a more structured design approach, together with a wider utilization of more advanced prototyping methods.

Keywords
Product Design, Physical Prototyping, Design process, Design methodology, Internship

Abbreviation Index

ABS	Acrylonitrile butadiene styrene
AM	Additive Manufacturing
CAD	Computer-Aided Design
CAM	Computer-Aided Manufacturing
CJP	ColorJet Printing
DMLS	Direct Metal Laser Sintering
DODI	Drop on Demand Inkjet
EBM	Electron Beam Melting
FDM	Fused Deposition Modeling
FFF	Fused Filament Fabrication
JIT	Just in time manufacturing
LOM	Laminate Object Manufacturing
MJM	Multi Jet Modeling
MP	Managing Partner
NC	Numerical control
OEM	Original Equipment Manufacturer
PA	Polyamide
PEEK	Polyether Ether Ketone
PEI	Polyetherimide
PETG	Polyethylene terephthalate
PLA	Polylactic acid
PP	Physical Prototyping
RP	Rapid Prototyping
SDL	Selective Deposition Lamination
SLA	Stereolithography Apparatus
SLM	Selective Laser Melting
SLS	Selective Laser Sintering
SLS	Selective Laser Sintering
STL	Stereolithography
TPU	Thermoplastic polyurethane
HCD	Human Centered Design

Glossary

Additive manufacturing (AM)

This technology has also been referred to as layered manufacturing, material deposit manufacturing, material addition manufacturing, solid freeform manufacturing and three-dimensional printing (Chua,2013). It is defined by ASTM international, as a process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies. Additive manufacturing is part of the rapid prototyping methods.

Design Methodology

Indicates how the design process should be structured and which steps should be followed in a specific order. The objective is that at the result of the design process will produce efficiently and reliably conclusions.

G-code

Also RS-274, the most widely used numerical control (NC) programing language. It is used mainly in computer-aided manufacturing and rapid prototyping to control automated machine tools.

Innovative Design

The process of translating an idea or invention into a good or service that creates value or for which customers will pay. To be called an innovation, an idea must be replicable at an economical cost and must satisfy a specific need.

Modelmaking

Describes the step by step method of creating physical prototypes.

Physical prototype & model

These terms can be used interchangeably to describe a preliminary three-dimensional representation of a product, service or system.

Physical Prototyping

Is described as the design method that uses physical prototypes to study how a product will work, look, feel, and function

Product design Process

The set of strategic and tactical activities, from idea generation to commercialization, used to create a product design. In a systematic approach, product designers conceptualize and evaluate ideas, turning them into tangible inventions and products.

Rapid Manufacturing

Is a tool-less process of production of end-use parts, manufactured by additive technologies without the need to invest in tooling.

Rapid prototyping

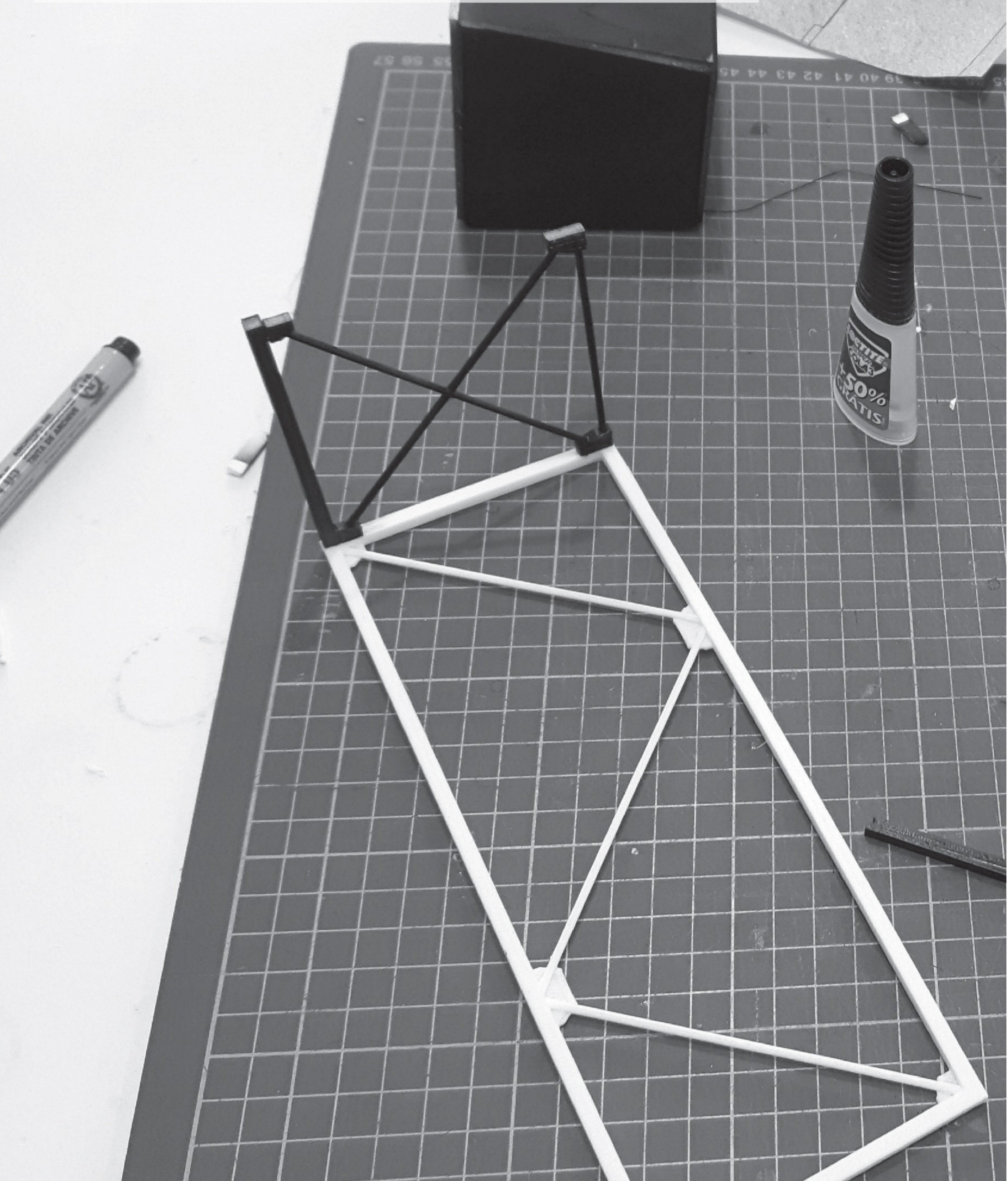
The production of a physical model directly from a computer model without the need for any jig or fixture.

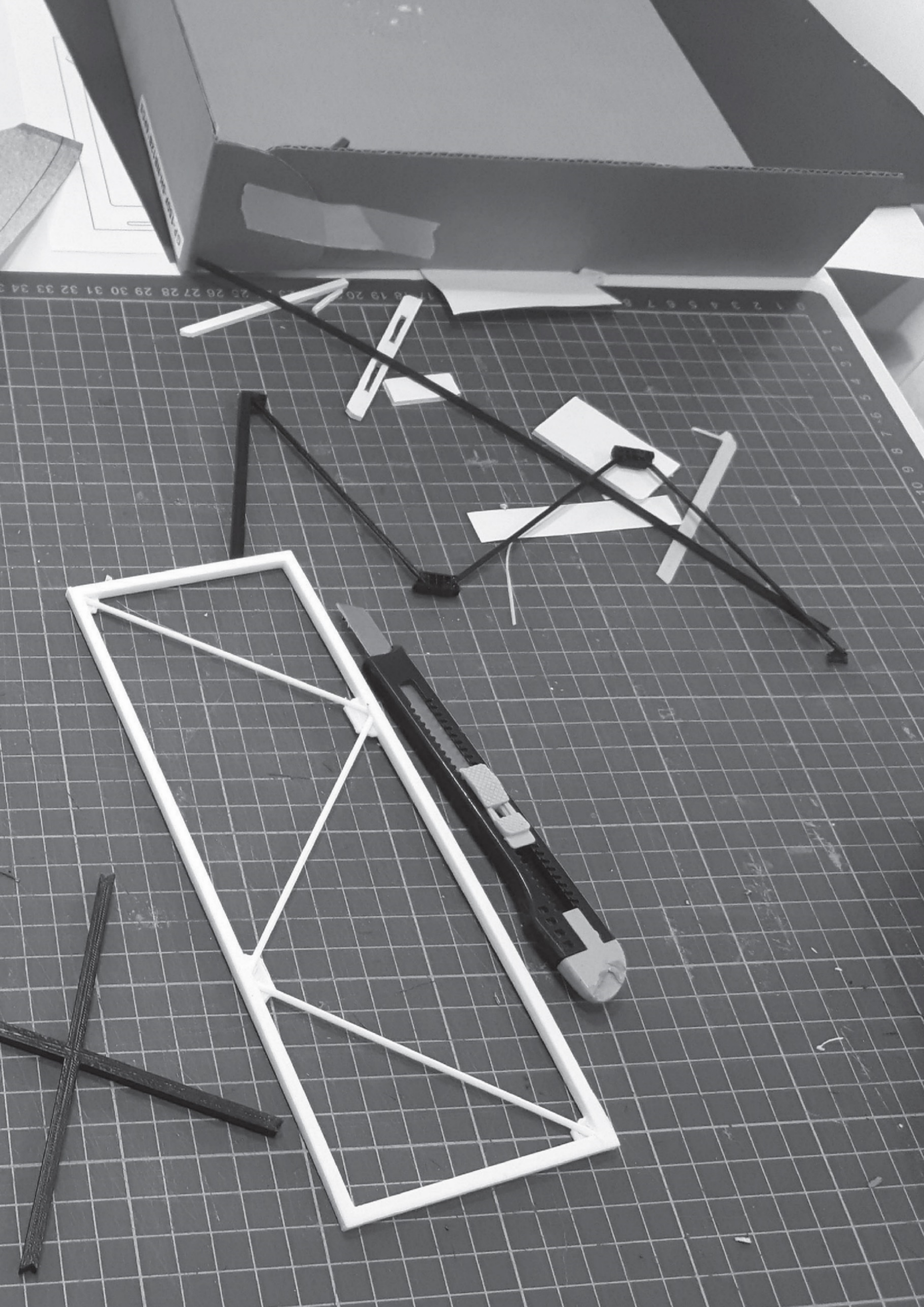
Systems engineering

An interdisciplinary approach to enable the realization of successful systems. It focuses on defining customer needs and required functionality early in the development cycle, documenting requirements, then proceeding with design synthesis and system validation while considering the complete problem.

Part I Introduction

In this part an introduction to this work is presented, defining the research topic, objectives, motivation, success factors and beneficiaries.





Part I

1.1. Introduction

Creating innovative products and systems is pursued by all the stakeholders, when designing a new product innovation leads to higher financial reward and bigger market share. But as problems become more complex, the desirable solution becomes harder to predict and the job of the product designer becomes more demanding. To be successful in this process it is essential to be up to date with the latest tools and have practical experience on using them.

Taking into consideration of the above, the realization of an internship in a product design studio as a final project was undoubtedly the ideal choice. This internship took place during the second semester of the second year of the Master in Product Design program between the 13th of February 2017 end the 30th of June 2017, in the Design Studio INNGAE in Seixal Portugal. INNGAGE is specialized in consumer product design and offers other secondary services such as Market Research and Graphic Design.

This work is divided into two parts, first an extended theoretical research is done to cover the main areas that affect this work including, design studios, consumer products, physical prototyping and design methods. The second part is the documentation of the practical experience gained during the internship. Where the theoretical knowledge was applied. The results of this part are presented as case studies.

1.2. Title

The Importance of Physical Prototyping in an Iterative Product Design Process. A Practical Experience in a Professional Environment

1.3. Investigation Topic

Physical Prototyping in the product design process.

1.4. Objectives

To guide this work, objectives where established in the beginning. These objectives where divided in general and specific as presented below.

General

- To acquire professional experience in product design;
- Allow for a better integration of the author in the labor market;
- To use physical prototypes in a systematic product design approach;

Specific

- Develop and use different types of prototypes during the design process;
- Create prototypes with a variety of methods including: manual, rapid prototyping tools: additive, subtractive and combination of both;
- Evaluate the role and contribution of Physical Prototyping (PP) in the real-world design process;
- Use a systematic approach (method) in the product development process.
- Apply research into additive manufacturing technologies;
- Apply research into different design and product development methods;

1.5. Argument

Prototyping has always played a key role in the design process. It has become even more important nowadays with the rise of Rapid Prototyping and the dramatic reduction of product development time. Design methods are essential in structuring the design process, so it concludes a good and reliable solution. With the increase of product complexity and with the search for innovative solutions with short development time, the use of a design method that serves these goals is essential in today's competitive market. This knowledge and skills can be best achieved with a mix of theoretical and practical work in a professional environment.

1.6. Critical Success Factors

The success or failure of this work depends in a series of factors that can be predicted. The factors are listed below divided to Favorable and Not favorable.

Favorable

- The culture of prototyping is well established and valued in the in INNGAGE design studio.
- Adequate facilities for construction of prototypes are present in the workplace such as a FDM 3D printer (Hephestos 2), cutting board, cardboard, glue, etc. and other crafts materials are readily available.
- The relative ease of access of information since there is a lot of information available in literature and online regarding, physical prototyping and design methodologies.
- The knowledge accumulated during the authors academic career, in physical prototyping and manufacturing technologies.
- The author has access to other rapid prototyping machines that can use to aid the fabrication of physical prototypes if the resources present in INNGAGE design studio are not sufficient.

Not favorable

- Time: the available time frame might not be sufficient to fulfil the research. Since with work is done in a professional environment resources and time might be requested to be allocated into other projects or activities that don't require physical prototyping thus not contribute to the goal of this work.
- Resources: the availability of materials and resources to complete prototypes. Prototypes can be expensive to make and time-consuming.

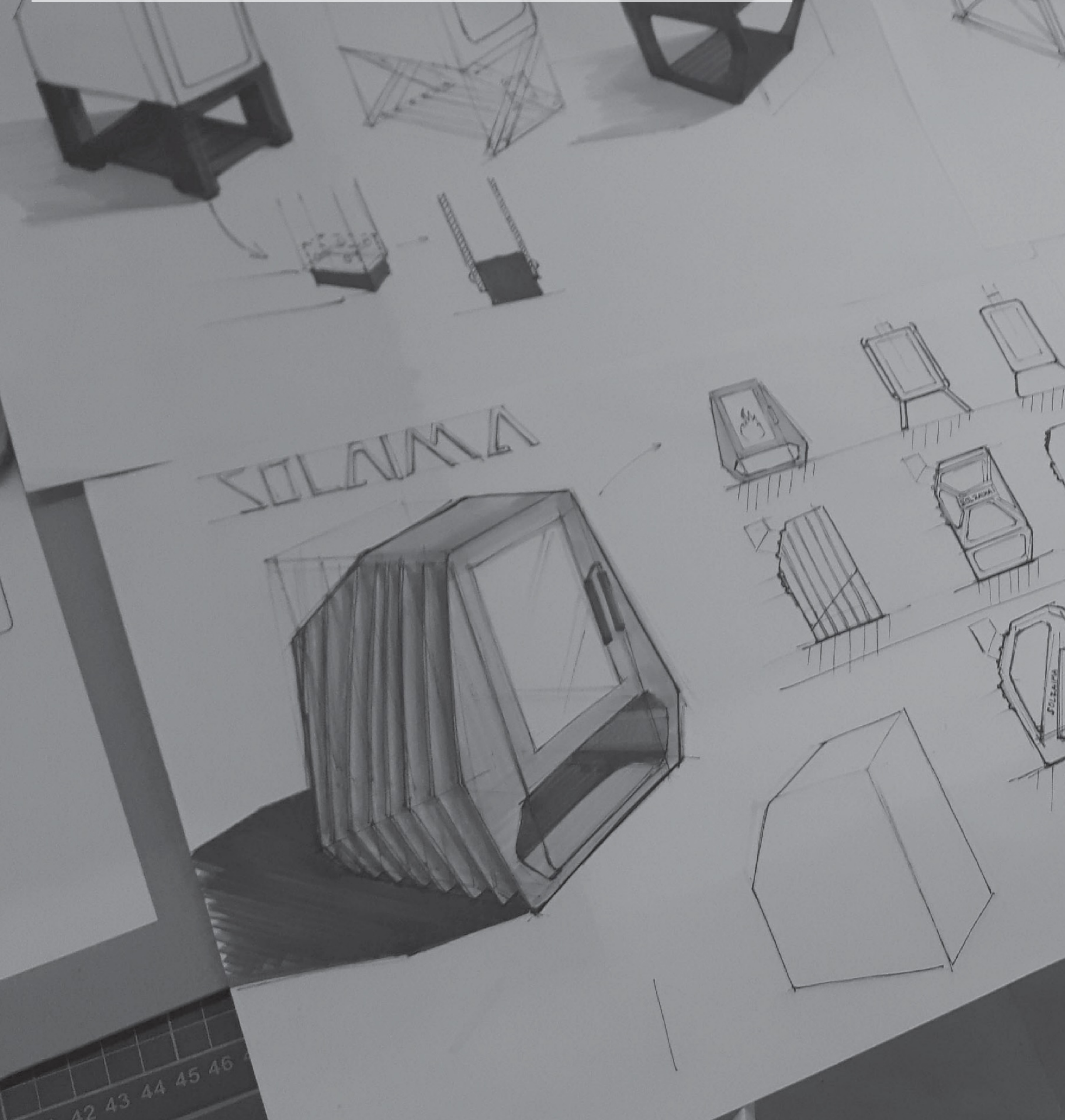
- INNGAGE has only one RP machine and does have other rapid prototyping tools such as laser cutter or CNC milling machines.

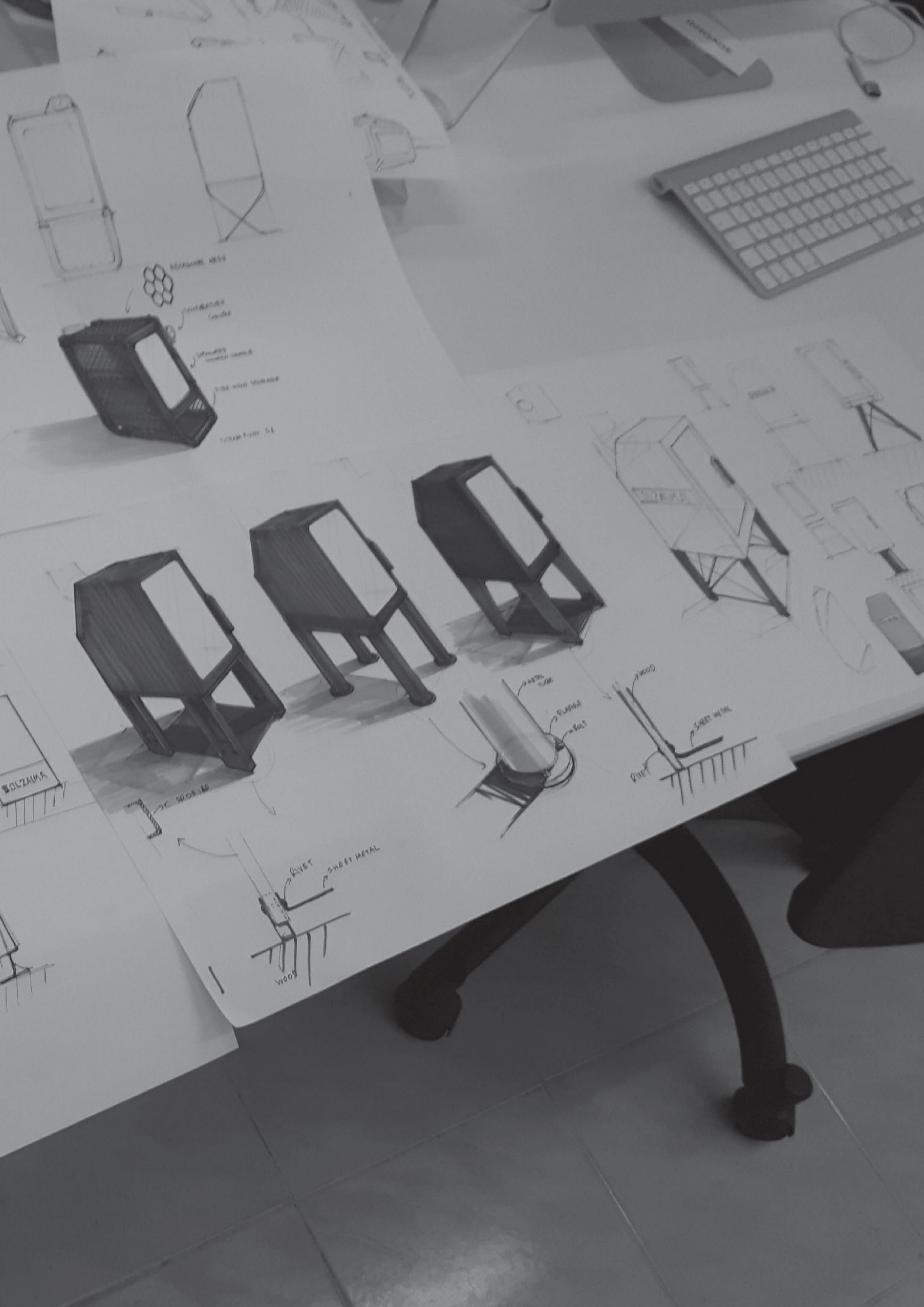
1.7. Beneficiaries

The contribution of this work is expected to add to the existing literature about how and why physical prototyping is important during the product design process. Moreover it will provide an updated overview of the available physical prototyping methods and design methodologies. The results will be useful for design professionals, engineers, researcher and project managers amongst others that are involved in the product design process. Indirectly this work can help professionals that are involved in the product design process in the development of better and more innovative products that address better the user's needs. At personal level this research will consolidate the acquired knowledge and skills during the academic studies by practical application into daily professional design activities. Thus, this experience will facilitate for a smooth transition from the academic environment to the professional environment. Finally, this work will develop further and expand the skills of the author in the field of physical prototyping with different methods and materials. If completed successfully will be used as final work for obtaining a Master's degree in Product Design.

Part 2. Theoretical Contextualization

To get a better understanding of all the areas related to this work a theoretical research was performed in the four main areas that affected this work: design studios, consumer products, design methods and physical prototyping. The results of this research are presented here and support the state-of-art that this work was based on.

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Part II. Theoretical framework

2. Product Design Studios

Since this work was conducted in a design studio it was beneficial to get a better understanding on what is a design studio, what types of design studios exist, what is their structure and how do they work. In the following text some of these questions are answered.

2.1. Design studios a general view

The design studio, drawing office or also known as atelier in French (Atelier, nd) can be defined as a workplace for artists, artisans or designers, engaged in conceiving, designing and developing of new products or objects (Design Studio, n.d).

Design studios is very diverse and broad category of workplaces that make the classification of the different types of design studios difficult. One way to classify is by the number of designers in a design studio that can vary from a single individual to 1000 members. Usually small design studios are held by individuals where large design studios are operated by a corporation (Design Studio, n.d). Design teams tend to be multidisciplinary including industrial designers, communication designer, engineers, researchers and more. Another way is to classify them according to their expertise on a particular field such as communication design, packaging, consumer products, automotive, or medical products. But it is common for design studios to work on a broad range of product sectors. According to Nicol Boyd from OfficeforProductDesign, in the recent years with the emergence of technology start-ups, there is an increasing need for holistic approach to the design services so it is common for product design studios to offer product branding, communication design along their usual industrial design services

The facilities in a design studio usually include work desks, computers, boards for presentations, meeting rooms, machines and other facilities can be present, such as paint shop, prototyping workshops. Good illumination (preferably natural) is an important aspect of the work ambience. The workplace of a design studio is usually decorated informally with items such as sketches prototypes products to promote creativity.

2.1.1. How does a design studio work;

Design studio is more than just a physical space or a work place, the most important is the culture and the spirit in which the designers work is done in a design studio. The design teams are compose by professionals with diverse skill sets such as, design, product management, communication design, engineering amongst other, employing a flat hierarchy with great individual autonomy. According to Evans the workflow in a design studio is usually structured in an **iterative** and **collaborative,** creative manner composing of the following phases: **illumination, sketching, presentation, critique** and **iteration.** The goal of this process is to arrive at a solid design solution in a collaborative setting. (Evans, 2014)

Illumination

In this phase is where the team gains a shared understanding to problem and gathers the insights from the stakeholders, business context, customers, challenges.

Collaborative Ideation

Brainstorming is used to generate as many possible ideas and potential solutions around the problem or project. Fast ideation drawing is used as an efficient tool for to get the ideas on to paper fast, this fast-passed sketching process prevents the attachment to a particular idea or solution. One of the key rules of this process is to withhold any criticism at this phase, all ideas are collected sorted or grouped for similarities. (Kucko et al, 1994)

Critique

Critique in a design studio is different from criticism or evaluation, it moves the process forward through speculation and as well analysis. It is used to select the strong ideas worthy of further development while discarding weak ideas in a safe, positive and friendly environment. Starting for the problem definition and defined at the beginning of the session and focus on the two or three strongest concepts in each sketch addressing the questions, who, how, what and why? (Evans, 2014)

Iteration

Concepts and ideas from each iteration of the design process are extracted, combined and transformed across the team. The participants are encouraged to take feedback from critique and from concepts from other participants. The design process works by incorporating new information as it is introduced along the way.

2.1.2. IDEO Design studio

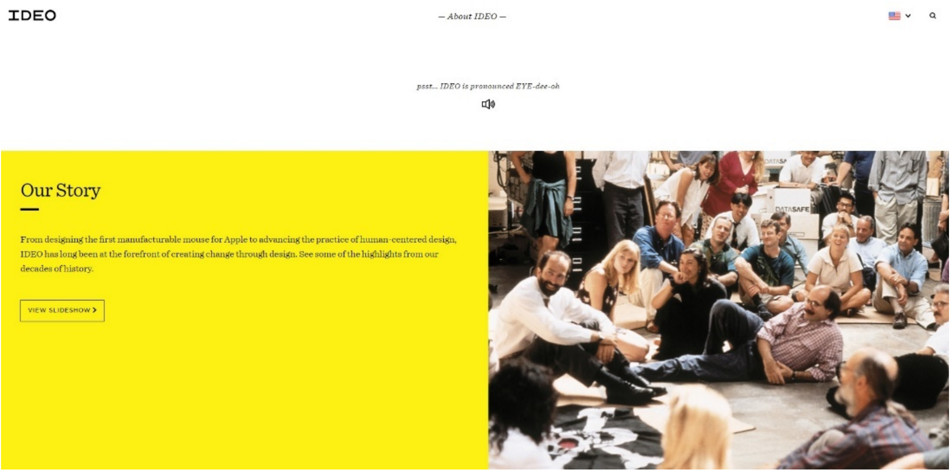


Figure 1: Part of IDEO's website about the firm's history.

IDEO is one of the most well-known and award-winning design firms in the world. The company was founded In 1991, by David Kelley, Bill Moggridge, and Mike Nuttall by merged their companies to form IDEO. (IDEO, n.d) At the moment IDEO is a global design company with design studios in North America, Asia and Europe. The firm employs over 600 people in a number of disciplines including: Behavioral Science, Branding, Business Design, Communication Design, Design Research, Digital Design, Education, Electrical Engineering, Environments Design, Food Science, Healthcare Services, Industrial Design, Interaction Design, Mechanical Engineering, Organizational Design, and Software Engineering (IDEO n.d, Lanoue 2015). The story of IDEO design firm is mostly related with the designing of the first manufacturable mouse for Apple to advancing the practice of human-centered design. Their moto is in creating positive impact through design. IDEO's main principle is empathy for the end-user of their products. There are two important elements for a successful human centered design (HCD) approach according to IDEO ***a) observation,*** of users behavior while using a product or service ***b) empathizing***, understanding users experience and the feelings it elicits (Lanoue 2015). The organizational culture consists of project teams, flat hierarchy, individual autonomy, creativity and socialization of the recruits (IDEO, n.d). IDEO design philosophy focuses on consumer experiences by suing the design thinking methodology to provide design solutions across different industries. Their design services spans in a broad area of products and services including wealth & wellness, digital, mobility, government to name a few. The portfolio of clients and products includes large multinational corporations such as Microsoft, Apple, Hewlett-Packard among others. IDEO has contributed significantly in advancing the Human Centered Design (HCD) approach by applying the design thinking methodology successfully to a wider range of industries makes them undoubtedly one of the most influential design firms in the world.

2.2. Consumer products

Consumer products, consumer goods or merchandise are products that are purchased for consumption by the average consumer. Products can be **tangible** or **intangible** (services). The consumer goods can be further divided into: **durable goods** and **nondurable goods.** Durable goods are consumer goods that have a long life span such as cars, or electrical appliance and can last for several years. Nondurable goods are products with short life spans such as food and drinks. (Products vs. Services, n.d) Although in recent years the diving line between tangible and intangible good tends to blur more and more, and services become more and more tightly integrated into the product creating **ecosystems** rather than just products (Babiolakis, 2016).

2.2.1. Brief Industrial design history

Here a brief presentation of the history of industrial design is attempted covering key moments, people highlighting the pivotal events through the pace of time. It is important to understand the origins of industrial design as a distinct discipline. Since the birth of industrial design is linked to complex social and technological events through history. This historical knowledge of its origins should relate to the practical knowledge of knowing and doing design. (Lees-Maffei & Houze, 2010).

Before the industrial revolution the design, technical expertise and manufacturing of the product was done by the craftsman. So the form of the product was determined by the product's creator at the time of its creation. With the rise of the industrial revolution in Great Britain in the mid-18th century resulted in the industrialization of many consumer products and marks the beginning of the industrial design. Industrial design was one of the byproducts of the industrial revolution along with the terms **capitalism, consumerism** and **division of labor** among others.

Industrial design is a design process applied to products that will be manufactures through techniques of mass production (Heskett, 1980). This meant a great change on how things where made since that the creative act of determining and defining a product's form and features takes place in advance of the physical act of making a product, which consists purely of repeated and automated replication. The term industrial design is attributed to the industrial designer Joseph Claude Sinel in 1919. Christopher Dresser is considered as one of the first industrial designer. Throughout the 20th century, along with balancing the needs of the user and manufacturer, differences in politics and culture were evident in the design of objects. A rising consumer culture in the post-WWII period meant that manufactured goods doubled as a social status representation. Along with regional differences, numerous philosophical and stylistic periods created distinct and recognizable eras within industrial design, including Modernism, Bauhaus school, Art deco, Streamlining, Functionalism and Postmodernism.

In Europe before World War Two one of the most influential art schools in the history of design was founded Staatliches Bauhaus **(1919 to 1933)** commonly known simply as Bauhaus. It had a profound influence upon subsequent developments in **art, architecture, graphic design, interior design, industrial design, and typography.** The school moved to Dessau in 1925, which was an industrial city, this was done so it would be easier to collaborate with the local industry. At that period the school adopted the slogan "Art into Industry." (Winton A., 2016) Bauhaus managed to produce some very iconic and commercially successful products by taking advantage of mass production technologies, creating well designed products for the average people. In contrast to single hand-crafted products, which the workmanship cost made them too expensive for the average people and were considered luxury goods. The Bauhaus designers above all focused in products functionality, "a form derived from the function", as well as the simplicity which does not interfere with human life (Winton 2016)

In USA Henry Dreyfuss and Raymond Loewy two of the most influential industrial designers, with their distinctly different approach to design helped shape America in the post war era. Raymond Lowey (1893-1986) also referred as The Father of Streamlining applied his design philosophy emphasizing on curvy forms with long horizontal lines, in a diverse range of industries. Among some of his notable designs are the streamlining design of the Pennsylvania Railroad locomotives the K4s *#3768* Pacific, the design of the original logos of the Exxon, TWA, BP and the design of the Air Force One livery (Biography, (n.d)).

Henry Dreyfuss (1904-1972) design philosophy was based on applied common sense and scientific principles in his design process to meet user's needs. He was a pioneer in incorporating human factors in the industrial design process. Dreyfuss worked in a wide spectrum of consumer products and the dramatically improved their look, feel, and usability. Some examples of his work including the Western Electric 302 telephone and the Hudson J3 locomotive. His work also contributed considerably in the areas of anthropometry and usability and was the author of books in those subjects. Dreyfuss emphasized that good design is for everyone. (Dreyfuss, 1955).

In the beginning of the 20th century the functionalism movement influenced heavily the industrial design approach and was a common feature of products up to and including the 1980s. One of the pioneers of this movement is the German industrial designer Dieter Rams. His design philosophy has been about achieving purity in design through reduction and restrain. His design are characterized by a restrain in the amount of language used to label knobs and switches, his designs rely on shapes, colors and information graphics to communicate to the user the product's function, in an intuitive manner. Rams designed simple, iconic products for German household appliance company Braun for over 40 years, where he served as the Chief Design Officer. His understated approach and principle of "less but better" resulted in products with a timeless and universal nature. (Functionalism, n.d) Part of Rams's enduring legacy is his ten principles for good design which are rooted in his deep industrial design experience and remain relevant until now. (King & Chang, 2016)

In the late 20thcentury a new movement in architecture, art and design was developed as the response on simplicity and rationality of modernism, this movement was named Postmodernism. The main reason for the creation of this new movement in design was that the user didn't want to live in austere environment forced by the functionalism movement in design. This style took inspiration from older historical styles and mixed them to create the new style. In this movement the design took in to consideration the body, mind and the soul of the user creating objects with decorative elements (Winston 2015).

Over the relatively short history of product design a lot of stylistic trends have come and passed, and the discipline of product design has matured considerably. From being perceived as purely aesthetic or ergonomics to become more as form of problem solving and way of thinking. Product design is more and more integrated to the whole product development process from the first stages along the whole process of product development until the product or service it reaches the market.

2.2.2. Human Centered Design (HCD)

For creating successful and innovative solutions three main aspects must be considered according to Tim Brown from IDEO, people's needs, technology and business requirements, these factors must all be considered before concluding to the desired solution. Norman states that the designed solution besides meeting ergonomics, engineering and manufacturing requirements, the user must understand the product, and if possible, enjoy the whole experience. This approach is known as human centered design HCD were human needs, capabilities, behavior, culture are put in the center of the design process in order to designs solutions to accommodate those needs (Human Centered Design, n.d.). Many researchers agree that for the development of successful product and services the HCD is the best approach (Norman. 2015, Brown n.d).

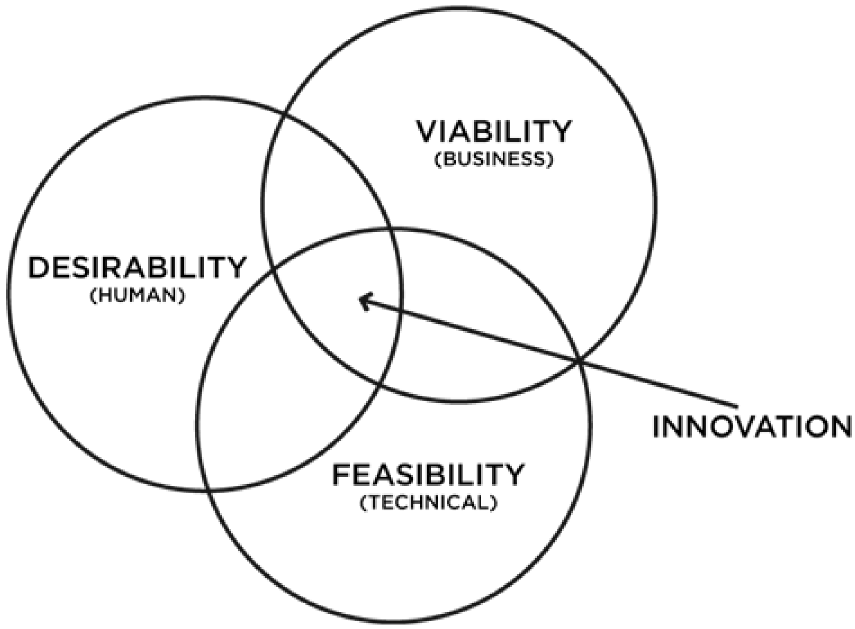


Figure 2: The triad of factor for a successful product, based on the design thinking, a human center design (HCD) approach by IDEO. (Brown, n.d.)

How can the user center approach be implemented;

HCD ensures that the design matches the needs and capabilities of the people for whom they are intended. The process starts with good understanding/empathizing with people and their needs. The definition of the user needs is the most difficult part in every project. When using the empathetic design approach observation is the preferred tool to understand and define the user's needs. This is done because most of the time people are not even conscious of their struggles that are encountering. Observation is preferred instead of questionnaires or traditional market research to avoid bias or false information. By utilizing this approach, the designer can come up with solutions that truly address the problems and needs of the user that couldn't come up by simply asking them what they need. This happens because the users might not be aware what they desire, or it is difficult for the user to envision a particular solution. This can be due to lack of familiarity with new technology or due to old mindset. "*A lot of times, people don't know what they want until you show it to them.*" (Steve Jobs)

Design for Behavior, Emotional Design

The dogma *"form follows function"* in design was highly accepted in the design industry in the beginnings of the 20th century with the functionalism design movement that rejected the incorporation of an emotional dynamic in the design (Functionalism, 2010). In contrast the Emotional design acknowledges the importance of emotions that a product elicits and how can strongly influence users' perceptions of it. In human life emotions play a central role and affects the way of living and decision-making process. This approach to design strives to create products that create appropriate emotions, to give a positive experience for the user (Emotional Design, n.d). For example, the sound that a car door does when it closes is a subject of a careful engineering and design to generate the appropriate sound, that will elicit the appropriate emotion. A door for a sedan might be engineered to sound more robust to communicate safety whereas the door of coupe might be engineered to sound more light and sporty. (Boeriu, 2014)

How does the mechanism of emotions work;

The approach is based on a basic model of emotion in design the key variables that elicit emotions are **concerns** and **appraisal** (Desmet, 2003). Humans form emotional connections with objects on three levels: the **visceral, behavioral** and **reflective levels**. A designer should address the human cognitive ability at each level—to elicit appropriate emotions to provide a positive experience (Norman 2007), **Visceral** emotional design appeals to the first reactions when a user encounters a product. It mainly deals with aesthetics and the perceived quality from mere look and feel, and the engagement of the senses.

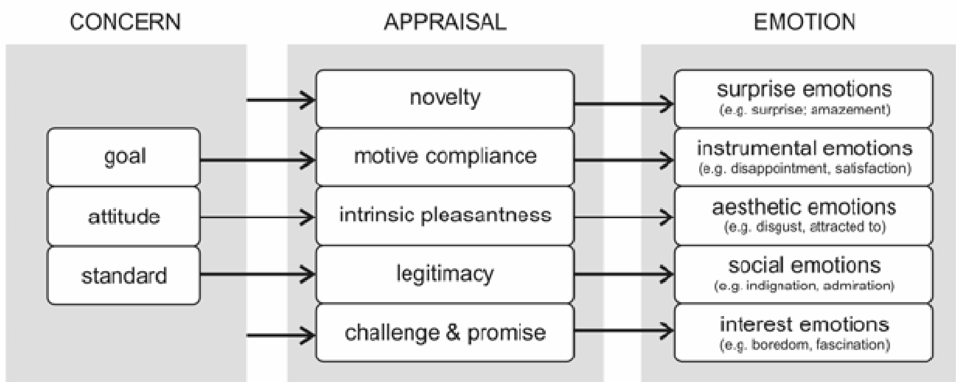


Figure 3: The classification of product emotions (Desmet, 2003)

Behavioral emotional design refers to the usability of the product. It is the assessment of how well it performs how it performs the required functions, and how easy it is to use it. By this stage, the user forms a more justified opinion of the item. **Reflective** emotional design is concerned with the ability to project the product's impact on the user's life. The values attached to the product in retrospect. In this layer of emotion, the designers can maximize the users' desire to own that item.

How emotions effect the user experience;

The human brain works by doing connections between neurons, neurotransmitters change how neurons transmit neural impulses from one nerve cell to another. Most importantly the affective state, whether positive or negative affect change how we think. When a person is at a state of negative effect, feeling anxious or endangered, the neurotransmitters focuses and hinders the brain's processing power. This response is tightly connected with survival and dangerous situations thus this kind of alertness focuses upon the problem and it's details rather than solutions. In contrary when in a state of positive affect, other kind of neurotransmitters broaden the brain's processing, relaxes the muscles and makes the brain more receptive to new ideas or events. This means that when the user is at a pleasant mood is far more likely to overlook and don't bother with minor problems or flaws of the product. (Norman 2007) By following this design approach a product will not only fulfil its functionality, but also evoke strong positive emotions through the entire experience.

2.3. Design methods & New Product development (NPD)

In the following text is presented a broad range of design and product development methods developed over the years. This list includes a broad selection of methods, some of them where originally developed for systems engineering, stock management or for the IT sector. This is done to get a general view of design methods by understanding the similarities or differences by comparing them. By doing so the designer can consciously decide which method suits best according to the particular project, resources, team or personal preference to adopt for the product design process.

Introduction

The main tasks of design methodology are to indicate how design process should be arranged so that they lead to reliable, effective and efficient conclusions (Roozenburg and Eekels, 1995). Project management is the discipline of initiating, planning, executing, controlling, and closing the work of a team to achieve specific goals and meet specific success criteria. New product development (NPD) process is the sequence of steps or activities that an enterprise employs to conceive, design, and commercialize a product (Bhuiyan, 2011). During our work we have considered different approaches to design and NPD process.

Waterfall model

The waterfall model of project management is a linear sequential (non-iterative) design approach for software development, in which progress flows in one direction downwards (like a waterfall) through the phases of conception, initiation, analysis, design, construction, testing, deployment and maintenance. (Benington, 1956). This model originated in the manufacturing and construction industries in which after the investment in a particular solution the changes are impossible or at least prohibitively expensive.

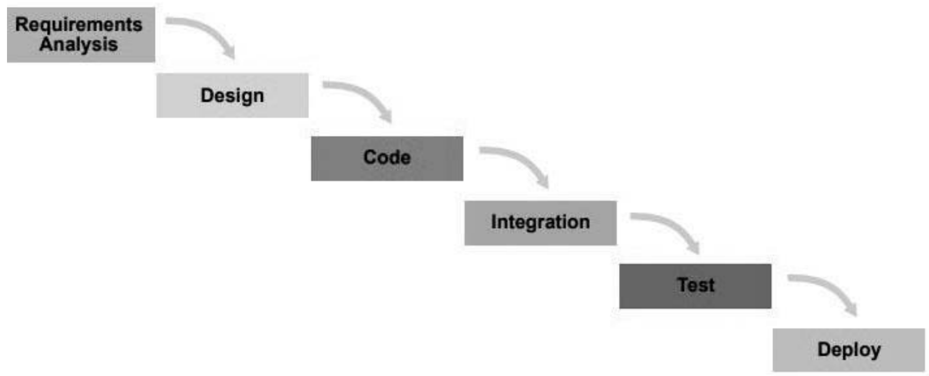


Figure 4:The Waterfall systems engineering model (TechiJunk, n/d)

BAH model

One of the best well known NPD models was developed in 1982 by Booz, Allen and Hamilton known as the BAH model. his model represents the foundation of all the other models that have been developed afterwards. The seven steps of BAH model are new product strategy, idea generation, screening and evaluation, business analysis, development, testing, and commercialization.

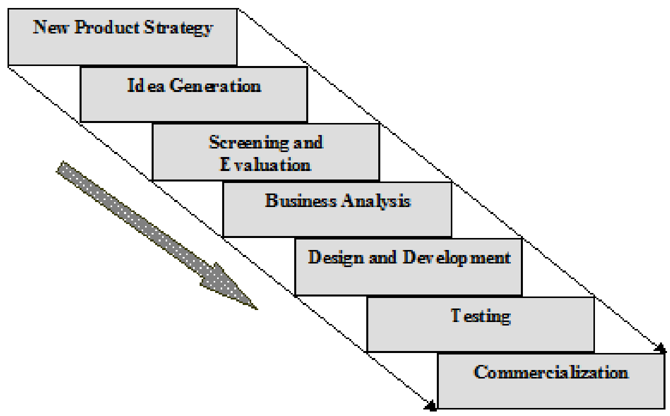


Figure 5:Stages of New Product Development (NPD) (Booz, Allen & Hamilton, 1982)

The "V" model

The "V"-Model can be traced as a refinement of the original Waterfall model. Since its first conception and development in the 1980s, the "V" model has been refined and applied in many different industries. It is based on the same steps, but in different order, and have processes happening at the same time, providing feedback. Worldwide, there are several different versions and interpretations of this model. (National ITS Architecture Team, 2007).

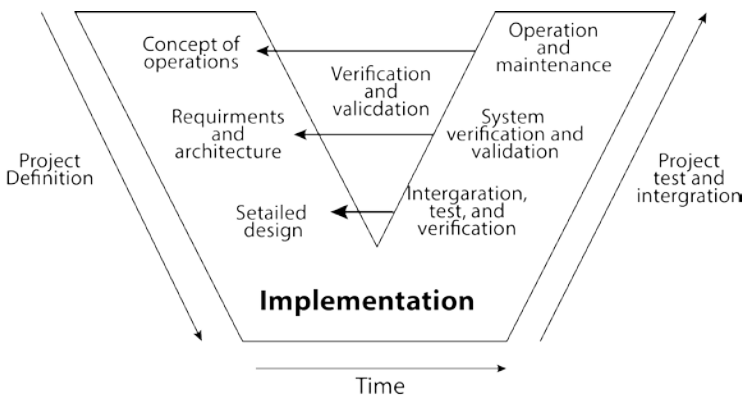


Figure 6:The V project management model framework (National ITS Architecture Team, 2007)

Problem solving

The design process is mainly conceived as a form of problem solving, and an empirical cycle is the basic model for problem solving (Roozenburg & Eekels , 1995) (Figure 4).

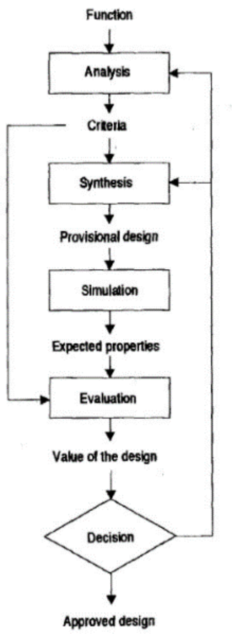


Figure 7:Roozemburg & Eekels model (1995)

Pahl and Beitz

Is one of the most popular models for structuring the product development process also considered as the bible of product design methods. It was originally developed for the development of industrial machinery in 1977 but has been adopted widely by many industries. In this method the design process and problems are worked in different levels of abstraction. Pahl et al. (2007) and VDI (Verein Deutscher Ingenieure) (Figures 8).

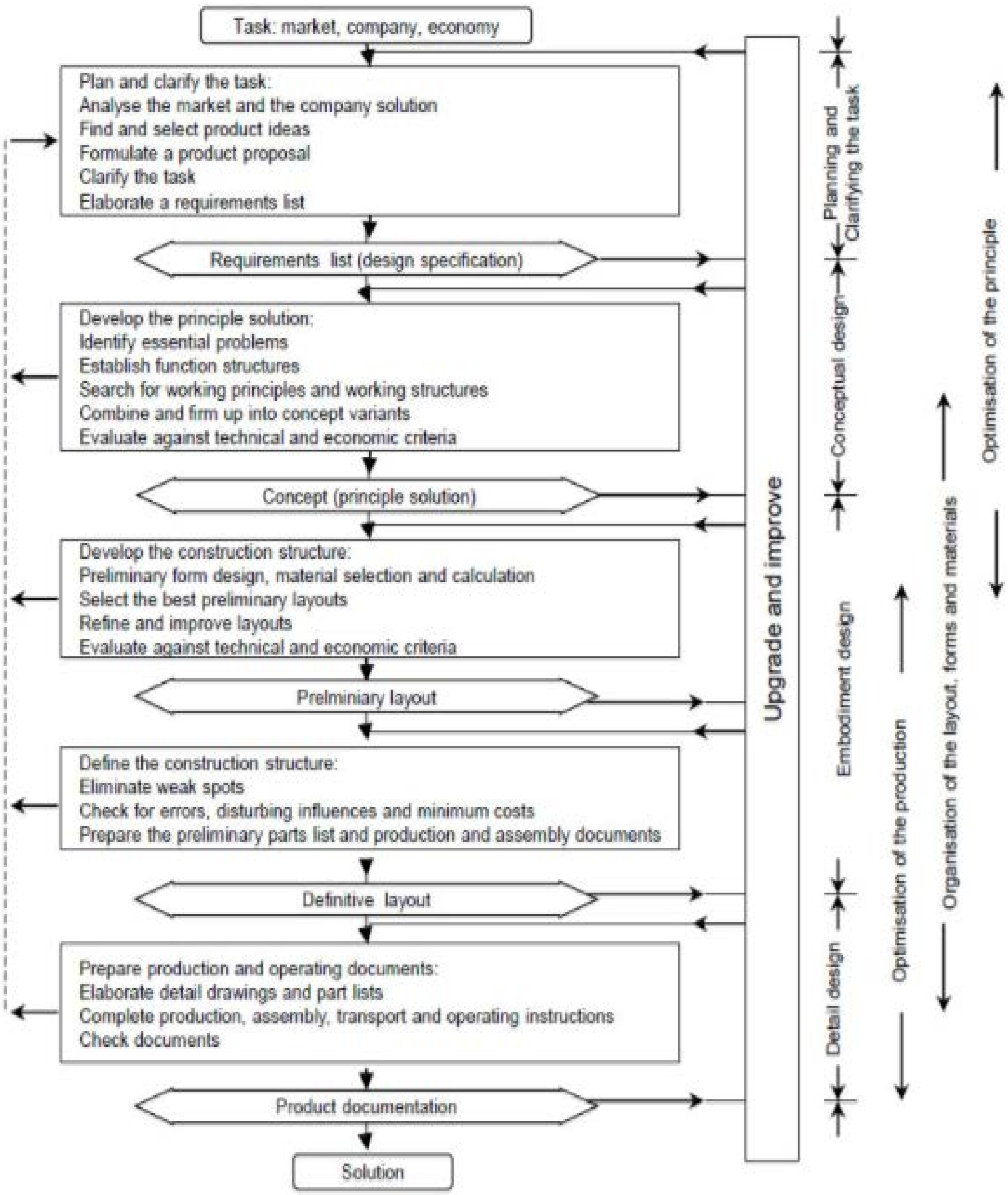


Figure 8: Engineering Design. A Systematic Approach. (Pahl, G. et al, 1988)

Phase model of product development process

In this method the product design and product development process is marketing plan is worked out. The purpose of these model is to design not only a product but a whole new business development plan (Figure 9).

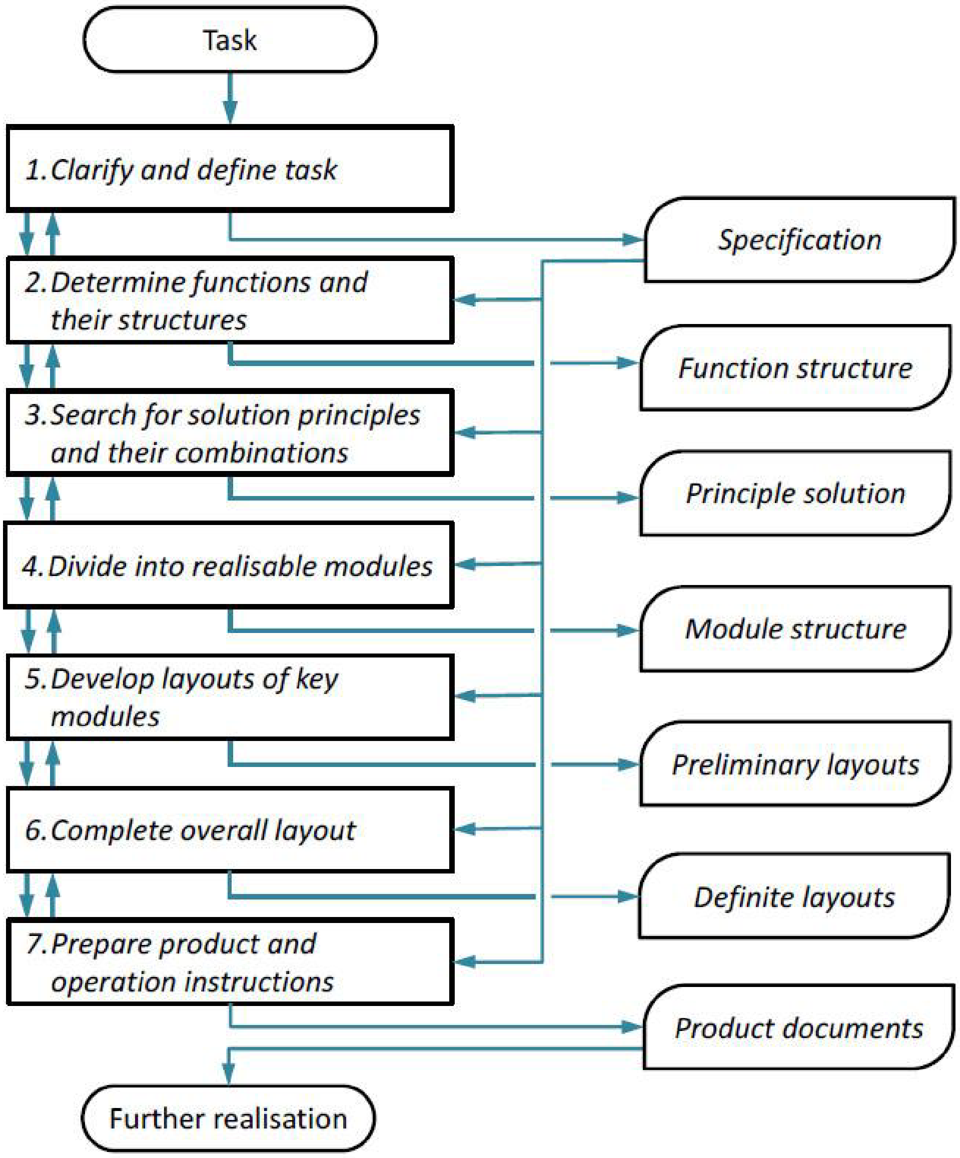


Figure 9:VDI Guideline 2221 – Systematic design approach

The generic product phase model

Ulrich & Eppinger (2012) present a linear product design method, beginning with a wide set of alternative concepts and then the subsequent narrowing, in a process of increasing specification of the product until the it can be reliably and repeatedly produced by the production system (Figure 10). Most of the phases of development are defined in terms of the development state of the product.

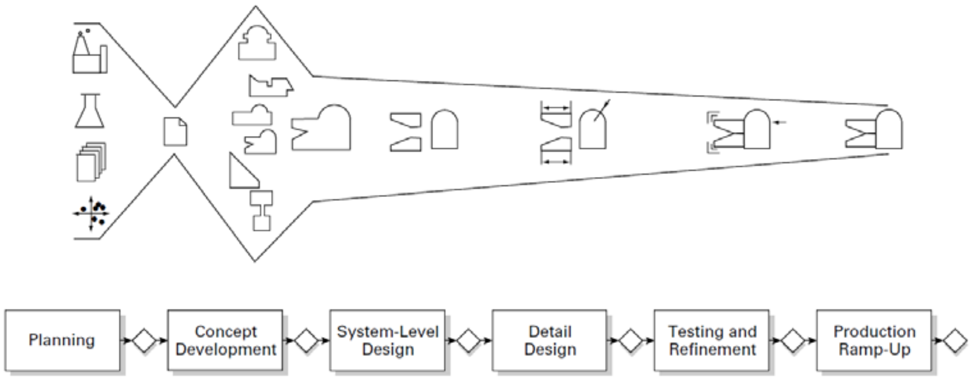


Figure 10: The generic product phase model development process according to Ulrich & Eppinger (2012)

Those authors also presented a method where the product design and product development process are well related with the marketing plan, as a purpose to design not only a product but a whole new business development plan (Figure 11).

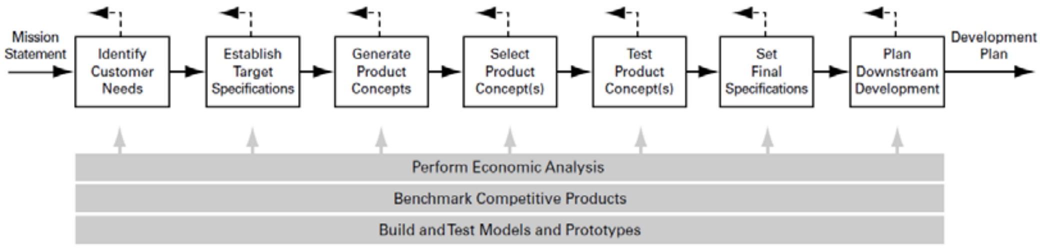


Figure 11:The front-end activities comprising the concept development phase Ulrich & Eppinger (2012)

Design Thinking

Herbert Simon (1969) outlined the design thinking concept as a highly iterative process in which the objective is to understand the user and challenge early in the design process while redefining the problem along the design process. IDEO, one of the most successful and world-renowned design studios, was one of the pioneers in implementing this HCD approach to generate innovative solutions (Brown,2009). In this approach it is encouraged to iterate, prototype and test as much as possible, to come up with solutions and strategies that are not apparent in the early stages of the design process due to the limited initial level of understanding. As a result, design thinking is mostly useful for tackling unknown or ill-defined problems. It involves five phases:

Empathize, Define, Ideate, Prototype, and **Test** (figure 12).

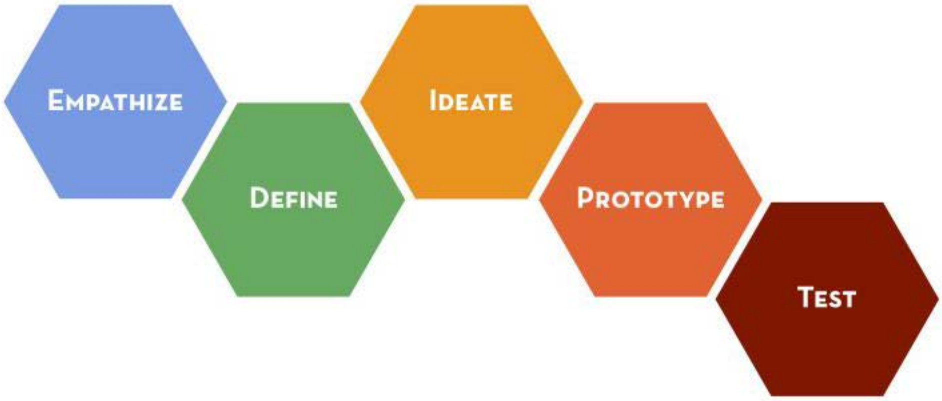


Figure 12:The design thinking processes visualized

Physical Prototyping (PP) is considered as an integral part of design thinking method because it allows ideas to be tested quickly and based on the results to improve on them. As Both et al. (2016) refers «bias towards action», in the design thinking approach building and testing, is more valued over thinking and elaborating. Design thinking provides a more intuitive and less rigid structure to the design process and encourages the designer to iterate, without pre-defining which activities or objectives should be completed before moving to the next step. Physical prototyping plays a key role in this approach, so ideas can be tested fast and assist in the iterative development of the process from problem to the solution. Nowadays where there is a shift from design of product to product ecosystems as a result problems become more complex and less defined coming up with the appropriate solution more flexible design methodologies are better suitable to tackle these challenges (Babiolakis, 2016).

Agile

Agile development origin can be traced a set of computer programming methodologies that emphasize flexibility, collaboration, efficiency, simplicity, and most of all, delivering working product to end users within short time frames (Andriyani et al., 2017; Shastri et al., 2017). Since its formal inception it has been widely adopted across diverse business sectors such as aerospace, manufacturing, finance, medicine, and education (Presley et al., 1995).

Traditionally, software development processes have relied on the use of the "Waterfall" and "Vee" models. Later, Agile methodologies were used to handle the challenges of managing complex projects during the development phase. Agile methodologies are a group of incremental and iterative methods that are more effective, and have been used in project management. Kanban and Scrum softwares are two Agile project management approaches mostly used in the software development world (see their evaluation in Marschall, 2015)

The development of Agile can be better described as a set of values, can be tracked back to 1957 in the field of the incremental and iterative software development methods. During the 1990s a number of lightweight software development methods evolved in reaction to the prevailing heavyweight methods in the software development world. Similar change and philosophy towards more flexible and shorter procedure where happening in the manufacturing and aerospace industry. (Presley et al., 1995)

A Manifesto for Agile Software Development was published in 2001 (Beck et al., 2001) and their main sets of values are the following:

- Individuals and Interactions more than processes and tools
- Working Software more than comprehensive documentation
- Customer Collaboration more than contract negotiation
- Responding to Change more than following a plan

While the secondary concerns are important the primary concerns are more critical to success.

Scrum

Is an implementation of Agile management framework for incremental product development using one or more small self-organizing teams. The objective of Scrum is achieved by optimizing the development process by identifying the tasks, managing time more effectively, and setting-up teams.

Scrum uses short fixed-length iterations (figure 13), called Sprints. At the end of each Sprint a potentially releasable product is produced. Scrum sets a structure of roles, artefacts and ceremonies. Teams are responsible for creating and adapting their processes within this framework (Marschall 2015, James & Walker 2014)

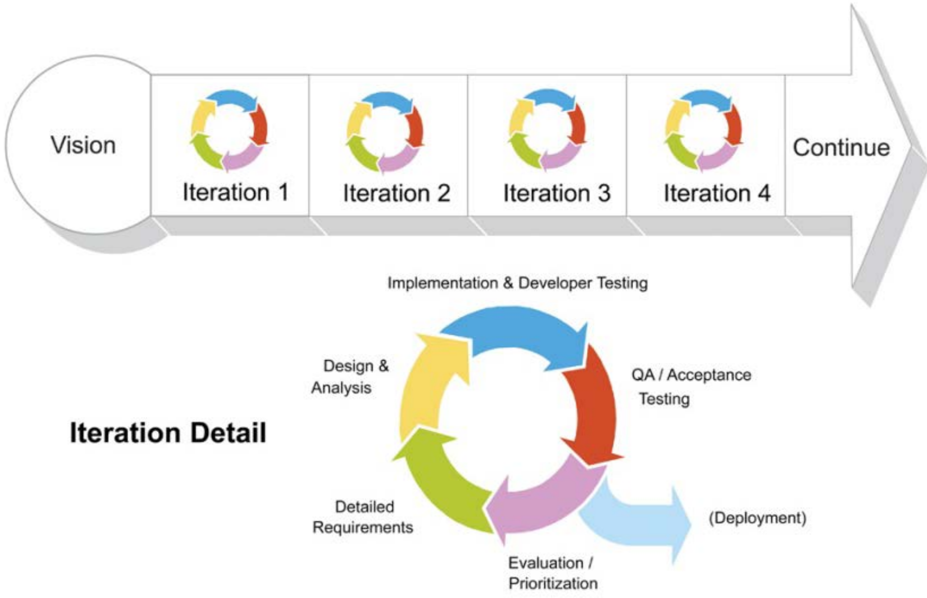


Figure 13: Scrum iterative project development process (James & Walker 2014).

Kanban

Kanban is a lean scheduling system that was developed in Japan by the Toyota motor corporation. Kanban literally means signboard or billboard in Japanese, and originally was developed as an inventory control system to control the supply chain. As a project management system, it utilizes a system of card that includes visual cues of what to produce, how much to produce and when to produce it (Ohno, 1988), as a method to achieve just in time manufacturing (JIT).

Kanban framework consists uses a board to keep track of the work progress divided in workflow steps e.g. new, in progress and completed. The cards or task move from left to right in a steady flow. Kanban imposes limits on the number of items that can be in any workflow step at any given moment. These are set in order that work moves as smoothly as possible, make visible and easy where are the bottlenecks in the progress. When a bottleneck occurs, other team members can help on the workload and focus their effort on resolving this problem before moving on to other tasks. This helps teamwork and collaboration helps tasks to be completed on time and eliminating task switching. Kanban has been implemented and widely adopted in fields such as in IT and software development and manufacturing (Ohno, 1988).

2.3.1. Summary of the design process methods

The purpose of a design method is to structure the design process, so it arrives in good and reliable solutions. Over the years many design methods have been developed, most of them are "borrowed" from systems engineering design such as the famous Pahl & Beitz methodology. Some design methods define in detail each design step, the order to be executed and what must be completed in each step before moving forward, (e.g. waterfall model). Some other methods use a more abstract design approach such as the Design thinking method. Here the design activity is divided into logical steps, but strict rules are not made, on what must be completed in each step or which must be the next step. Moreover, the designer is encouraged to iterate instead of elaborating and analyzing. We can observe a steady evolution of the design methods in all fields to adopt a less defined structure (can be better described as a way of thinking or values) and adopt a more iterative approach to the design process. (e.g. Design thinking, Agile). Other methods such as the Scrum and Kanban incorporate time management and team management tools to make group work more efficient.

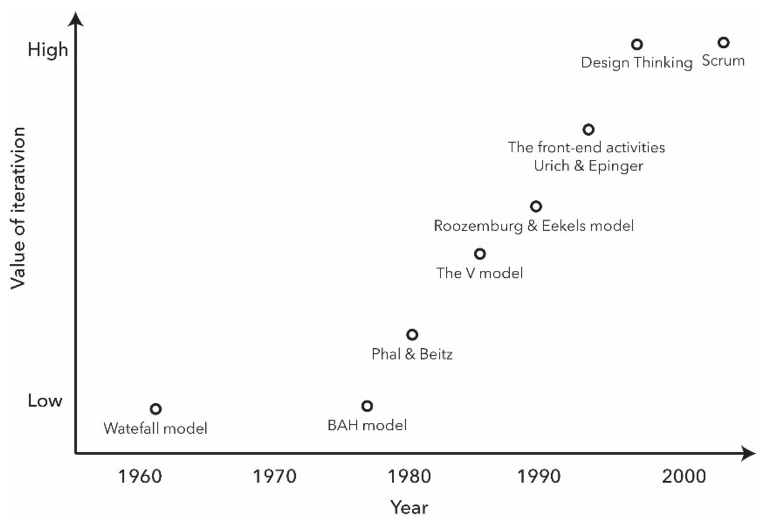


Figure 14: Design methods arranged according to the time period that were introduced and the importance they give, on iterations within the design process.

2.4. Physical prototyping and modelmaking in the Design Process

The word prototype derives from the Greek word πρωτότυπος (prototypes), meaning «original, primitive», deriving from πρῶτος (protos), «first», and τύπος (typos), «impression. According to Bjarke (2016) the term physical prototype and model can be used interchangeably to describe a preliminary three-dimensional representation of a product, service or system. But the process of prototyping and modelmaking describe different things. Prototyping is described as the design method that uses physical prototypes to study how a product will work, look, feel, and function. The term modelmaking is described as a step by step method of creating physical prototypes.

2.4.1. The use-purpose of physical-prototypes (PP)

Learning and cognitive benefits

According to Ulrich & Eppinger (2012), prototypes are often used to answer two types of questions: «Will it work? » and «How well does it meet the customer needs? ». Answer such questions, prototypes serve as learning tools. Design work is a complicated activity that stresses the finite cognitive abilities such as goal maintenance, memory, focused attention, and so on. Taking in account such cognitive burdens, many artists and designers reduce their mental workload with iterative models or prototypes that store current ideas, evolving as the design process unfolds (Goldschmidt, 1995). Creating physical prototypes (PP) increases the mental and physical representation of ideas, and may ease the burdens of the limited cognitive system of the designer (Youmans, 2011).

Physical prototyping is used as a tool to generate innovative solutions. One of the main obstacles of innovation is the unconsciously repeating of pre-existing solutions, which is known as design fixation. It is defined as a blind adherence to a set of ideas or concepts of the past. Fixation limits a designer’s creative thoughts at the early stages of the design process, limiting the output of the conceptual process. The value of prototyping is that it is proven that to can be a contribution to overcome design fixation (Youmans & Arciszewski, 2014).

Communication

As Kelly (2001) has stated "if a picture tells a thousand words a prototype is worth a thousand images". PP are one of the best mediums to facilitate the communication between stakeholders: top management, vendor, partners, team members. communication among engineers, managers, suppliers, and customers. Where insights can be acquired and help make decisions.

Integration

According to Ulrich and Eppinger (2012) physical prototypes are used to ensure that components and subsystems of the product work together as expected. Comprehensive physical prototypes are the most effective as integration tools in product development projects.

What kind of prototypes and how are they used in the design process?

Physical prototypes can be divided into four main categories based on designers usual practice and are meant serve different purpose in the design process. Table 1

Soft model	Hard model	Presentation model	Prototype
-Rough modeling assess the overall size, -Proportions and shape -Fast evaluate of many different designs -Constructed usually from foam -Reshape and refine by hand	-Technical non-functional yet are close replicas of the final design very realistic look and feel -Made from wood, dense foam, plastic, or metal, painted, and textured -Have some "working" features	-Model that is constructed and matched from CAD data or control drawing -Complete model and fully detailed composition of product -Component of this model will be simplified or neglected due to cost ot time shortages	-High-quality model or functioning product that is produced to realize a design solution -Would be tested and evaluated before the product is considered for production

Table 1: Classifications of models and prototypes (Isa, 2014)

Soft Models

The purpose of soft models is to represent roughly quick and accurate dimensions and proportions of the concept. Suitable materials for this phase are easy to shape and form mannually, such as dense sculpting foam, cardboard, etc. At this stage, the design is reshaped and refined by hand. Soft models help the designer to refine the idea and identify the design direction (Figure 15).

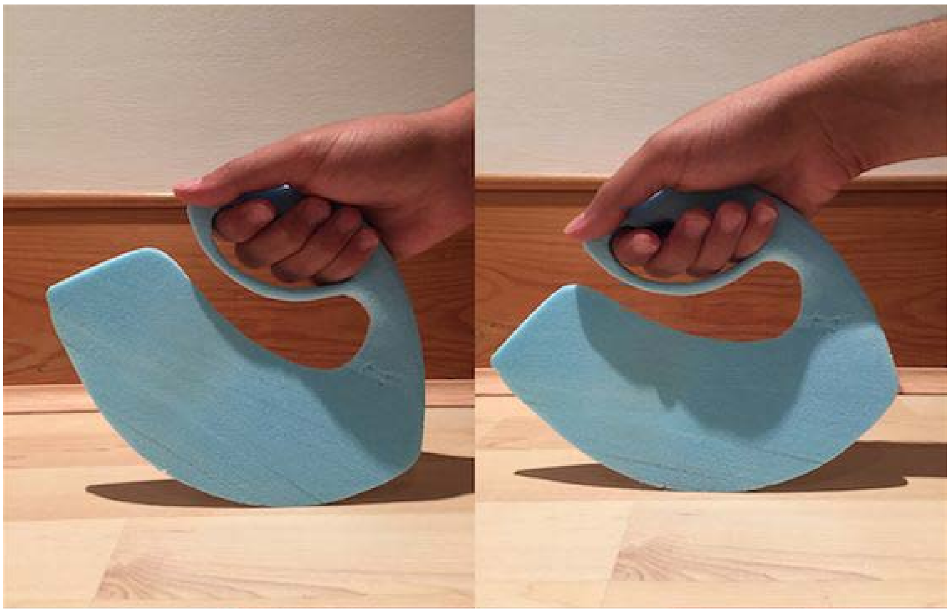


Figure 15: Soft model from sculpting foam of a kitchen utensil (Yemi, n/d)

Hard Models

Are further defined than the soft models but still nonfunctional, but can have some working features. Hard models are more accurate replicas of the final design in terms of appearance. Materials used for hard model are normally wood, dense foam, plastic, or metal. These models can be used for user testing, to better communicate with other stakeholders. Figure 15 hard model was used to communicate to early customers the physical size of the PackBot and the range of mobility of its camera support arm. Constructed from components using stereolithography technology, it was assembled and painted to represent the actual size and appearance of the product. (Ulrich & Eppinger, 2012)

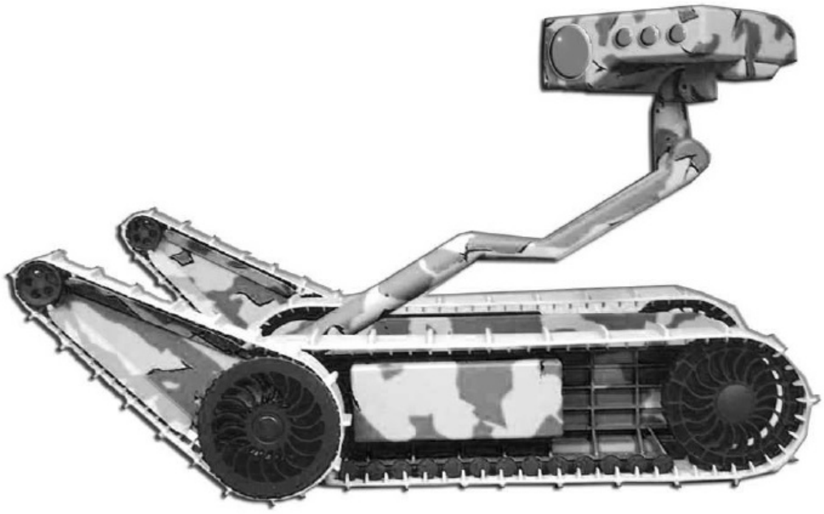


Figure 16: PackBot hard model (Ulrich & Eppinger, 2012)

Presentation Models

A presentation model is considered to be the exact image and detailing of the final product. The prototype is usually constructed from the CAD model data or from detailed drawings. Techniques used for presentation models can be rapid prototyping, 3D printing, CNC milling, amongst other. This is very important to facilitate the communication between the design and the stakeholder at the final stages of decision making (Shimizu et al., 1991).

Prototype Models

They are high-quality models or functioning products that are produced to realize a design solution, being tested and evaluated before the product is considered for production. A prototype in today's reality is constructed from CAD data and exhibits a high level of functionality. Prototypes are expected to have exact or similar representation of the final product in terms of materials, construction, functionality and appearance (Evan & Pos, 2004).

2.4.2. The impact of prototypes during the design process

The economic impact of different types of prototypes during different phases of the product design process (Figure 17). The designer should be aware of the cost of making changes during the different stages of product development.

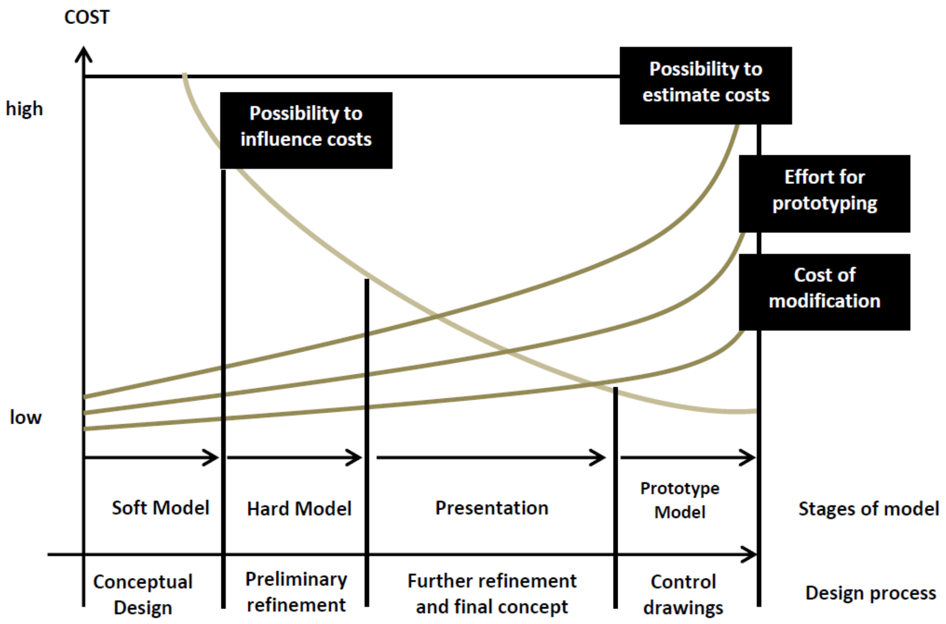


Figure 17: Costs and prototyping (Ehrlenspiel et al. , 2007)

According to Ehrlenspiel et al. (2007), the cost of making changes in the beginning of the process are minimal, but changes towards the final later stages increase exponentially. According to Isa & Liem (2014), the designer should use physical models extensively and as early as possible. They underline the importance of using of soft models as a tool, in the early design stages, to ideate and find the correct design solution, which leads to a more cost-effective product development process.

2.4.3. Physical prototyping and modelmaking

There is a basic workflow that is followed to create physical prototypes (Bjarki, 2016) presented in this (Figure 18).

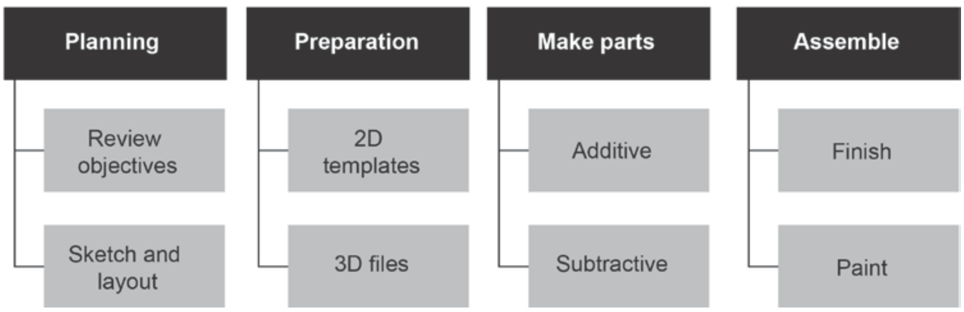


Figure 18: Basic modelmaking workflow (Bjarki, 2016)

Planning

Is the first step in the model making workflow. In this step, the prototyping and modelmaking objectives are defined. The fidelity of the prototype depends to the project development phase. The second task is to plan what parts are going to be made, from what material and how. For the early models usually there is only a single material that is used and rough sketches serve the purpose since the design will be worked out more or less in the «fly». For more advanced prototypes such as presentation models there is the need for more detailed drawings and there is a use of multiple materials.

Preparation

The use of 2D drawing or 3D models is usual in this phase. 2D drawing can be printed in paper and used as a pattern for the creation of the prototype by hand. (Bjarke, 2016). Or the prototypes can be created directly from the 3D data of the digital model. In this case the model is converted with in the CAD software to STL or IGES which are the industry's standard for manufacturing. Depending the fabrication method such as additive (3D printing) or subtractive (CNC milling) is generated the machine code or also known as g-code.

Making of parts

Is the process of forming material to the desired shape of the intended design. Different methods can be chosen, and there are three fundamental fabrication processes, according to Chua & Leong (2017): subtractive, such as milling, additive (3d printing), and formative, such as bending and molding, or combination of any of these, known as hybrid manufacturing. The process can be automated or manual. Automated procedures are known as computer numerical control (CNC). Automated fabrication has an increasing influence in the modelmaking procedure, dramatically reducing the time required. But according to Bjarki (2016), this doesn't result that hand making of parts is becoming obsolete. There is commonly a mix of handmade parts and rapid prototyping parts.

Assembly

The final step of the modelmaking workflow is assembly. In this step, it has to be considered the purpose of the constructed prototype. A functional prototype that is created to test a specific aspect of the design might not require painting. Where as a presentation prototype would need to have an appearance as close as the intended final product.

2.4.4. Fundamentals of Fabrication Process

Modelmaking and prototype fabrication use some kind of fabrication processes, as such it is important to understand the fundamentals of fabrication process. According to Chua & Leong (2017), we can consider three fundamental fabrication processes: **subtractive, additive** and **formative** (figure 19).

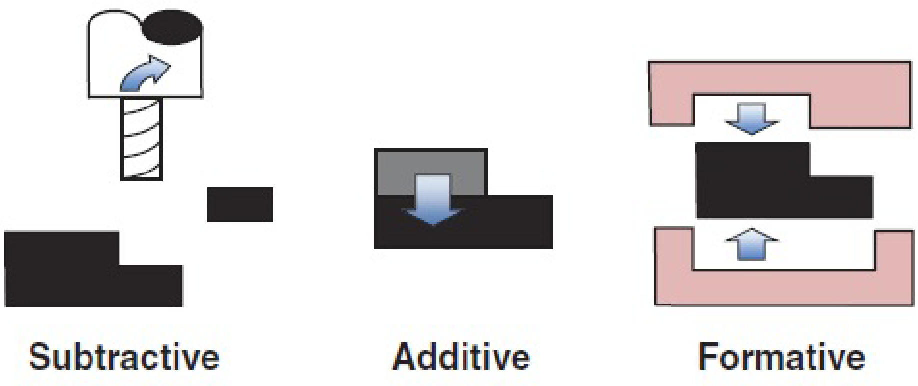


Figure 19: Types of fabrication process (Chua & Leong, 2017)

Subtractive methods

This is the most well-known fabrication method were the process starts with a block of material larger than the final object thus the term subtractive or decremental. Portions of the material are removed until the desired shape is reached. These include milling turning drilling, sawing, grinding, electric discharge machining (EDM), laser cutting, waterjet cutting.

Additive methods

In contrast to subtractive manufacturing, additive or incremental process is the exact reverse procedure. Additive or incremental manufacturing according to Verlinden et al. (2003) is more well know as part of the rapid prototyping technologies and has increasing popularity in fabrication process since its conception in the 80s. In additive manufacturing material, it is added layer upon layer to create the object. No matter the type of additive method, all of them utilize this concept of 2D layers built on top of each other to form a final 3D object. It is apparent that one of the key factors affecting the quality of the produced objects by this method is the height of each layer that the object is built.

Formative methods

One of the most widely used and common forming fabrication method is injection molding. Other examples of formative methods include bending, water pressure forming and electromagnetic forming amongst other.

2.4.5. Rapid Prototyping (RP)

Rapid prototyping (RP) is one of the most recent methods of prototyping, introduced in the late 1980s, and still developing rapidly. According to Verlinden et al. (2003), RP can be referred as a process to create physical forms based on digital technology in an automated manner. More than 30 different techniques of RP have been developed and commercialized (Chua, Leong, 2017). Nowadays, the term is often used in a vague manner to describe mostly additive manufacturing technologies.

Rapid Prototyping is classified under three categories: **incremental, decremental** and **hybrid technologies** (Verlinden et al., 2003). **Incremental** prototyping, is when the object is being built by adding material in a controlled manner so that a desired shape is formed (3D printing). **Decremental** prototyping is a process where material is being removed from a stock of raw material to create the desire object: for example, CNC milling. **Hybrid technologies** is defined when both manufacturing methods decremental and incremental are used to produce a part (Verlinden et al., 2003). In this sense, AM should be considered as a part of RP technologies.

2.4.6. Additive Manufacturing (AM) technologies

The beginnings of AM technologies

In 1983 Chuck Hull invented the first 3D printing process called 'stereolithography' in 1983 (Figure 20). In a patent, he defined stereolithography as 'a method and apparatus for making solid objects by successively "printing" thin layers of the ultraviolet curable material one on top of the other'. Later he founded 3D system and in 1987 the first commercial AM system, stereolithography apparatus (SLA), was launched by 3D systems in United States. It worked on the principle of stereolithography (STL) and for the first time enabled users to generate physical objects from digital data in an incremental/additive method. The invention of AM was a fundamental break-through in the manufacturing world due to it produced tremendous time saving in the fabrication of complicated and difficult to produce models.

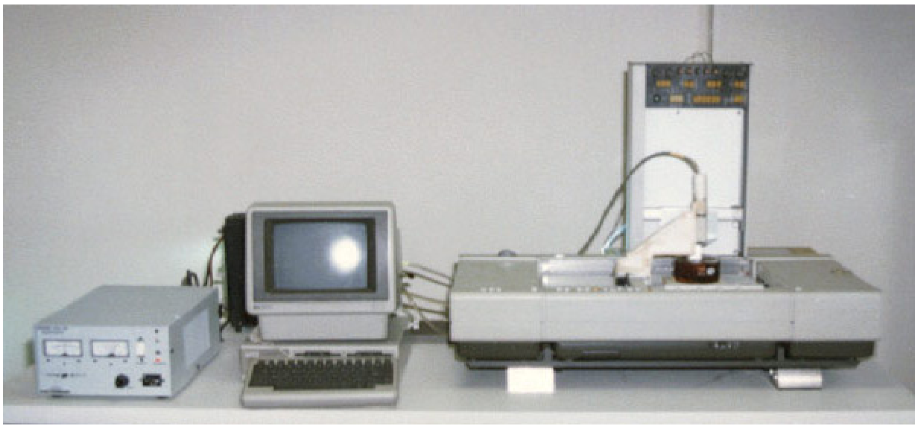


Figure 20: The first 3D printer invented by Chcuk Hull in 1983 (Sivertsen,2016).

Fundamentals of AM

Regardless of the different techniques all AM technologies generally require the same workflow:

A model or component is modelled on a Computer-Aided Design software (CAD). The digital model that will be manufactured with AM technologies has to be represented as closed surfaces which define a closed volume. This is also referred as a watertight model meaning that all the surfaces are closed and represent a closed volume. This ensures that all horizontal cross sections of the model represent closed curves to create a solid object;

The solid model is then converted into a format called STL. The STL file is the de facto a standard used by RP systems in the representation of the solid 3D CAD models. STL files represent all the surfaces of the model in a triangulated mesh meaning that highly curved surfaces employ many triangles and the files can be quite large;

A computer program receives the STL file and "slices" the model in its 2D cross sections. These cross sections are called layers. The user can specify the layer thickness. Depending on the layer thickness, the prototype can have different surface finish. Lower layer height creates better surface finish, but requires more time. From this operation the machine language named g-code is created. This code is "feed" to the AM machine to control numerically (NC) the fabrication process, the object is fabricated additively layer by layer with no user intervention.

2.4.7. Types of AM technologies

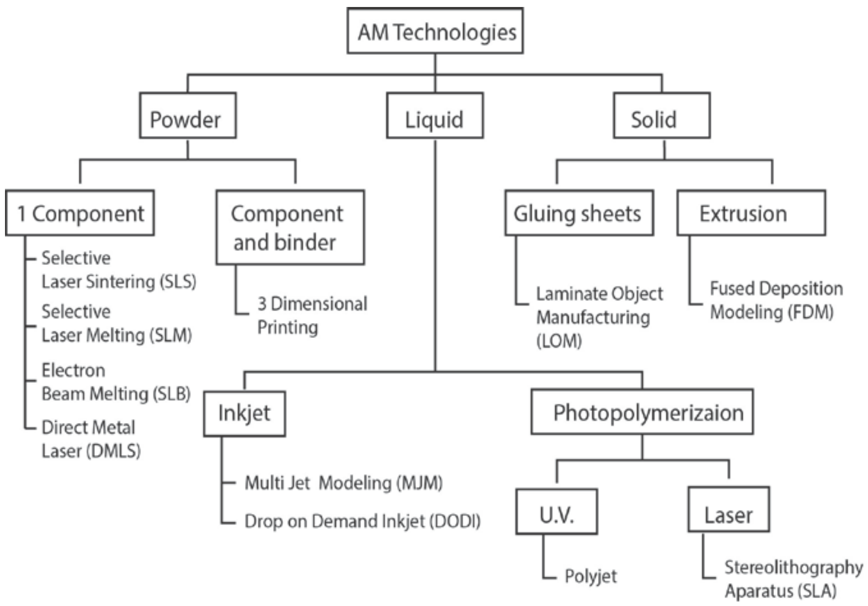


Figure 21: Division of AM technologies based on the initial raw material.

The AM technologies can be divided into three main categories based on the initial raw material they use to produce the parts. These are **Powder, liquid** and **Solid**. (Figure 21)

Solid based

In this category the raw material is in solid state including wires, rolls, laminates and pellets. Most popular method is the FDM (Fused Deposition Modeling) initially developed by Stratasys or also known as FFF standing for Fused Filament Fabrication.

Liquid based

The raw material here is a liquid during the fabrication process this liquid. Most liquid based systems build parts in a vat of photocurable liquid resin. This organic resin solidifies in the UV range usually. The light-source type and wavelength varies depending the resin and the machine. Most well known liquid based AM technologies include Selective Laser Apparatus (SLA) by 3D Systems, Polyjet by stratasys, Multi Jet Printing (MJP) by 3D Systems

Powder Based

Powder based systems utilizes powder in grain-like form. The solidification of the layer of powder either happens by direct energy - such as a laser or with a binder «glue», that binds the powder particles together to generate a solid object. In this category, commercially there are available systems, known as Selective Laser Sintering (SLS) from 3D systems, Colour Jet Printing (CJP), Selective Laser Melting (SLM) by GmbH.

2.4.8. Impact of additive manufacturing technologies in the design process

As product complexity has increased steadily over the years, the project completion time has not correspondingly increased. This is due to the technological development and the invention of new tools that aid designers in the design process. One of this is definitely AM which by its invention has a fundamental impact in the reduction of project completion (figure 22).

The use of AM technologies in the design process has significant advantage compared to other prototyping systems. The ability to fabricate physical models of almost any complexity can be conducted in relatively short time. AM prototyping methods are considerably easier to program and set up, requiring less time and input from the user.

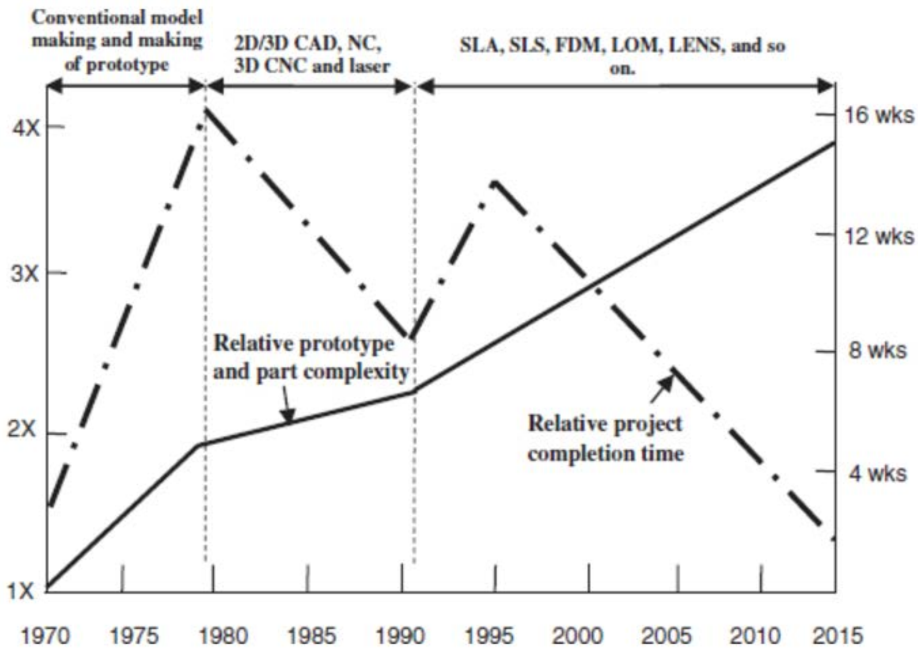


Figure 22:Project time and product complexity over a 40 years time frame (Chua & Leong, 2017)

2.4.9. Examples of AM technologies in more detail

Fused Deposition Modeling (FDM)

Fused Deposition Modelling (FDM), or Fused Filament Fabrication (FFF), or even less commonly known Plastic Jet Printing (PJP), is a solid based AM technology, that was first developed by Scott Crump in 1988 (Sivertsen, 2016) Stratasys was the first company to deliver to the market, in 1992, a AM machine using this technology and marketed it with the term FDM. After the expiration of the patent, there was a large open source development community (called RepRap) that used the same principles and developed open source design. Thus, the term FFF was created to prevent any legal issues with Stratasys. It was this open source movement that created the proliferation of 3D printing with the dramatic reduction of price. FFF is now the most commonly used 3D printing technique worldwide.

The FFF printing process starts with a string of solid material called the filament. The materials used are thermoplastic polymers and come in a filament form. An object is built by selectively depositing melted material in a pre-determined path layer-by-layer. As the material is extruded as a layer of the object on this path, it instantly cools down and solidifies, providing the foundation for the next layer of material until the entire object is manufactured (figure 23).

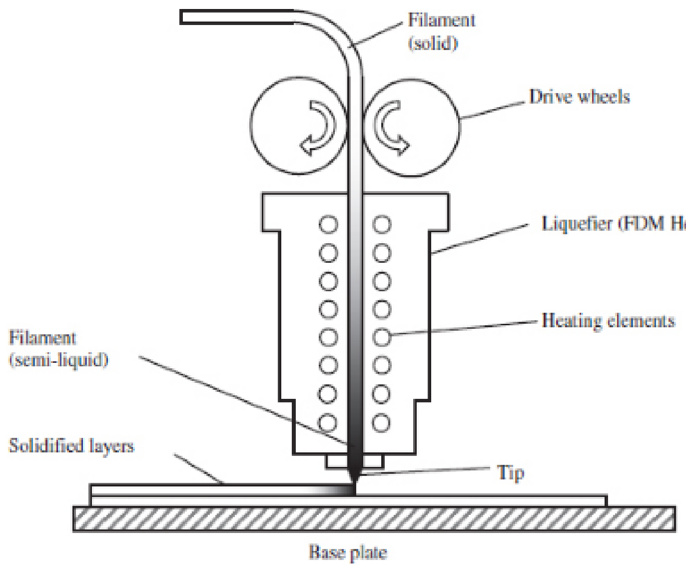


Figure 23: The FDM process visualized (Chua & Leong, 2017)

One of the key strengths of FDM is the wide range of available materials. These can go from commodity thermoplastics (such as PLA and ABS), to engineering materials, such as PA, TPU and PETG, or high-performance thermoplastics, such as PEEK and PEI. PEI also known with the brand name "ULTEM", it is an FDM thermoplastic ideal for aerospace, automotive and military with high strength-to-weight ratio. It enables the production of functional parts and production parts (Molitch-Hou, 2017)

Figure 24: 3D printed parts with FDM technology 3D printing (Alkaios, n/d)

Advantages

Cost-effective. FFF 3D printing is by far the most readily available and way to produce custom thermoplastic parts. Mostly due to the open source movement of RepRap community. There is a wide range of materials that parts can be made including commodity, engineering and high-performance plastics. No post processing of the 3dprinted parts with this technology is require other than the removal of the support material.

Limitations

Restricted accuracy. Parts have lower dimensional tolerance and lower surface finish. Low surface finish translates to visible layers this is part due to the nature of the raw material that comes in form of filament. Thus, very small layer height is not practically possible. Shrinkage and warping, depending the material used parts might show signs of shrinkage or warping. The most appropriate material to be used with this technology are ones with low shrinkage ration when cooled. One of the greatest disadvantages of this technology is the layer adhesion mechanism between layers that makes the parts inherently anisotropic.

Stereolithography Apparatus (SLA)

Stereolithography apparatus (SLA) or also known as simply as stereolithography is a form of liquid based AM technology used for creating models, prototypes, patterns, The procedure starts by a vat filled with liquid photocurable liquid resin. This resin is activated by a source of light. The wavelength of the light source can vary, usually is in the UV or in the near UV visible spectrum. The generation of this light source can either be a laser or an LED apparatus. The laser «scans» or traces on the surface of the liquid resin in the vat the 2D contours of each layer being produced. The control of the light source can vary from a simple x,y motion system moving the light source laser along the contours the contours of layer, to more advanced ones, such as a galvo scanner, LCD, or a DLP (Digital Light Processing) chip. The liquid resin gets activated and hardens only in the areas where it was exposed to the laser. After one layer is completed the build platform is lower in the liquid resin and the process is repeated until the completion of the object (figure 25).

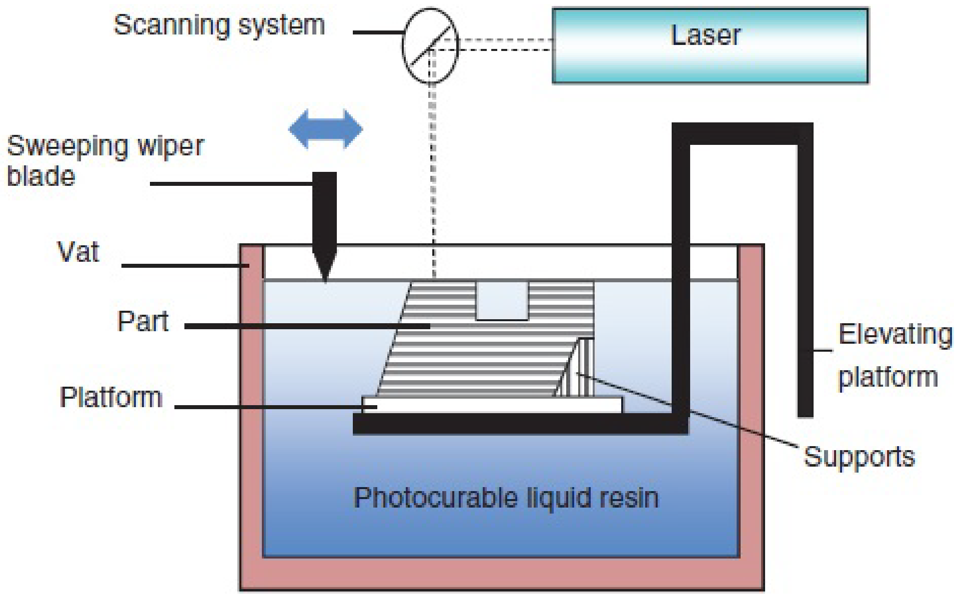


Figure 25: SLA process example (Chua & Leong, 2017)

Advantages

The main advantages of liquid based systems are that they create parts with the highest surface finish amongst the AM technologies. Parts are with good dimensional accuracy and can produce extremely fine details. This kind of machine is usually used for producing relatively small parts that require exceptional detail such as jewellery, dental implants for casting and presentation prototypes. Parts created with this technology have isotropic strength properties.

Limitations

Some of the weaknesses of SLA is its high cost including the equipment and its consumables (resin). The toxicity and fumes generated by the liquid resin They need a post processing, such as cleaning the surface of the part from the uncured resin and post curing of the part. Also if the part required support structure, this has to be removed manually and has the disadvantage of extra work, and also reduces the surface finish of the object where the support structure was connected with the model.

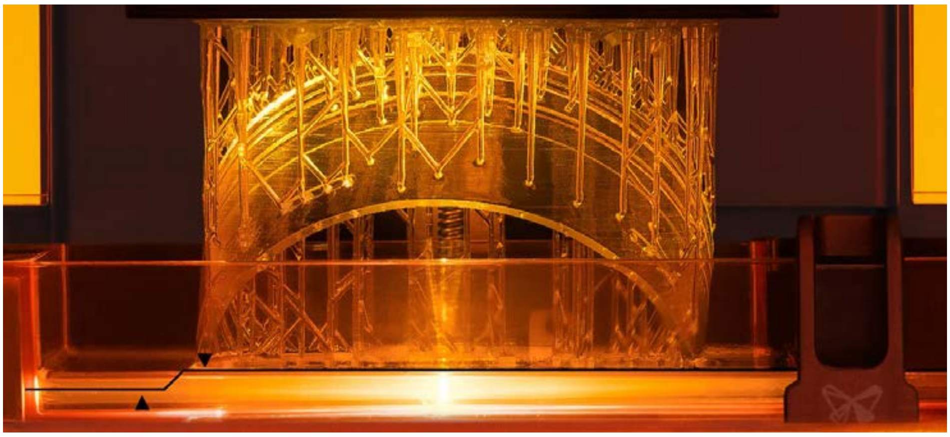


Figure 26: Formlabs 3D SLA 3D printer (Formlabs, n/d)

Material Jetting

Material Jetting Modelling (MJM)

Material Jetting Modelling (MJM) technology, or as marketed by Stratasys PolyJet and 3D Systems MultiJet Modeling, is similar to inkjet printing, but instead of jetting drops of ink onto paper, these 3D printers jet layers of liquid photopolymer onto a build tray and cure them instantly using UV light. The build process begins when the printer jetting the liquid material onto the build tray. These jets are followed by UV light, which instantly cures the tiny droplets of liquid photopolymer. As the process is repeated, these thin layers accumulate on the build tray to create a precise object. Where overhangs or complex shapes require support, the printer jets a dissolvable support material that is used temporarily, but can be removed after the print is completed. MJM is used in industrial 3D printers. Material choices consist of liquid photopolymers that can provide the final objects various properties including toughness, transparency or rubber-like flexibility.

The most advanced systems can even use multiple jets that allow the combination of different material properties and colors. Material Jetting offers many advantages for rapid tooling and prototyping, as it allows users to create realistic and functional prototypes with fine details and precision. These are the most precise 3D printing technologies today, printing with up to 16-micron layers (figure 27).

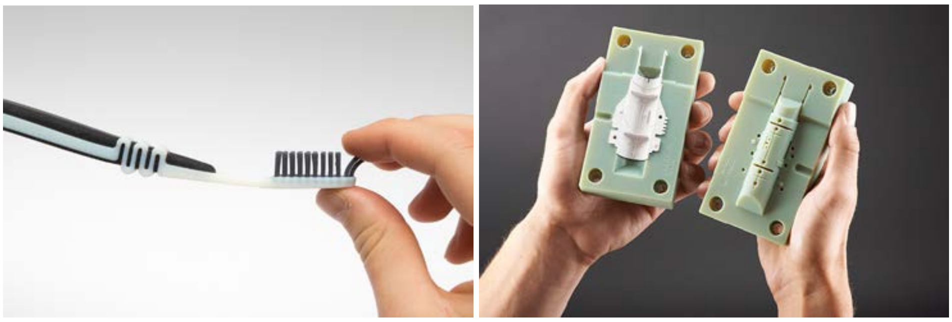


Figure 27: Left - examples of MJM technology fabricated parts combining different materials; Right - a prototype for injection molding (3D Hubs, n/d)

Selective Laser Sintering (SLS)

Selective Laser Sintering (SLS) technology uses a laser to harden and bond small grains of plastic, ceramic, glass, metal, or other materials into layers in a 3D structure (3D Systems, n/d). A thin layer of powder is spread, and then a laser beam melts the material in the appropriate pattern of the 2D cross section. This process is repeated until the whole object is completed. Once a layer has been solidified, the print bed moves down slightly, as another layer of powder is spread on top of the previous one. This process is repeated, and the laser melts successive layers one by one until the desired object has been completed (figure 28).

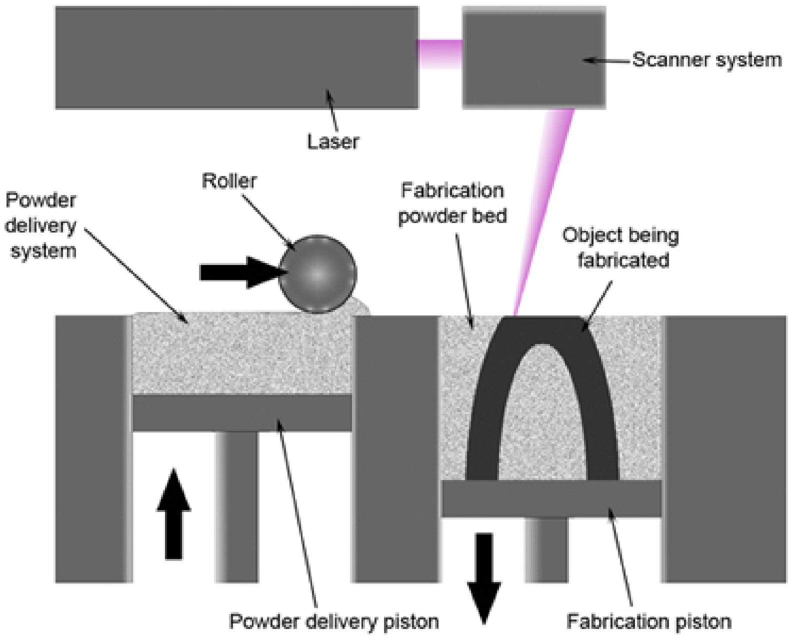


Figure 28:Schematic of SLS technology (clone3d, n/d)

SLS is mostly used on industrial 3D printing applications. Materials include various plastics such as polyamides (nylon) PA 12, polystyrenes and thermoplastic elastomers. SLS is widely used for producing functional prototypes and end use products (figure 29).

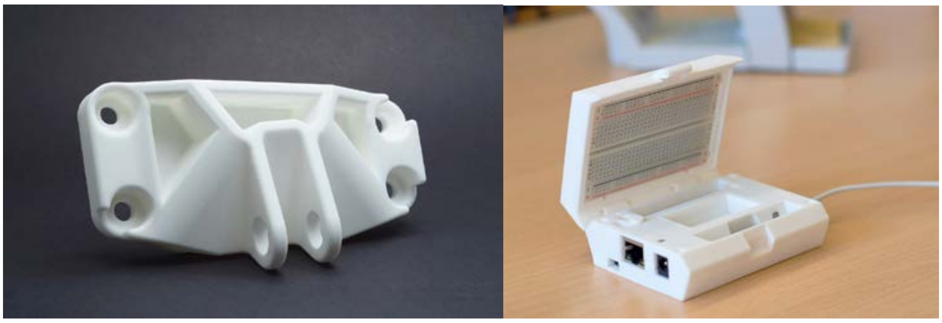


Figure 29:Examples of parts made with SLS technology (3D Hubs, n/d)

Advantages

SLS can produce parts with very good surface finish and very high strength with isotropic strength properties. The unmelted powder is also used as a support structure, allowing complex and intricate shapes to be manufactured with no additional support needed. The unused powder can be reused multiple times. Parts exhibit isotropic strength properties (3D Systems, n/d).

Limitations

One of the limitations is the slow cycle times since the built platform is heated to high temperature more than100 °C. As a result the part requires time to cool down after the printing procedure is completed. The fine powder particles present a health hazard and proper respiration and safety equipment should be used when removing the part from the build platform and subsequent cleaning operations of the part from the unbinded powder.

Binder Jetting

The binder jetting technology or ColorJet Printing (CJP) technology is similar to SLS in the way that the printer uses thin layers of powdered material to build up an object, but instead of using a laser these printers use a color binding agent is in liquid form is selectively jetted from inkjet heads to join and colorize at the same time the powder particles. The build platform lowers, and another layer of powder is then spread and binder is added. Over time, the part develops through the layering of powder and binder (Exone, n/d).

After it is removed from the print bed, the object is cleaned from excess powder and coated with an adhesive glue to give it strength.

Figure 30:Image of a PP fabricated with Color Jet Printing (CJP) (Addema, n/d)

Advantages

There is no heat required in the building process minimizing the stress in the part and eliminating warping. Relatively large parts can be built at a more cost-effective way compared to other AM technologies. The loose powder provides support structure as in the SLS technology. Different kind of coloring binding agents can be used creating parts with multiple color. Ideally suited for applications that showcase aesthetics and form, such as architectural models, packaging, etc.

Limitations

Part require post processing such as cleaning for the unused powder and need to be infused with an adhesive glue. Parts are very brittle and have poor mechanical properties.

Selective Laser Melting & Electron Beam Melting

These (SLM and EBM) are two of the most common metal 3D printing technologies. Their processes are identical to SLS technology where objects are created from thin layers of powdered material. In this case the powdered material is metal powder and due to the higher melting point of metals they require much more power a high power laser in the case of SLM or an electron beam for EBM. Both SLM and EBM requires support structures, which anchors the object and overhanging structures to the build platform and enables heat transfer away from the melted powder. In addition, SLM takes place in a low oxygen environment and EBM in vacuum, in order to reduce thermal stresses and prevent warping.

Figure 31:SuperDraco rocket engine combustion chamber (SpaceX, 2014)

2.4.10. Hybrid manufacturing

The term hybrid manufacturing is used in literature multiple times and sometime in vague manner. According to Bert et al. (2014), a hybrid manufacturing process combines two or more established manufacturing processes into a new combined set-up, whereby the advantages of each discrete process can be exploited synergistically.

A form of hybrid manufacturing is the combination of additive and subtractive manufacturing processes' methods use an additive process to build a near-net shape which will be subsequently machined to its final shape with desired accuracy by a subtractive process (Zhu et al., 2013). Until now, additive manufacturing processes have been limited to prototypes and small metal parts that are impossible to manufacture using conventional techniques. Hybrid manufacturing is an advancement to the AM technologies by combining it with metal machining processes on a single machine tool, unlocking new opportunities to make production-quality parts with the same AM technology flexibility (Frankel, 2014). One example of this technology is the laser cladding and mechanical machining. In this way, parts are made from high-performance metallic materials, and are built additively by laser cladding, which uses a laser beam to fuse a metal powder feed into layers on the surface of the workpiece. Once the metal is cooled, the workpiece can be machined using the traditional machining methods available directly on a machine (figure 32). This technology is relatively new, but it already shows promising results parts with complex geometries and organic designs can be manufactured with the desired surface finish with minimal setup (Joshi & Anand, 2017).

Figure 32:Example of building a part with a hybrid fabrication method, combining laser deposition AM and subtractive fabrication (CNC milling) done on a DMG Mori LASERTEC 65 3D hybrid manufacturing system. (Waterman, 2016)

2.4.11. Advanced prototyping combination of manual and-RP tools using oil-base clay

Although in today product development world the development of a product without the use of PC is almost unimaginable, there are some serious limitations of the current software tools in realization complex surfaces such as in the automotive design. To cope with this limitation designer and automotive companies use a much more traditional material, oil based clay. It is used as a medium by designers to express and refine their ideas, even today in the modern gold era of digital technology (Terauchi, n/d) The advantages of using clay to create smooth 3D shapes were acknowledged and adopted by engineers and designers since the early days of the industrial product design and clay is still until today the prefeed tool in the automotive design process (Gibson, 2016). The shape of the concept is milled on clay directly from the CAD model afterwards if the designer want to do a modification on the model can work directly on the clay model. Afterwards the prototype is digitalized with a form of 3d scanning and the concept can be reworked in CAD again. This process is reputed until the desired shape is achieved. Clay provides a very flexible medium for the designer to work and can create shapes much more intuitively than with the use of CAD modeling.

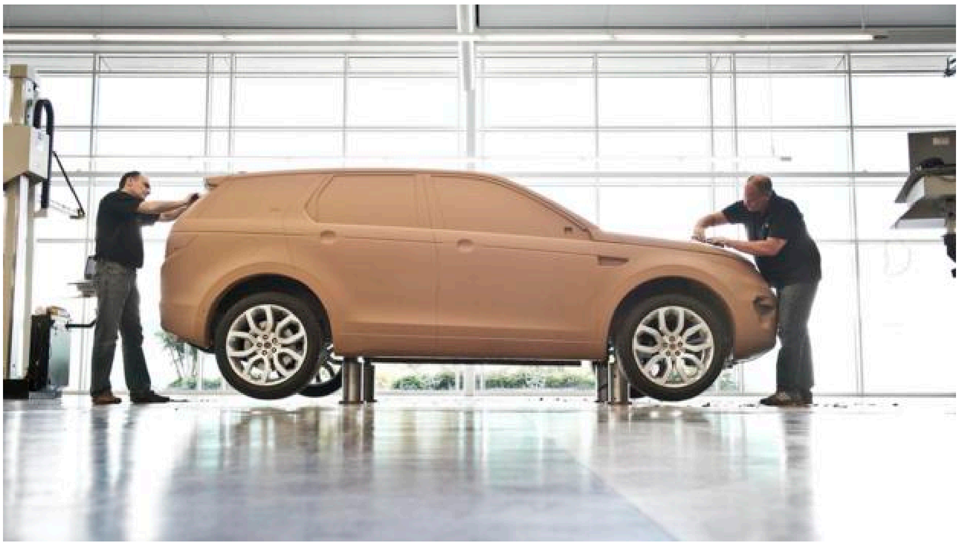


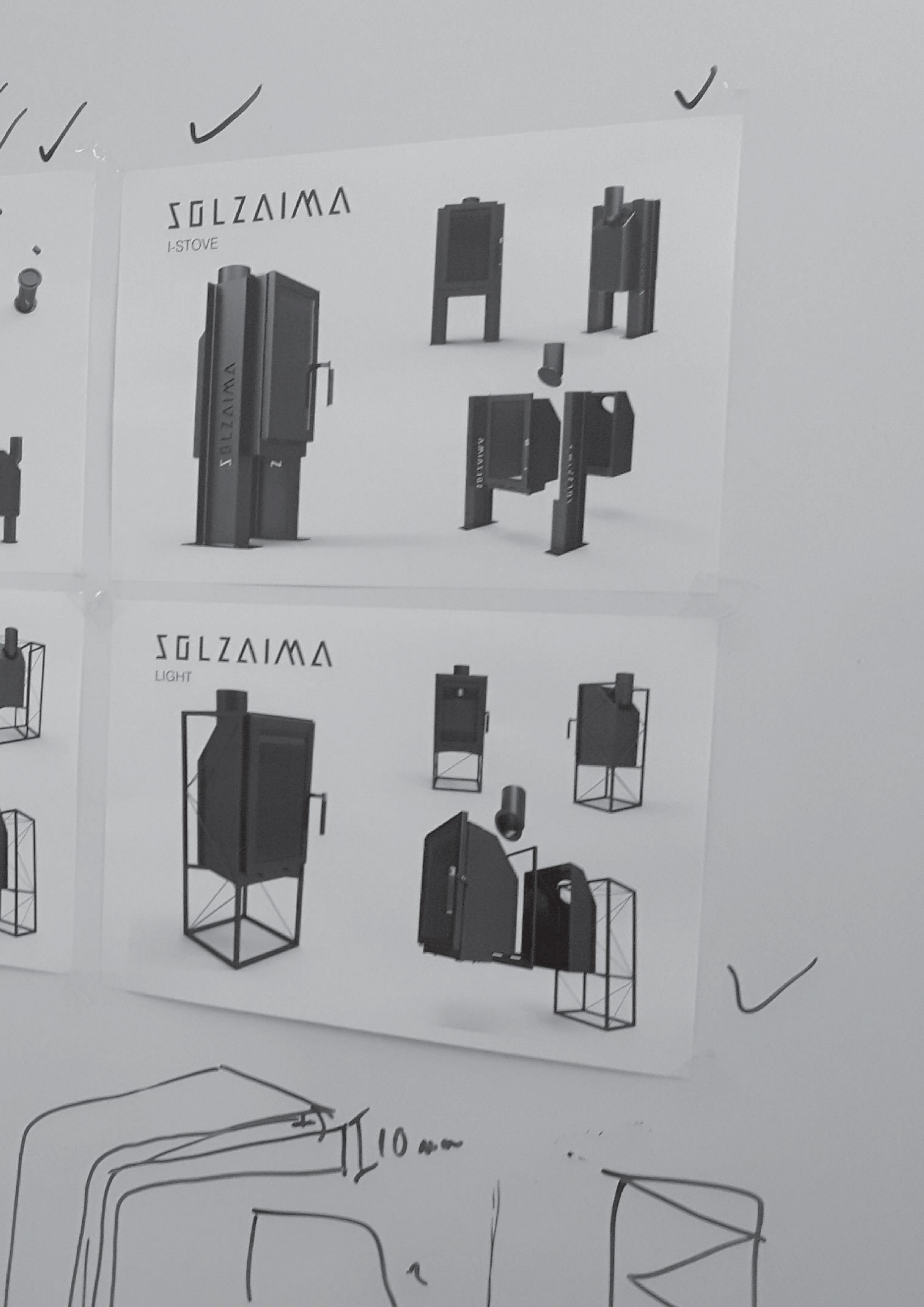
Figure 33: Land Rover modelers sculpt the Discovery Sport in clay at the company's design studio in Gaydon (Gibson,2016).

2.4.12. Summary of Physical Prototyping (PP) methods

RP and AM technologies (which is part of the RP methods) was one of the inventions that had the most dramatic impact on the product development process. AM technologies is a powerful prototyping tool in the disposal of the product designer to create free form objects directly from the CAD with minimal cost and at a short notice. This has enabled the shortness of the product development phase although the product complexity has increased. (Figure 22). It is important for the designer to know the strengths and limitations of each technology to be able to select the correct technology. The FDM or FFF AM technologies is by far the most popular RP method due to the many advantage such as user friendly, low cost per prototype, large selection of materials, the ability to produce functional parts with no need of post processing. The proliferation of the low-cost AM technologies such as the FFF 3D printers does not mean that the traditional and manual modelmaking techniques are obsolete but as Bjarki mentions there is a combination of both techniques. The manual modelmaking techniques are more predominant in the first phases of product design process with the construction of soft prototypes from foam and cardboard by hand. Whereas as the process advances there is an increasingly use of digital fabrication tools (RP) such as AM fabrication.

Part III Methodology & Research Questions

In this is part, the methodology for this work is presented together with the research questions, to provide a better exploration of the topic and to meet the objectives set in the beginning of this work.


SOLZAIMA
I-STOVE
SOLZAIMA
LIGHT
10 mm

Part III

3. Methodology

To explore the subject in a proper and systematic manner a plan to this research was established (figure 33). The methodology and the reasoning behind this approach is explained in the text bellow. After the research of the state of the art with an extensive literature review, the finding from the theoretical research were applied to the practical part of the work as a product design intern in INNGAGE. The findings from the internship part of this work were based on a case study research (Yin, 2014). The essence of a case study is that it tries to illuminate the decisions taken "why" and "how" they were implemented and with what results. (Schramm, 1971). Based on the theoretical research on design methodologies and prototyping methods where applied in the projects working of INNGAGE. From the five months, full time internship in INNGAGE a selection of three case studies are presented to illustrate how prototyping was used in real product design projects and what were the advantages of doing so. To be able to apply a case study research method, some criteria had to be applied according to Yin. 1. New project mostly or completely developed from zero. 2. Prototyping played a key role in the projects development. 3. A systematic design approach was followed. During the design process, due to company policy It was not possible to come in direct contact with the client, users or other stakeholders. Feedback on the design process from project stakeholders outside the company was received from the founder & managing partner (MP) of INNGAGE André Gouveia. This is not considered to affect the outcome of this research. The case studies are presented with the following structure: Introduction, Design process, Physical prototyping and Results. In each case study there is a brief introduction were the objective and the vision of the client for the concept are presented. Then there is a detailed presentation of the design process including the tools and methods used. Including the important design decision, factors and events that affected this process. In the results section the outcome of the selected methods and decision made in the design process are presented.

3.1. Research Framework

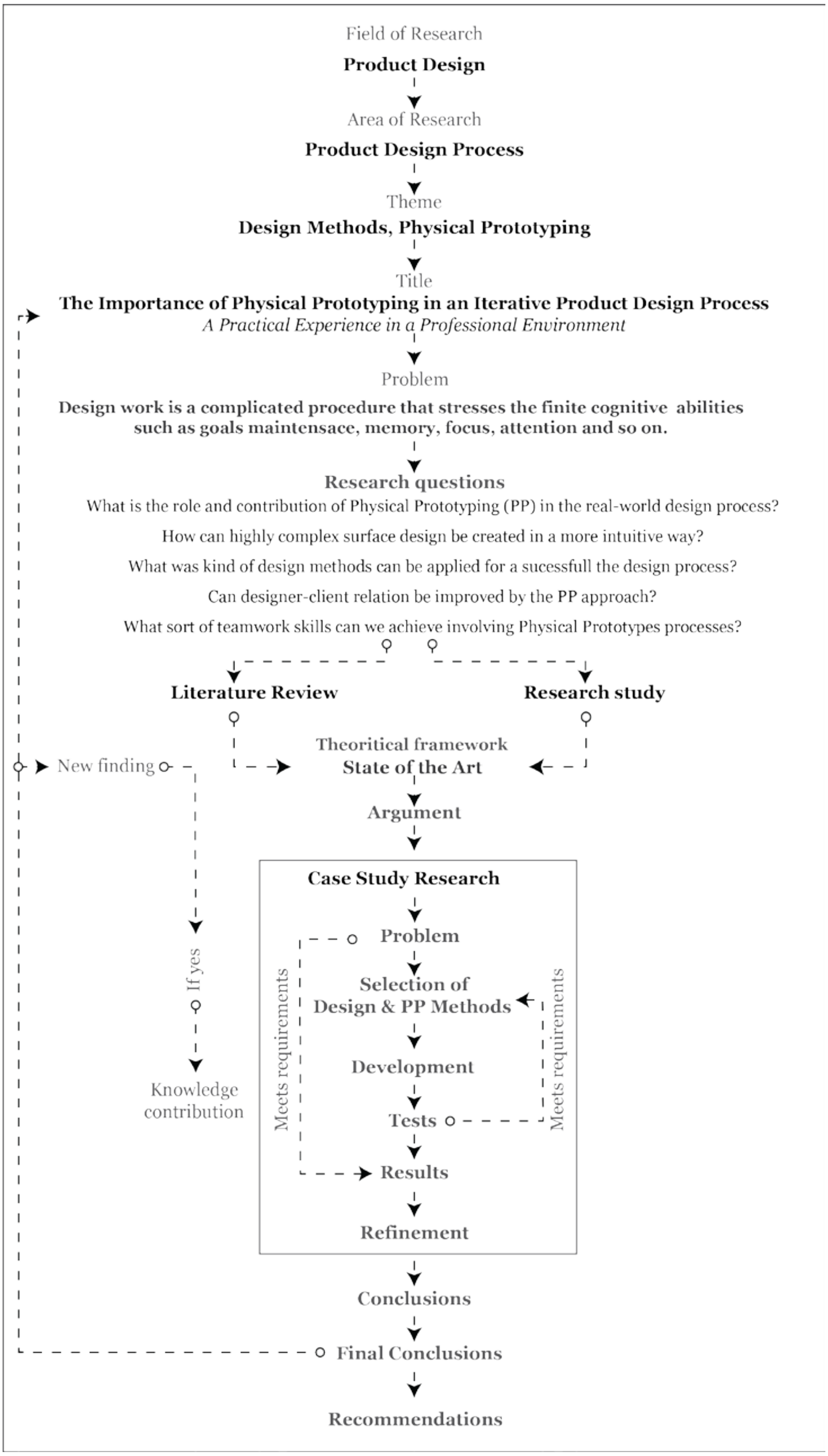


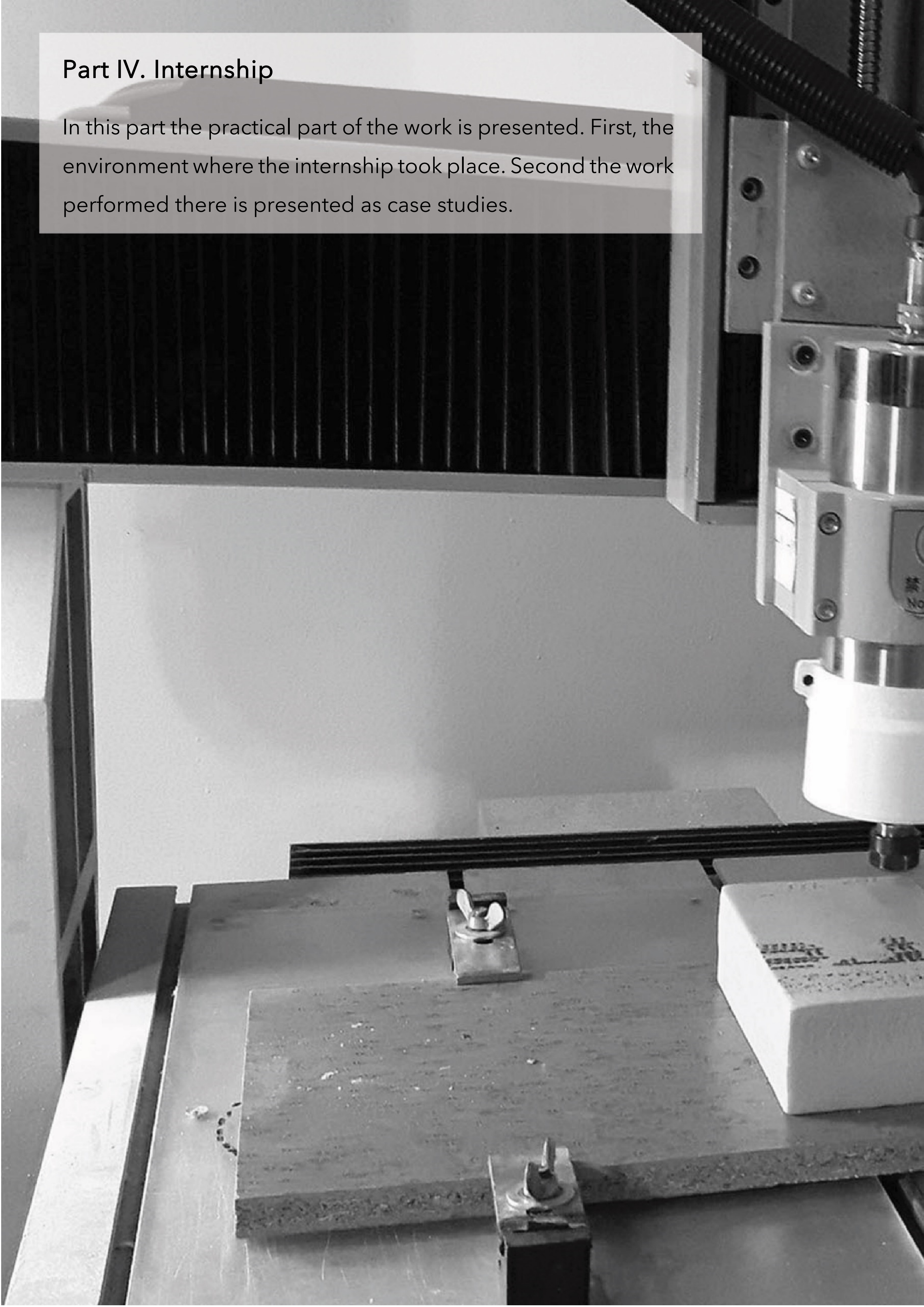
Figure 34:Research framework

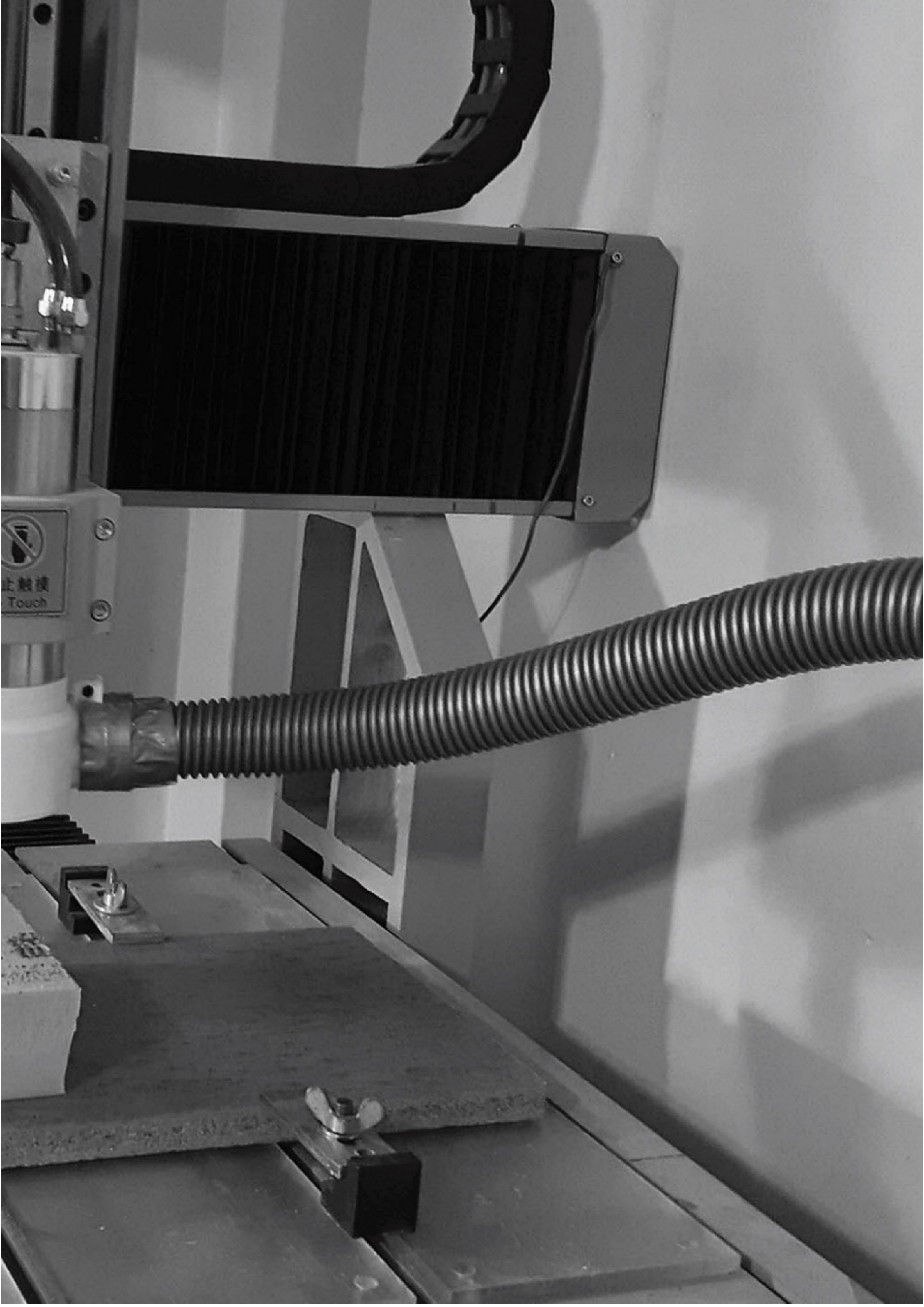
3.2. Research questions

- What is the role and contribution of Physical Prototyping (PP) in the real-world design process?
- What is the practical experience using different design methods in the design process?
- How prototyping can be used to stimulate creativity and develop more innovative solution.
- How can highly complex surface that elicit a more emotional response to the user can be designed in a more intuitive way?
- What sort of teamwork skills can we achieve involving Physical Prototypes processes?
- Can designer-client relation be improved by the PP approach?

Part IV. Internship

In this part the practical part of the work is presented. First, the environment where the internship took place. Second the work performed there is presented as case studies.




Touch

Part IV. Internship

4. A general view about INNGAGE

INNGAGE

Figure 35: INNGAGE logo (INNGAGE, n.d.).

The design studio INNGAGE was created in 2013 by André Gouveia in Seixal Portugal, with the vision to bridge the gap between the industry and the end users. After working in other design firms the founder decided to create his own, where he could apply in practice this philosophy of user-centered design. *"We partner with our clients to conceptualize and develop meaningful, efficient and innovative products that provide better experiences for the consumer, through a context centered, collaborative and iterative design processes"* (André, n.d.).

INNGAGE works in three main areas research, product design and communication. The focus is product design and services such as graphic design, branding and marketing can be offered along with the product development process. INNGAGE works with clients in the development of projects in the wider area of consumer products. The design team consists of three full-time designers with André Gouveia having the managing role in the design process.

Tagline: "Designing Products That Make Sense"
Website: http://www.inngage.pt
Adress: Rua Ayres de Sá, n.º 6A, Casal do Marco,
2840-016 Seixal - PORTUGAL
Tel: 351 216 009 970

4.1. Design philosophy & approach

With the moto designing products that make sense INNGAGE follows are user/human (HCD) centered design approach. The design process is simply divided into three phases: Discover, Envision and Implement. The process is not linear and fast iterations are preferred with a bias towards doing and experiencing instead of idling and overthinking. (Figure 36)

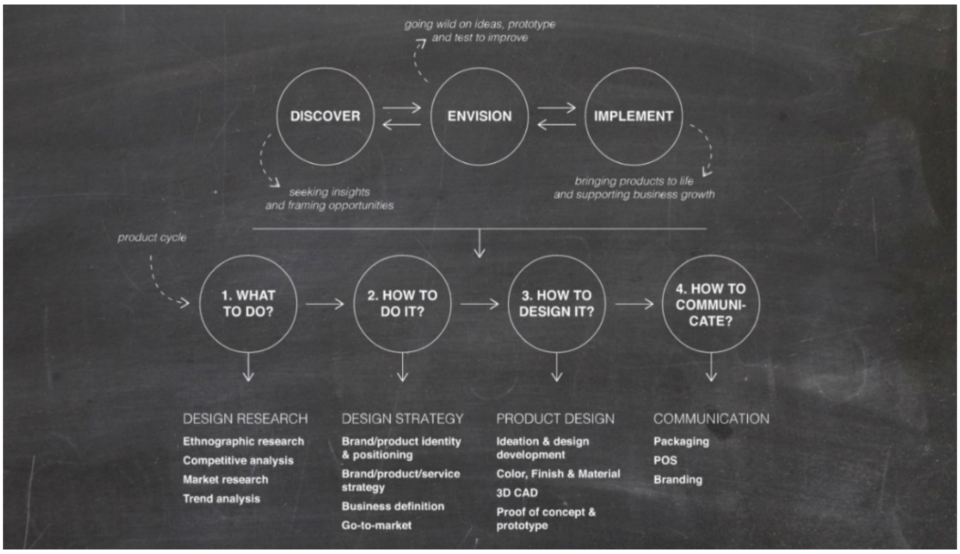


Figure 36:Design approach followed by INNGAGE design team.

(INNGAGE, n.d.)

The design process always starts with an extensive research on user, culture, market, competitors, ergonomics, design trends, technologies. This is done to identify design insights and establish where are the design opportunities in the market for a new product. Tools used to visualize in a graphical way this research such as market map, moodboard, user workshops, mind mapping and brainstorming.

User workshops

Depending on the briefing and the projects requirements user workshops, user interviews and user observation methods are used. This is done to more clearly understand the user's needs and empathize with user's reality (Figure 37). In this workshops, products, concepts or sketches are used as stimulus to get a more realistic feedback from the users.

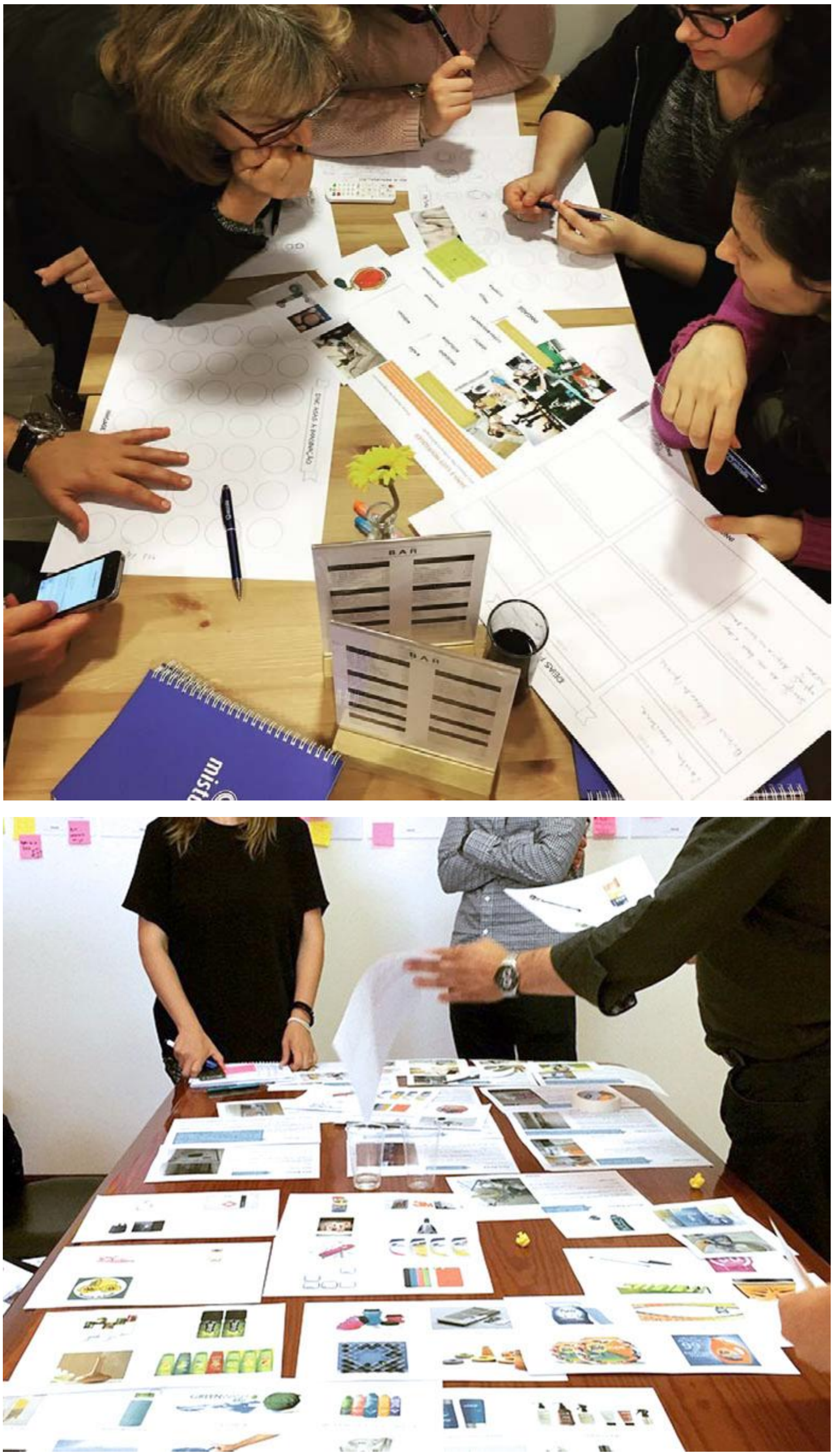


Figure 37: Pictures from user workshop organized by INNGAGE as a tool to get customers insights on the problem (INNGAGE, n.d.)

Prototyping

As mentioned before INNGAGE follows a very iterative design process this means many quick iterations of the design cycle. Prototypes together with sketches are used throughout the design process in different levels of approximation. In the design process a lot of soft prototypes are used to explore different design ideas tools used are traditional mediums such as paper, pens, markers and pencils. After establishing 3-4 concept ideas. 3D more detailed models are created to present to the client. To support and communicate the design idea to the client physical prototypes are also created either from paper or with RP prototyping.

Figure 38: Example of soft prototypes used by INNGAGE during the ideation phase (INNGAGE, n.d)

4.2. Portfolio of Projects & Awards

INNGAGE works with Portuguese and international companies and is developing projects in wide range including a wide variety of projects including, consumer electrical appliances, home appliances, industrial products, automotive, packaging, retail and point of sale design. Some of the developed products are presented in (Figures 39). Although a relatively new design studio has managed to collect numerous award for its designs. Including two ReddDot design awards for the Fogo Montanha wood stove Natura and the innovative tablet accessory Wonder Cover by Magnetica Apps & Crafts.

Figure 39:Portfolio of projects of INNGAGE

4.3. Internship experience at INNGAGE

The period of this academic internship in INNGAGE was five months, from 13 February 2017 to 30 June 2017. The internship was full time (8hrs) working at the INNGAGE design studio in Seixal, from 10:00 to 19:00 including a 1hour lunch break. The team consisted of three fulltime designers with diverse skill set, in engineering, product design and graphics design. In some project the help of an external design consultant would be used in the design process. The management of the design process and the business part of the design work was done by André as the founder and managing partner (MP) of INNGAGE. André applied a flat hierarchy within the design team, with ease of communication which helped to build good working environment and promoting creativity individual autonomy. All the design team used to take coffee breaks together and have lunch at the same table to socialize and relax from the design work. This social and human interaction was essential in the building of a good working environment and a good team spirit.

Figure 40: Group photograph of the INNGAGE design team including (Author)

My role as a design intern was to be fully engaged in the design process of INNGAGE projects. During this period I had the chance to develop a total of six main projects and five smaller sub projects. Three of these main projects are presented in the following pages and are used as a case study presentation of the advantage of using PP in a systematic design approach. The main task was product design and development. I had the complete responsibility of development of these five main projects mentioned, although at some point some design work was developed together with other members of the design team. During this period to be able to participate in two of the main projects I had to sign a non-disclosure agreement NDA due to confidentiality reasons. Thus, no information can be shared for these projects. It was also requested by André that I will not come into contact with customers or user´s due to confidentiality concerns. As such feedback about all the design process on all projects was received through André.

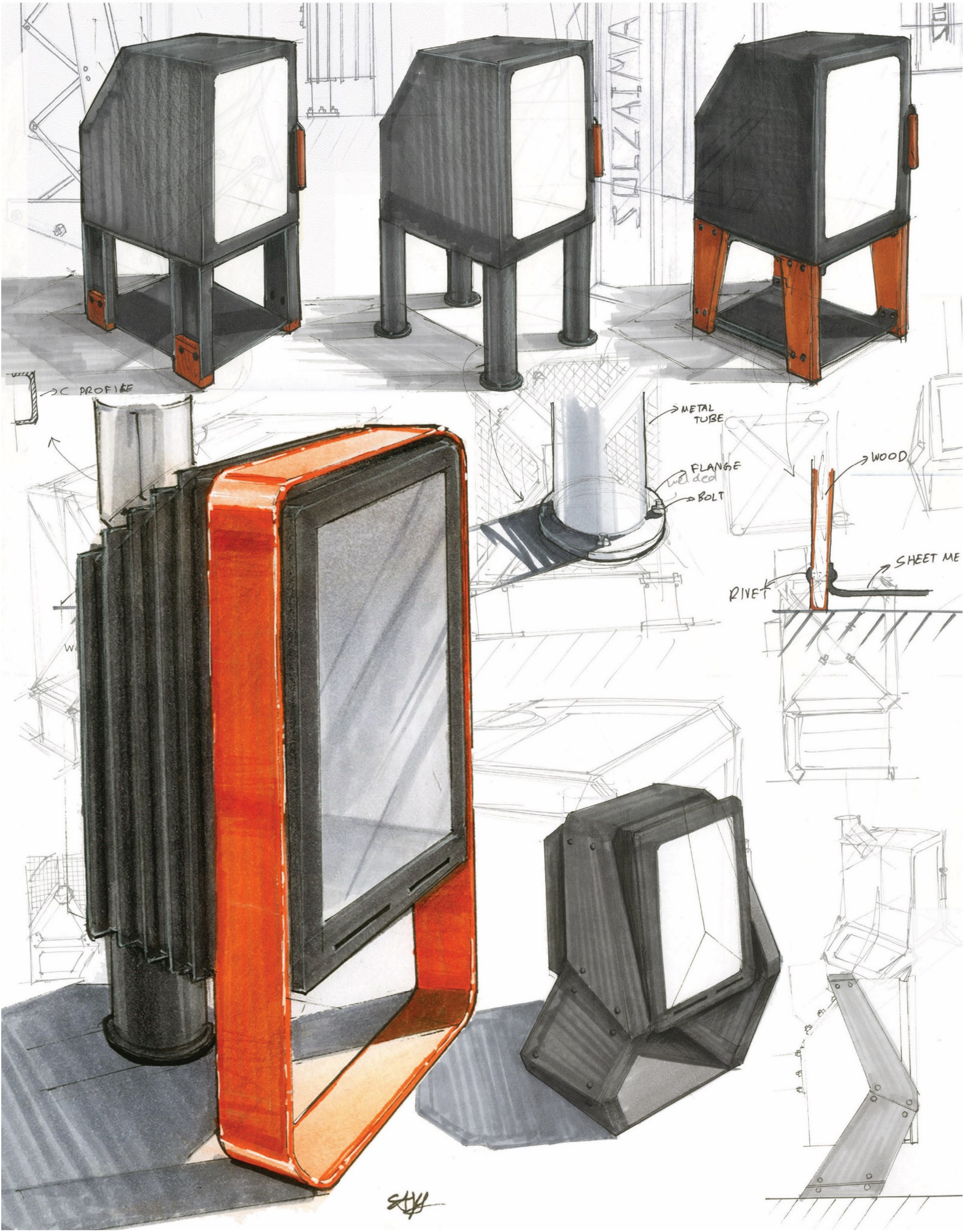
The areas of the projects developed included, consumer electrical appliances, industrial lighting fixtures, home appliances, consumer goods packaging, recycling, retail and point of sale design. The work conducted was predominantly product design including research, sourcing of components, ideation and sketching, developing of 3D models CAD design and CAE design, physical prototyping, rendering and presentations. I participate in all the design activities within INNGAGE design studio including brainstorming sessions, feedback & critique and testing sessions. Some of the sub-tasks that I was responsible was the creation of sketches to communicate the concept idea and to be used as stimulus in user workshops. Fabrication of prototypes for other projects from fellow designers and help in the general workload such as renderings and presentations. It has to be noted that considerable less time was spent into the subprojects mentioned above.

4.4. Project development routine in INNGAGE

A new design project would always start with a team meeting where the briefing of the project was given by André where the problem statement or vision of the client was state along with any requirements or specification for the possible solution. During the meeting there would be an open discussion on how to approach and how to define the problem, including selecting appropriate design strategy. Within this first meeting usually would take place the first group brainstorming session about possible solutions together with the use of quick sketches to communicate the idea or simple soft models made at the spot. In the end of the meeting would be set the time-schedule and the deliverables with each deadline. After that would follow the development of the project in short design iterations. Working in groups or individuality with a great level of autonomy on how to approach the solution, but with frequent group meetings to get feedback or to ideate on possible solutions. During this process a lot of physical prototypes would be built together with user feedback from user workshops and client meetings. The presentation to the client was done in the first stages with sketches or renderings and as the project advanced the project would be communicated more and more with prototypes. The presentation to the client were done from André together with a more senior designer from the design team.

This briefly summarizes the project development process followed in INNGAGE design studio during the period of the internship. In the next part three case studies are presented, to highlight the advantages of using a systematic design approach and physical prototyping in the product design process.

Case study 1
Solzaima "NAKED" woodstove



4.5. Case stud 1

Introduction

Client: Solzaima

Solzaima Is a Portuguese company created with the vision to provide clean, renewable and cost-effective heating solutions. Is one of the leading companies in the field of biomass heating systems with 39 years of experience.

Figure 41: Solzaima logo (Solzaima,n.d)

Website: http://www.solzaima.pt/

Tag line: *"Nature warms us, it gives us energy"*

Briefing

Clients vision was to create a new wood stove for home use that highlights the "beauty" and efficiency of the Solzaima combustion chamber. The vision of the client was to create a design that will appeal more to younger customers, with modern and industrial look. The deadline for this project is was four weeks.

Project Name: "Naked" woodstove

Project Duration: 13/2/2017 - 15/3/2017

Design Process

Design process overview

The objective was to design the exterior of a wood stove that would highlight the combustion chamber. The combustion chamber to work with was specified by the company could not be altered. To structure the design process instead of an intuitive based design approach, a systematic design method was chosen. The design thinking methodology was chosen with short roughly weekly iterations as the most appropriate approach to develop this project. In the end of each design iteration, the proposed designs were presented and evaluated by all the design team. The feedback received was used to initiate the new design cycle. There were in total three design iterations until the development of the final design that was presented to the client by the managing partner André Gouveia. Which will be referred in the text from now on with the abbreviation **MP**.

Iteration 1

Empathize/define

The design process started with the empathize phase. Extensive research was conducted in all three areas about brand identity of Solzaima, competitors, design trends, and consumer preferences. Moreover, to get a better understanding of the subject and to get a general familiarization with the sector of biomass heating solutions research was conducted in the different technologies and technical specifications of biomass heating systems. Due to company policy it was not able to come into contact with users, thus all feedback and user insight were received by the MP. The research was done by field observation of different biomass heating solutions in retail stores and by online research. The tools that were used in the research phase were **market map** and to empathize with the target user needs **consumer personas** were created.

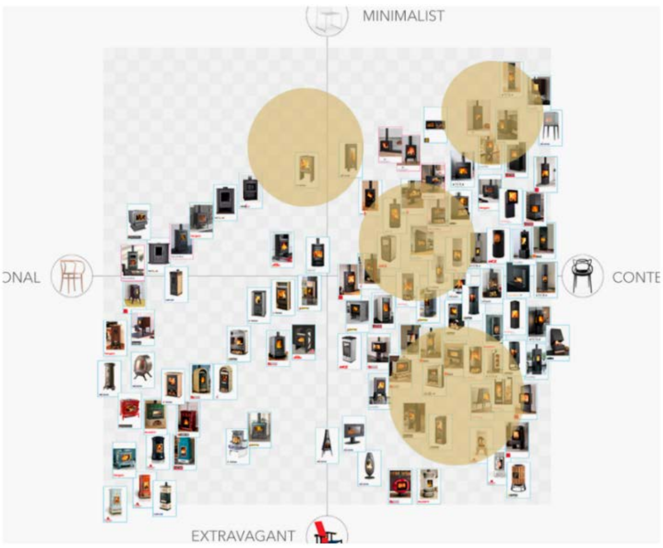


Figure 42: Market mapping, research tool. Project "naked" woodstove" Solzaima

After the Empathize phase was completed the results were analyzed and the key design insights and features that the product should meet were identified. In this phase were defined the visual features that the concept should have to meet the client's vision. Three moodboard were created to serve as guide and inspiration for the next phase of ideation. (Figure 43)

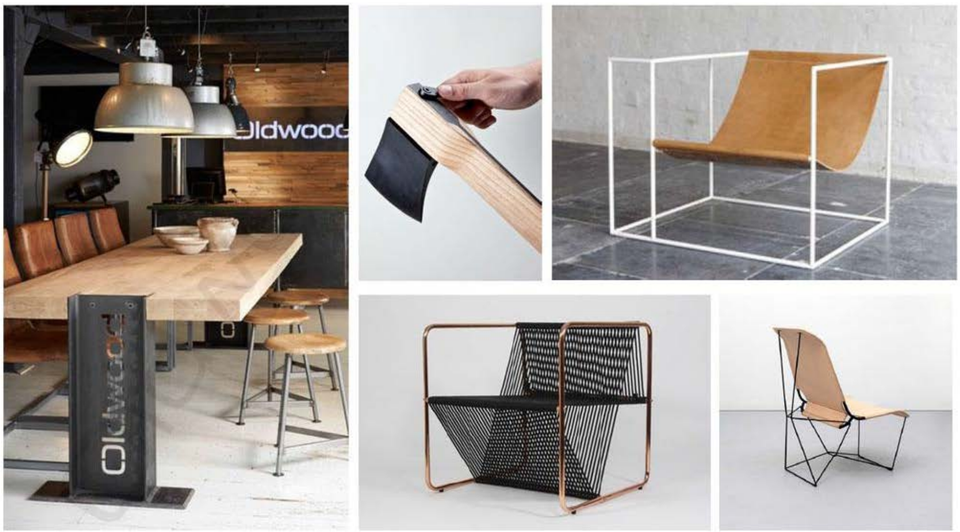


Figure 43:Moodboar, tool. Project "naked" woodstove" Solzaima

Ideation

In the ideation phase a lot of quick sketches were created in the beginning trying to explore as many design directions as possible. The concepts developed in the ideation phase were done individually (figure 44).

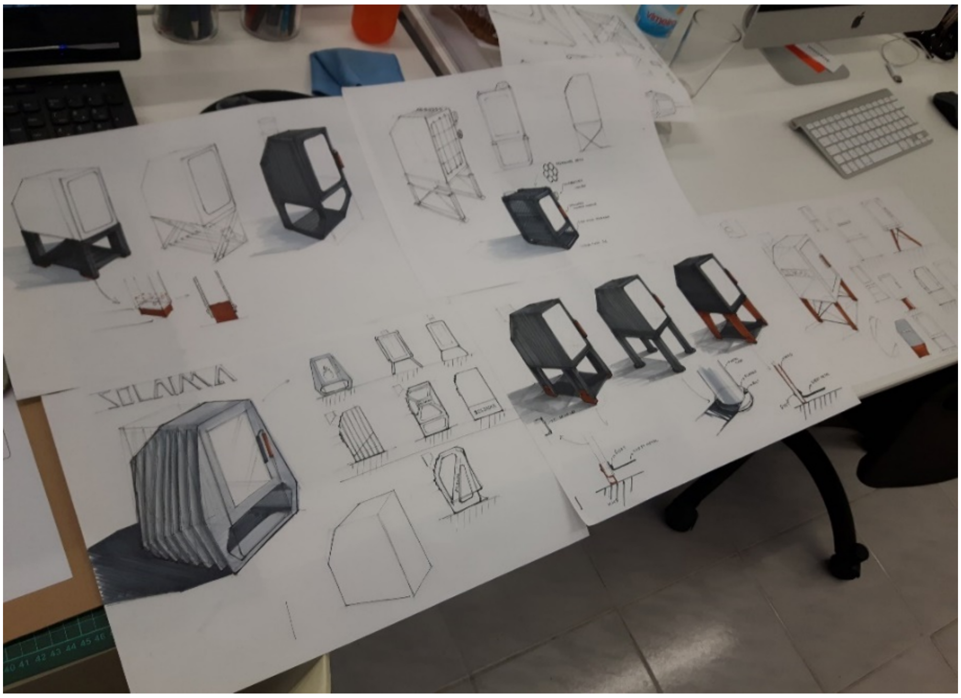


Figure 44: Ideation sketching during the process before the use of soft models for ideation. Project "naked" woodstove" Solzaima

During the process feedback and guidance was given by the MP. The results of the ideation phase were presented to all the design team for feedback. During the last phase of the ideation process there was the use of 3D CAD design tools, Rhino3D to design the basic volumes and create a simplified design of the basic concept.

Prototype

Due to the size and the objective of the concept a 1:5 scale prototype was considered sufficient to test the concept. In the first design iteration only, soft models were constructed to use as a further extension of the ideation phase. To assess the volume and dimensions of the real concept a scale figure was also constructed to use as a reference. (Figure 45)

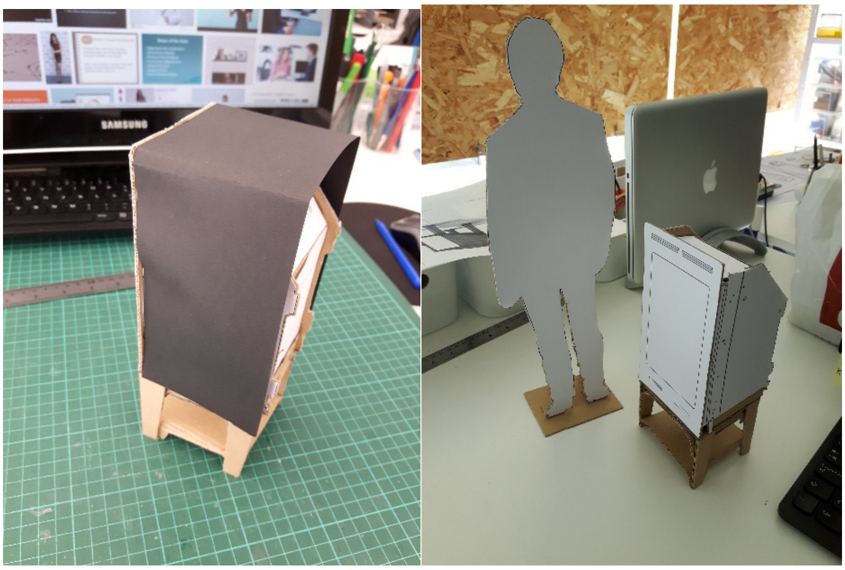


Figure 45: Soft models used during the ideation process for the Project "naked" woodstove" Solzaima

Test/ Critique

In this phase, the results of the design process were presented to the MP and to the rest of the design team. Where each person would express their ideas and opinion about the design. Since the project focused only on the exterior redesign there was no need for user testing or ergonomics testing (Figure 45).

Evaluation of first iteration

By the end of the first iteration in a very short time, the whole design process was concluded including evaluation of the design. The results and experience gained from the first iteration were used to the next design iteration (Figure 46).

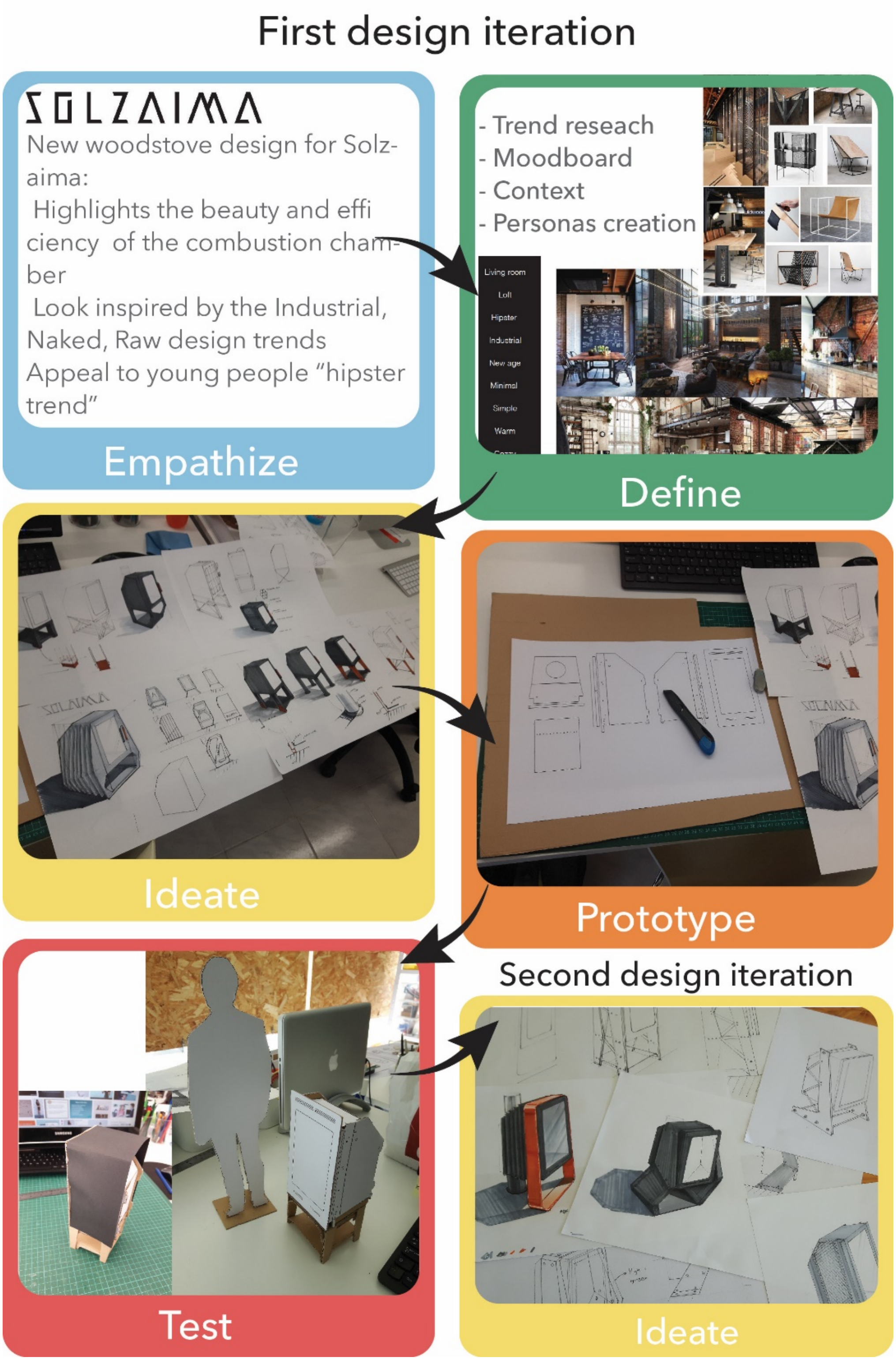


Figure 46:Visual representation of the first design iteration. Project "naked" woodstove" Solzaima

Iteration 2

The feedback received from the first iteration and the experience gained by the creation of the soft models was used as an input for the second design cycle. Here very little time was spent in the research and definition of the design direction since this phase received good feedback from the MP. In this phase the focused was on the ideation phase and to create a more appealing design. Many sketches were created with traditional mediums such as paper, pencil, fineliner and some were rendered with markers. The generated concepts were presented to the MP and to the whole design team. From the six generated concepts four basic designs were selected for further developments with 3D CAD modeling tools. (Figure 47)

Figure 47: Selection of concepts developed in the second design iteration. Project "naked" woodstove" for Solzaima

The 3d models were created with CAD software using Rhino3D, the objective in this phase was to create a more detailed design and to consider some preliminary engineering and fabrication requirements. After the conclusion of the CAD modeling process, the 3d models were rendered with Keyshot. Then an A4 presentation was created to be presented to all the design team. The presentation included feedback and voting in selecting the best concepts for further development (Figure 48).

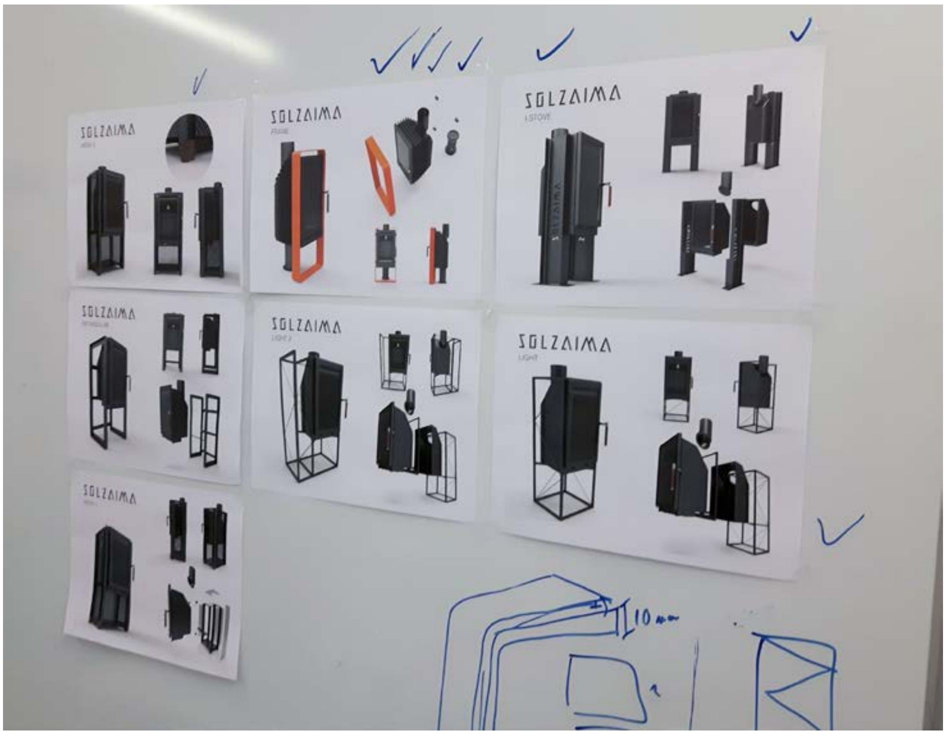


Figure 48: Presentation of proposed concepts and voting on the preferred design within the design team. From the seven proposed concepts, four were selected to be presented to the client.

Iteration 3

After the selection of the best concepts, the effort focused more toward further development and detailing of the designs. Together with the creation of a final presentation to be used during the presentation of the concepts to the client. For the refinement of the concepts again Rhino3D was used and later the rendering was done with Keyshot. The prototypes were constructed with a combination of RP and with manual modelmaking methods. The RP technology used was the FFF 3dprinter (Hephestos 2) available at the design studio. A more detailed presentation of the prototyping process is presented in the following section.

Figure 49: CAD model of the woodstove concepts, rendered with Keyshot

Physical prototypes used during the design process

In the first design iteration, soft models in 1:5 scale were created using 2D patterns generated from the CAD model of the combustion chamber. For scale reference, a 1:5 scale human figure was used also. This was done to get a sense of scale and volume and help with the generation more ideas on the possible exterior design. Not much effort was given to create a detailed model just the basic shape of the concept. The soft prototype was used to think in 3D and intuitively ideate by using cardboard and sketches to create the desired shape (figure 50).

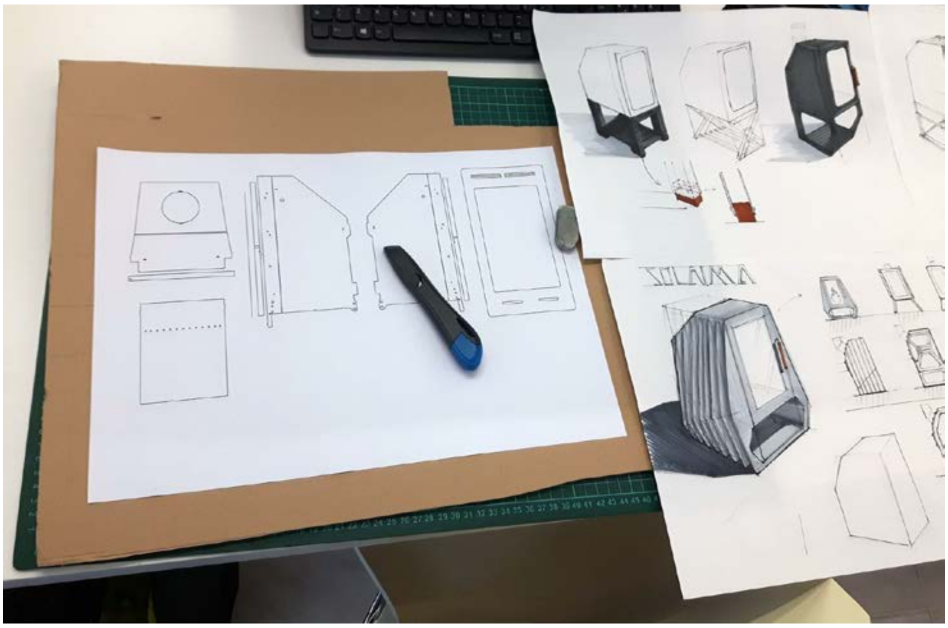


Figure 50: Top Fabrication process of soft models with cardboard.

After the selection of the best concepts in the end of the design iteration two, the task was to create high detail presentation models in scale. A 1:5 scale was again selected again due to the size of the concept, a 1:1 scale presentation model would be too expensive to fabricate. The prototypes were meant to resemble as close as possible the intended concept but with no functional features, so they can be considered as **hard models**. Their purpose was to be used as a supporting role during the presentation of the concepts to the client.

Figure 51: Fabrication process of presentation models with a combination of traditional modelmaking tools and AM, rapid prototyping technology.

For the fabrication of the hard models some CAD reworking was necessary, taking into consideration the abilities and limitations of the FFF 3D printer available at INNGAGE. It was simply not possible to just scale down the design and 3D print because parts of the models would have too small thickness to be fabricated, with the available AM machine. For example, in one of the wood stoves the sheet metal in 1:1 scale would be 3mm but in 1:5 scale it would have a thickness of just 0.6mm which would be too thin to fabricate. So these parts were redesigned so that the thickness would be at least 1.5mm in 1:5 scale.

The presentation models were constructed with a combination of cardboard and 3D printed parts. Since the combustion chamber has relatively flat sides, it was constructed from 3mm thick maquette paper, the smaller and more intricate parts were fabricated by 3D printing with PLA plastic (Figure 51). The prototypes were painted with acrylic spray paints and glued together with super glue. Small details such as the vermiculite combustion chamber tiles and the wood texture in the handles were printed in a common inkjet printer and glued to the model. The final presentation models were a close representation of the intended concept in scale (Figure 52).

Results

The design effort was completed after the conclusion of the third iteration, the presentation to the client was done only by the MP. The concepts received very positive feedback and the design effort was considered successful since the concepts met and even exceeded the expectation of the client. Especially the use of physical prototypes to communicate the design was highly appreciated.

Figure 52:Completed presentation models in 1:5 scale.

Design method

By using the design thinking methodology to structure the design process was overall highly beneficial. More specifically it helped to structure the design process by providing a logical and efficient way to explore the subject without constraining the creative thinking. This was done because in the design thinking the steps are not mandatory to be executed in a linear manner the designer can choose which step to complete next, giving a lot of freedom in the process and allow for fast iterations of the design. Also, the use of physical prototypes and soft models to test and advance the design is encouraged by this method which helped create successful concepts. Adopting short design cycles gives more confidence to the designer that the design effort will meet the requirements of the client since feedback is received early in the design process this means that the appropriate design direction could be chosen faster.

Physical Prototyping (PP)

In the process there were used two types of physical prototypes, **soft models** and **presentation models**. The use of soft models early in the design process clearly helped in the generation of new concepts and steered the design in a better direction. Since in the first iteration of the ideation all the concepts had a common design language, of two distinct volumes, a base and the chamber on top. This can be characterized as design fixation according to Youmans & Arciszewski, (2014). Since all the concepts had this core feature and no new ideas could be generated. After the use of soft prototypes, a new design direction was generated with a more integrated base and chamber. The use of presentation models to aid in the presentation of the concepts was very successful and was highly valued by the client. The advantages of communicating the design with a presentation models are considerable. Since the client can see the concept from all angles and can understand the design intention effortlessly. This proves the quote "prototypes are worth a thousand pictures". (Kelly, 2001). Overall the contribution of physical prototypes in the design process is evaluated as excellent since the soft models helped in the ideation and generation of better concepts and the presentation models were highly effective in communicating the design to the client.

SOLZAIMA

#1 FRAME


Front view


Side view


Back view

SOLZAIMA

#2 LIGHT

Front view

Side view

Back view

#3 I-STOVE

Front view

Side view

Back view

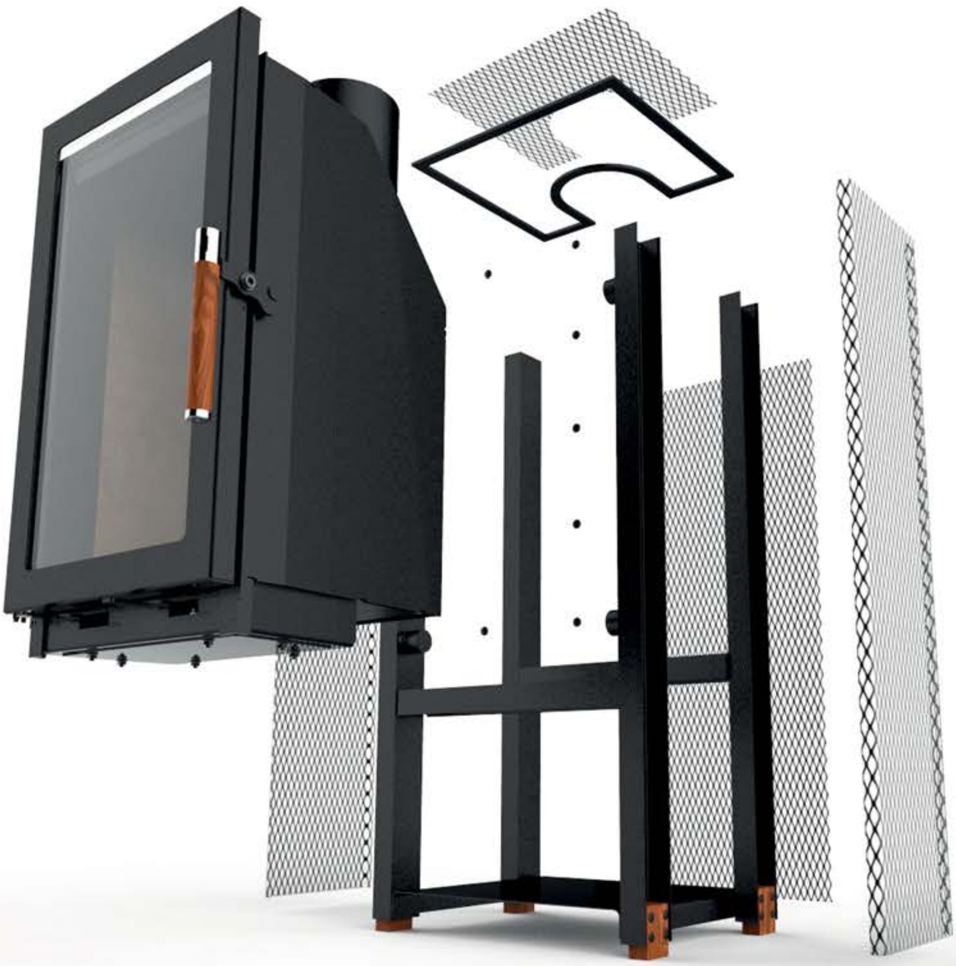
SOLZAIMA

#4 MESH

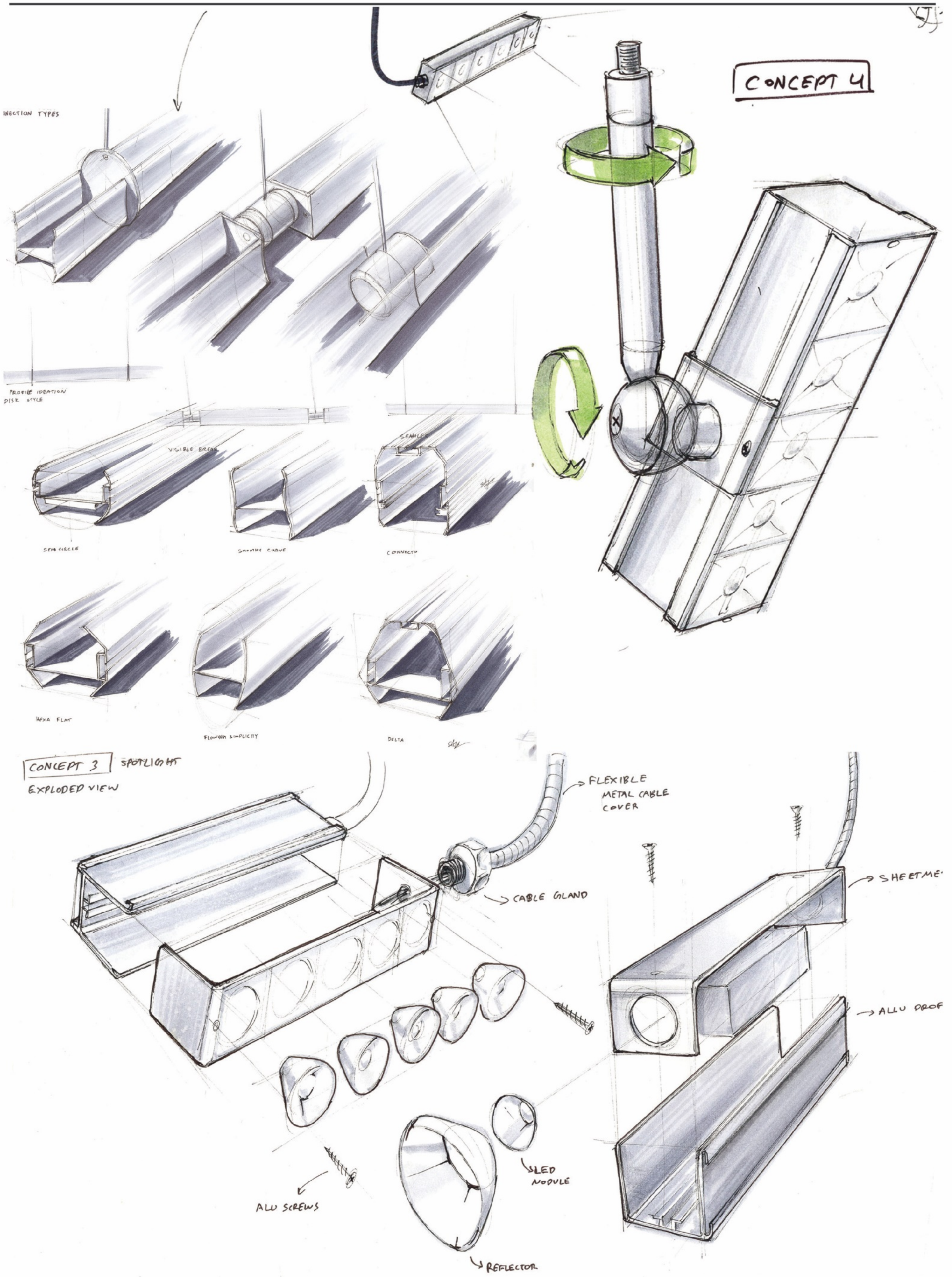
Front view

Side view

Back view



Case study 2
Systion LED **MULTI**



4.6. Case study 2.

Introduction

Client: SYSTION

Systion is a Portuguese based company working in the electronics industry with more than 20 years of experience in this sector. Providing manufacturing solutions in electronics, with extensive experience in the fields of medical, automotive, communications, industrial and commodities market.

Figure 53: Systion logo (Systion, n.d)

Website: http://www.systion.pt/

Tag line: *"Systems innovation behind your brand"*

Briefing

The need was to create a better and more cost-effective solution for the illumination of the linear selves and the general indoor retail areas of supermarkets. The main problem with current solutions according to the client was that linear lights couldn't be directed toward a specific point of interest and as such the existing linear lighting solutions were less efficient and created discomfort to the user by generating unnecessary reflection.

More specifically the developed concept would had to meet the following criteria:

- Direct light easily and intuitively
- Flexible and modular system
- Cost effective
- Easily serviceable
- Main material had to be Aluminum extrusions

Project Name: LED Multi

Project duration: 6/3/2017 - 28/4/2017

Design process

Design process overview

The design objective was to create a innovative linear lighting solution for use in retail stores illumination. Some of the important aspects of the design to be resolved was the necessity to come up with a simple, robust and cost-effective mechanism that could direct light in the desired direction. In the beginning of the design process two designers worked together (the intern and a fellow designer from INNGAGE) after the first design iteration the intern continued the development independently. Since in the first stage this project was a group project communication between the designers was essential for a productive work. For this reason, appropriate tools and techniques were selected to structure the design process. There were multiple iteration of the design and the use of rapid prototyping was essential during this process. In total there were three iterations and some subsequent refinements of the design.

Iteration 1

Due to the engineering nature of the project a more engineering-oriented method was initially selected. Following the Phal and Beitz methodology the first step was to plan the design activity, clarify the task, summarize requirements and conduct market, technology and competitors research. To get better insights in the problem a field research was also conducted were the problems of existing solutions were experienced in first hand (Figure 54). After the completion of the research all the data collected were analyzed and presented to the MP in a group meeting, using tools that can increase communication and cooperation such as the **group brainstorming, group mind mapping** (Figure 55). In this phase quiet, detailed specification of the developed concepts had to be defined according to the Phal & Beitz methodology. This was not possible at this stage of the design since not enough data had been provided by the customer such as the LED module dimensions, transformer size, etc… More over a principle solution could not be identified in the most important aspects of the design, one of which was the control of the direction of the light. This anomaly was created by the design and the client not working at the same pace. More specifically the client only presented a vision and a problem but didn't provide any further details in technical specifications about the possible solution.

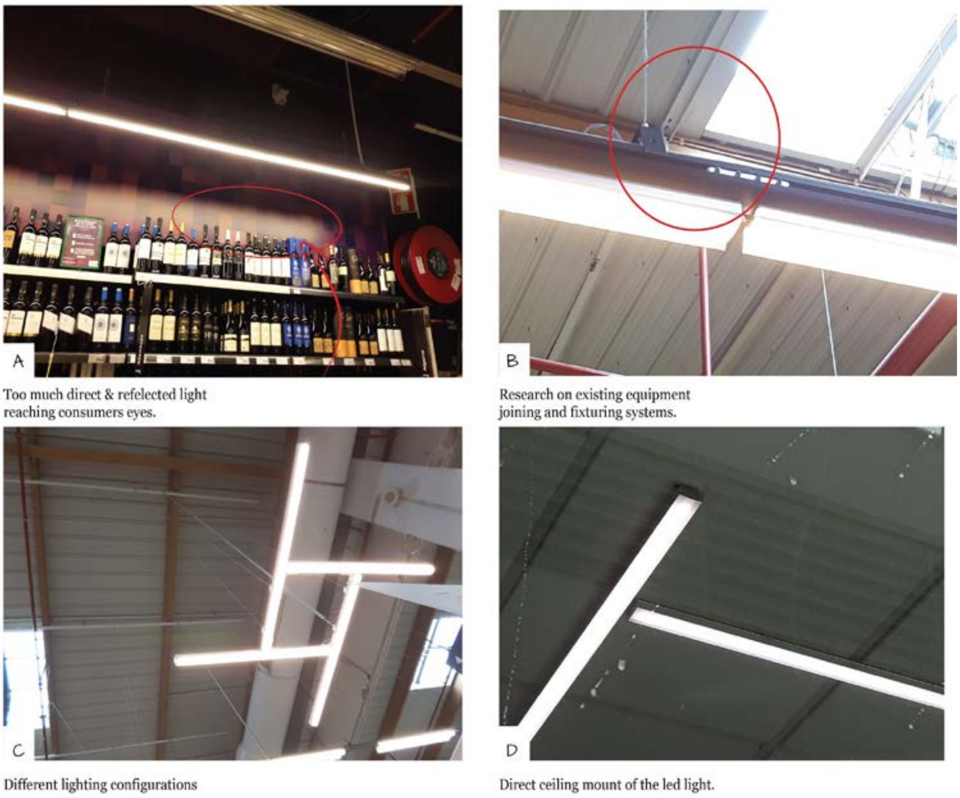


Figure 54: Field research in Jumbo supermarket.

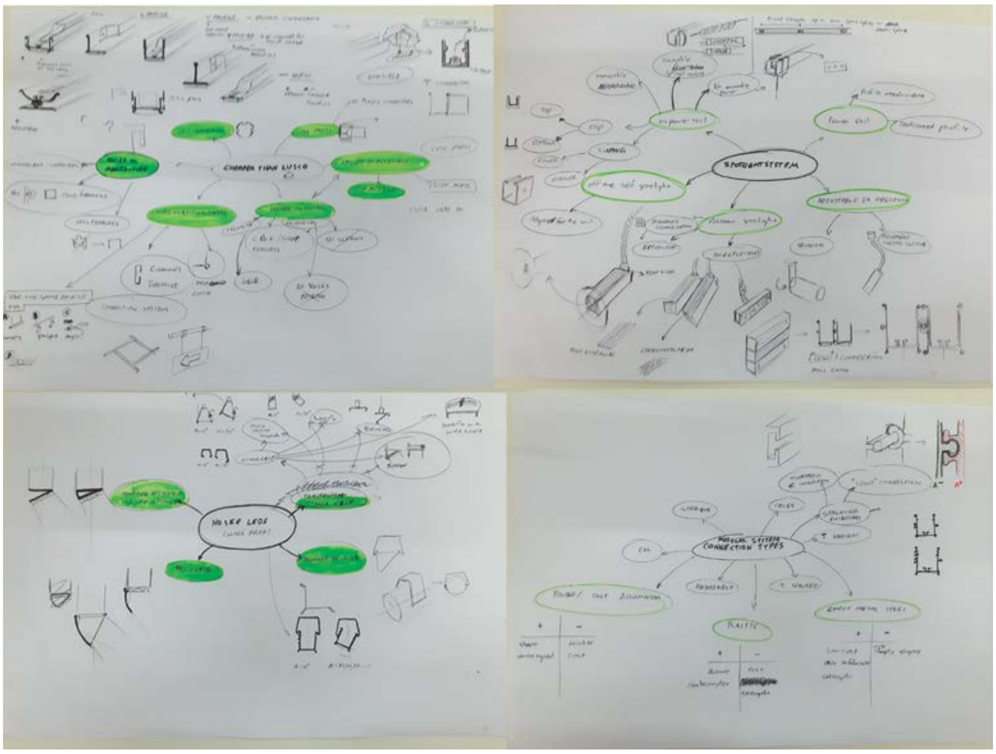


Figure 55: Mind Map and brainstorming panels created in group.

This meant that many criteria and steps of this method couldn't be met and had to be skipped. At this point it was decided that a less defined and a more explorational design approach would be more beneficial to schedule the design process.

The Design Thinking approach

In the second iteration the Design thinking method was selected to structure the design process.

Empathize & Define

These two phases were in most of the part covered from the previous method so not much work was done in this phase.

Ideation

Right after the empathize and define phase the ideation phase started with team ideation sketching sessions and brainstorming. Tools that were used during this phase were: **group brainstorming, ideation sketching and moodboards.**

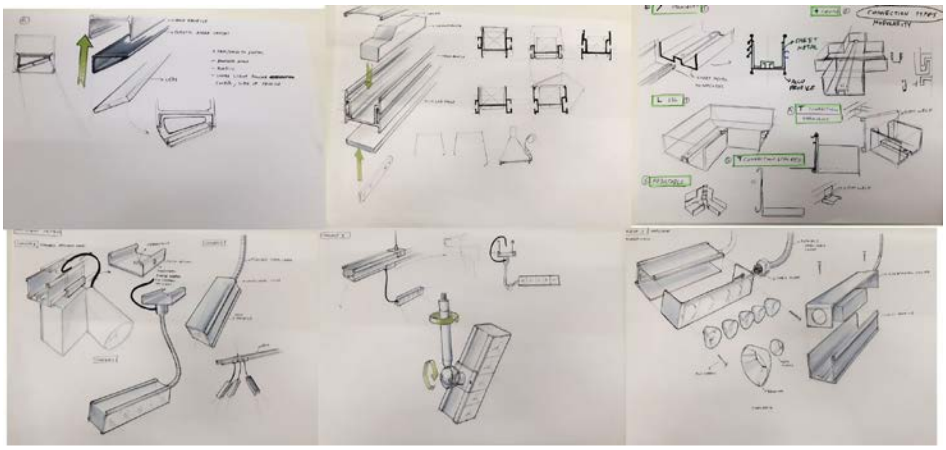


Figure 56:Ideation sketching of possible solutions

One of the main problems encountered was the design of the mechanism that could enable the light to be directed easily and intuitively. This had to be as simple and cost-effective as possible to meet the client's demand for a cost-effective and innovative solution. The design team working in group generating ideas and then sketching them trying to think as much as possible outside of the box (Figure 56). The ideation phase of the first design iteration finished with the preliminary CAD design of the selected concepts and presented to the MP in a group meeting. In the end of the meeting there was the selection of which concepts to be prototyped and tested.

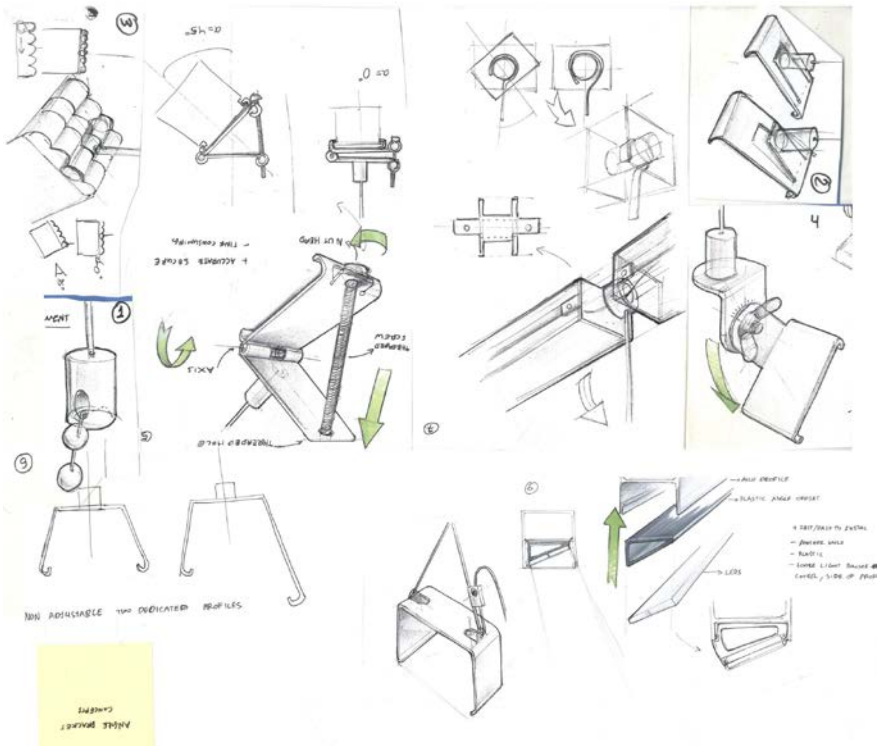


Figure 57:Ideation sketching for the linear LED rotational mechanism

Prototype

For the construction of the prototypes RP was utilized to produce accurate physical models from the CAD data. The FFF 3dpriner was used with in the design studio, to produce durable and functional presentation models that could be tested and evaluated. (Figure 58).

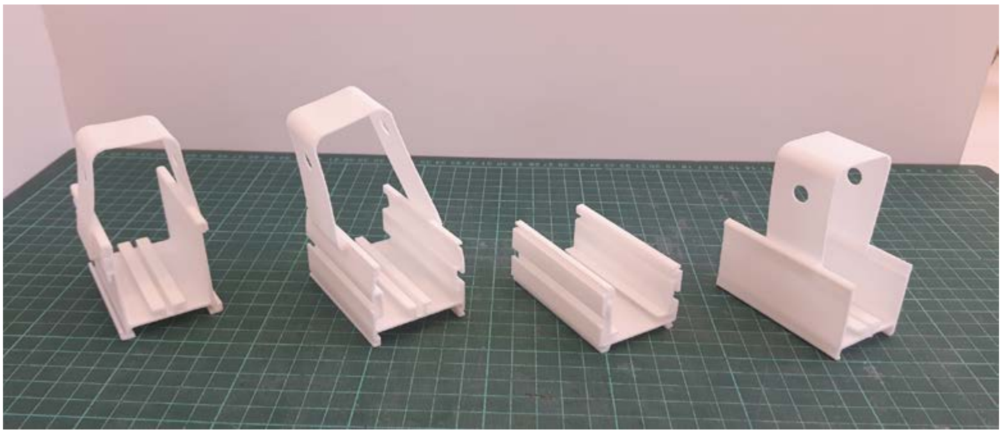


Figure 58:Prototypes created in the first design iteration.

Test

The prototypes were tested and evaluated. It was found during testing that the initially selected rotational approach using different types of sheet metal bracket was inefficient, created safety concerns by not securing the profile adequately and was not user friendly in setting the desired angle of the linear light. First iteration summarized (Figure 59)

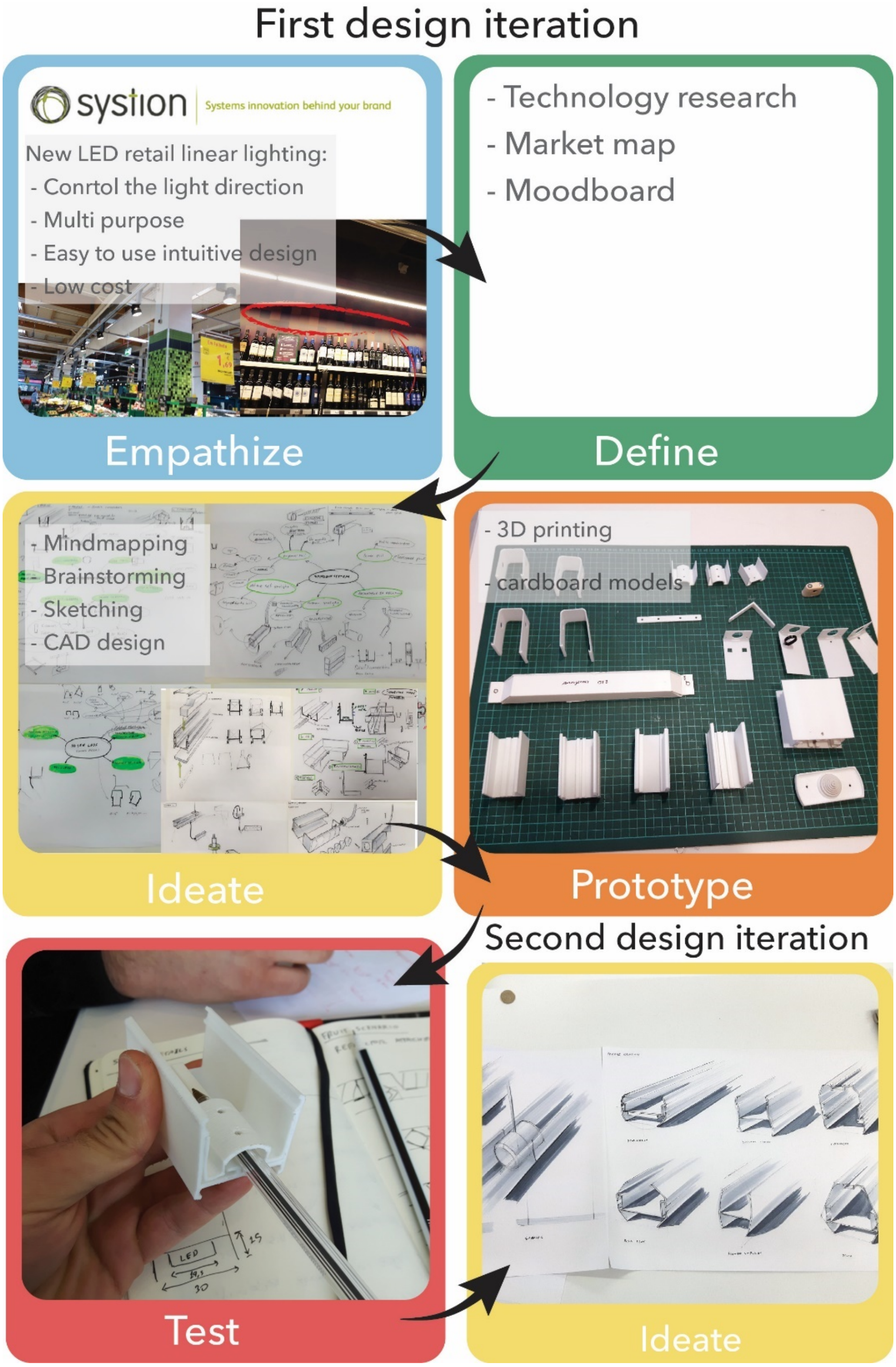


Figure 59: First design iteration of Project "LED Multi" for Systion

Iteration 2

After the conclusion of the first iteration it was apparent that a good solution for controlling the direction of the light had not been found yet. So there was subsequent research done to find an appropriate mechanism that could be used in the concept. From the research four probable solutions were identified (Figure 60).

Figure 60:Probable solutions of rotational mechanism used in other applications.

Ideation

In this phase first there was ideation sketching and then the concepts were designed in a parametric design software with Solidworks. The results of the ideation phase were presented to the MP and the selection was made to move forward and prototype four profile concepts and four rotation mechanism designs (Figure 61).

Figure 61: Generated concepts and selection process.(Project: "LED Multi" Systion)

The prototypes were fabricated exclusively with AM technology. In the testing phase, only two mechanisms provided satisfactory results. Moreover, a problem was identified with the cable passing from one led profile to the other when the led profiles were rotated in different degrees (figure 62).

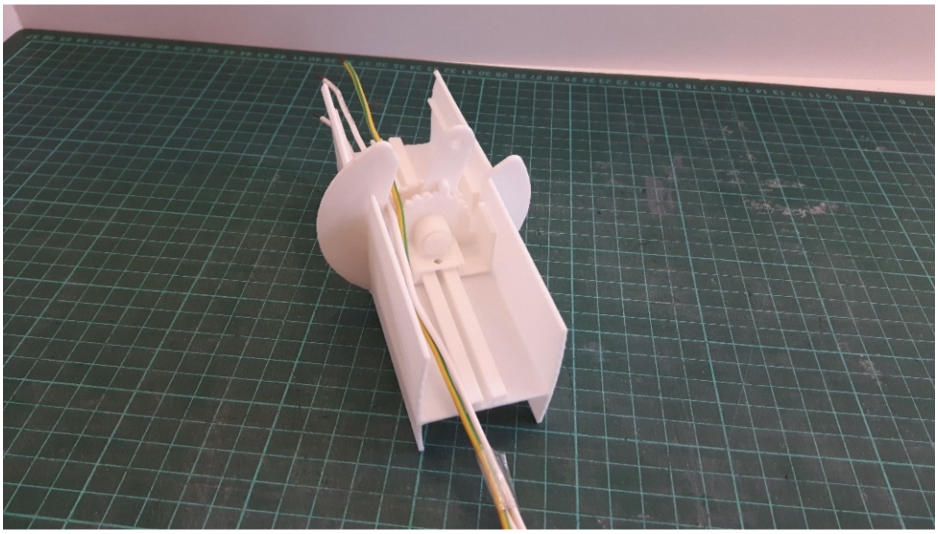


Figure 62: Testing of the concept during the second design iteration.

The prototypes were presented to the client by the MP and the feedback from the meeting was used for the third iteration of the design. In (Figure 62) is summarized the design process of the second iteration.

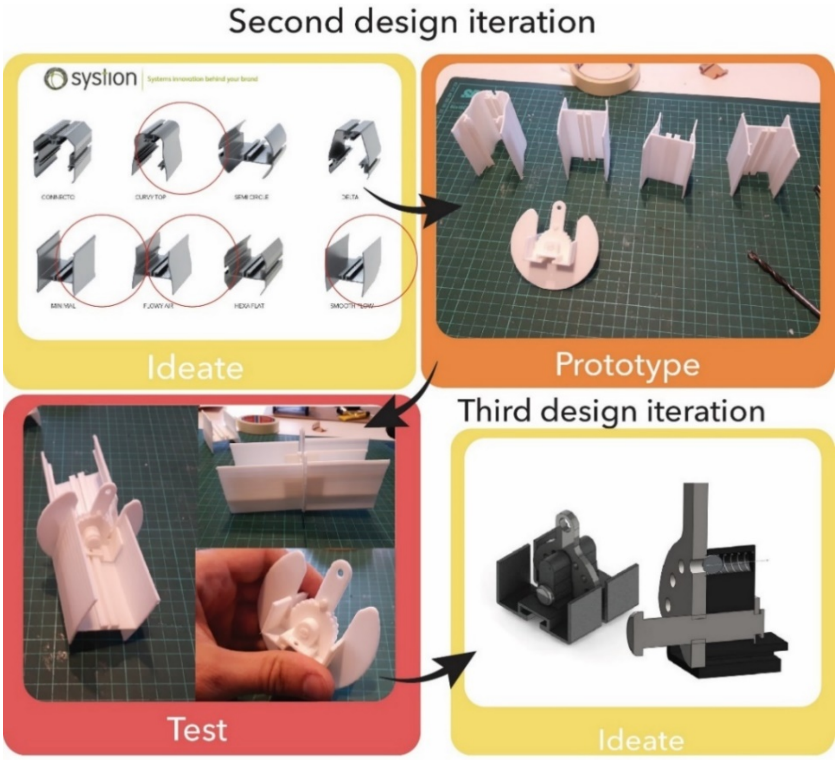


Figure 63: Second Design iteration two summarized.

Iteration three

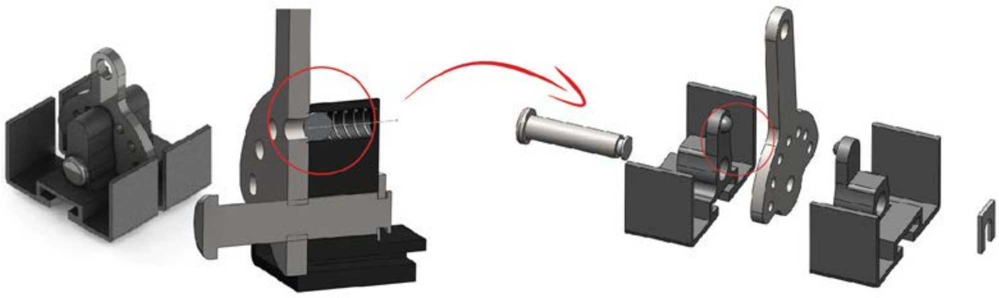


Figure 64: Simplification of the rotational mechanism due to prototyping constrains

In the third iteration, there was a refinement and further development of the selected design solutions. Some important aspects of the design had to be reworked in this iteration, for example the rotational mechanism had to be further developed towards a more robust and reliable indexing system. Due to the limitations of the FFF 3D printer that was available at the design studio some simplifications were necessary during the prototyping phase. The spring-loaded ball mechanism that was found during the research phase was not able to be prototype, scorching the component would take too much time instead it was decided to simulate the function of this mechanism with a semi flexible plastic part. This design decision proved very effective during testing and was adopted as the primary solution for the indexing mechanism (figure 64).

Another issue that needed to be solved was the cable management from one profile to the other. This was only discovered after using physical prototypes in the testing phase (Figure 62). The solution to this problem was given by using a M16 threaded tube to function both as a joining system of the two profiles and at the same time facilitate the passing of the cable from one profile to the other. After prototyping testing and validating of this solution. The design was presented to the client by the MP and the concept was accepted.

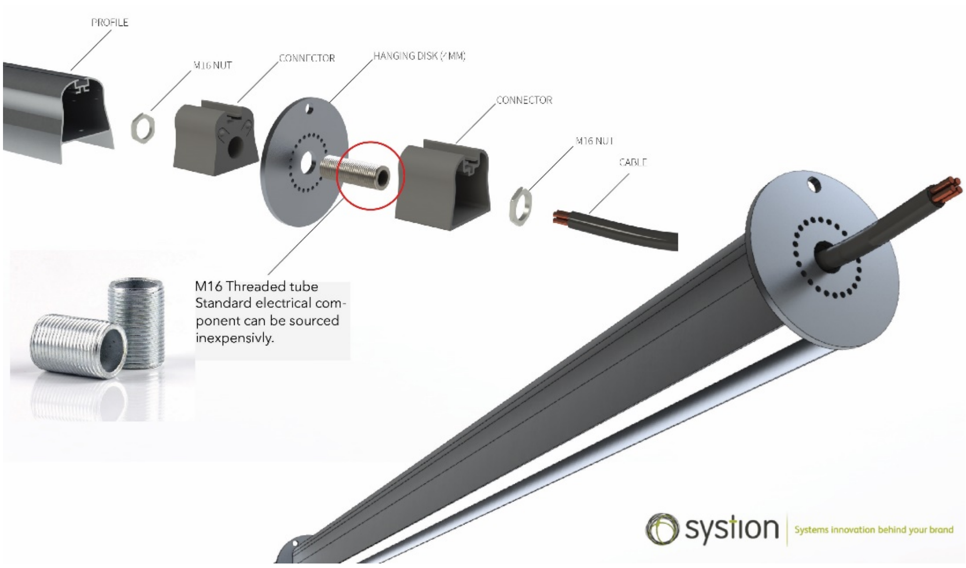


Figure 65: The result of the third design iteration, resulted in incorporating the main principle solutions and was accepted by the client.

Physical prototypes used in the Design process

The creation of physical prototypes was abundant in this project and played a key in the problem-solving process. The physical prototypes were constructed predominantly with RP additively using the FFF 3D printer Hephestos 2. The material used was PLA plastic and all models were printed in 1/1 scale. Figure 64 shows the scale in which AM fabricated physical prototypes were created.

Figure 66:Part of the physical prototypes created during the design process.

Additively manufactured prototypes played a key role in this project since the object was relatively easy to 3D model and rather difficult to fabricate by hand. 3D printing was the best solution to create fast and accurately prototypes directly from the CAD data, so the concept idea could be tested fast.

Results

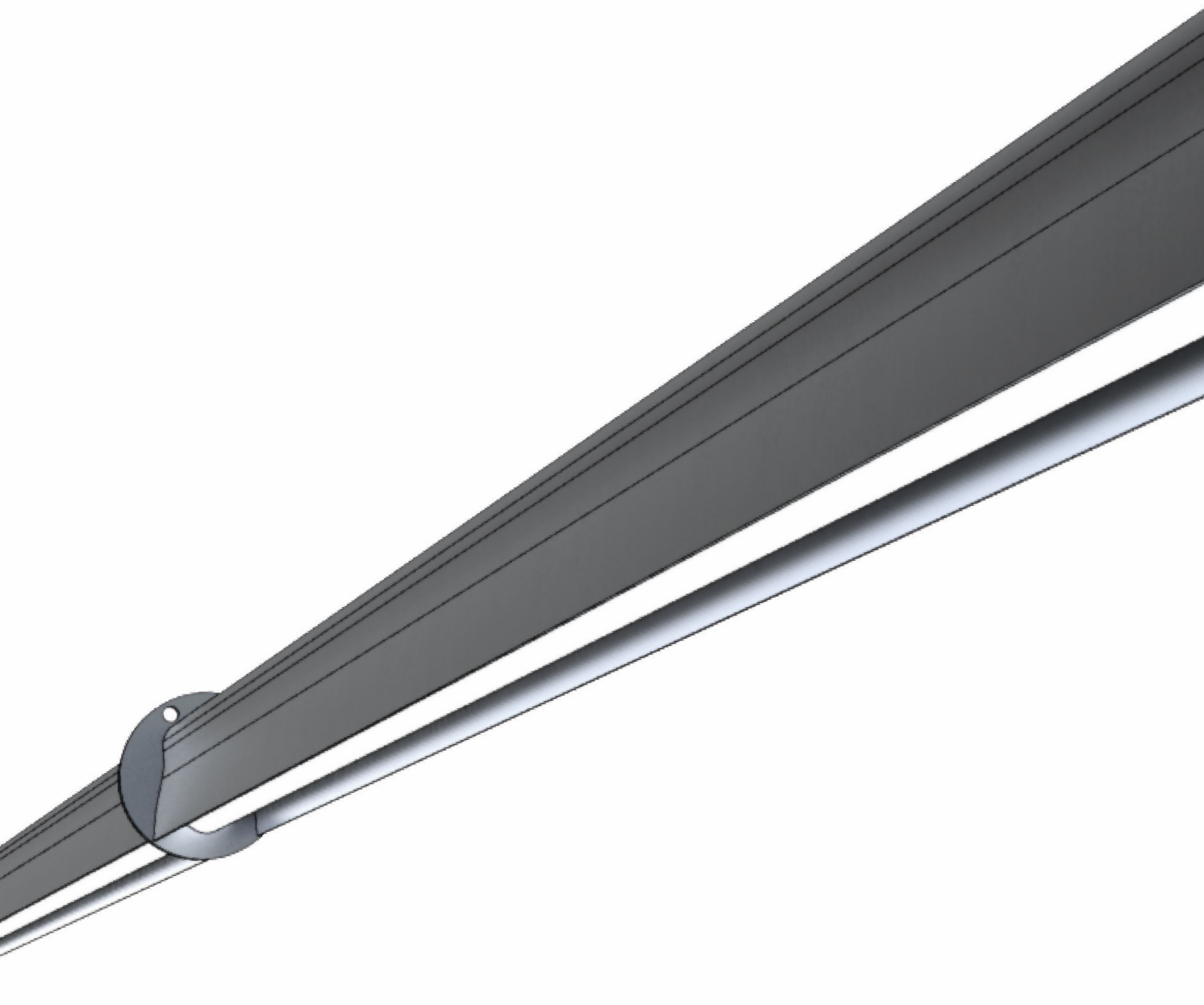
Design method

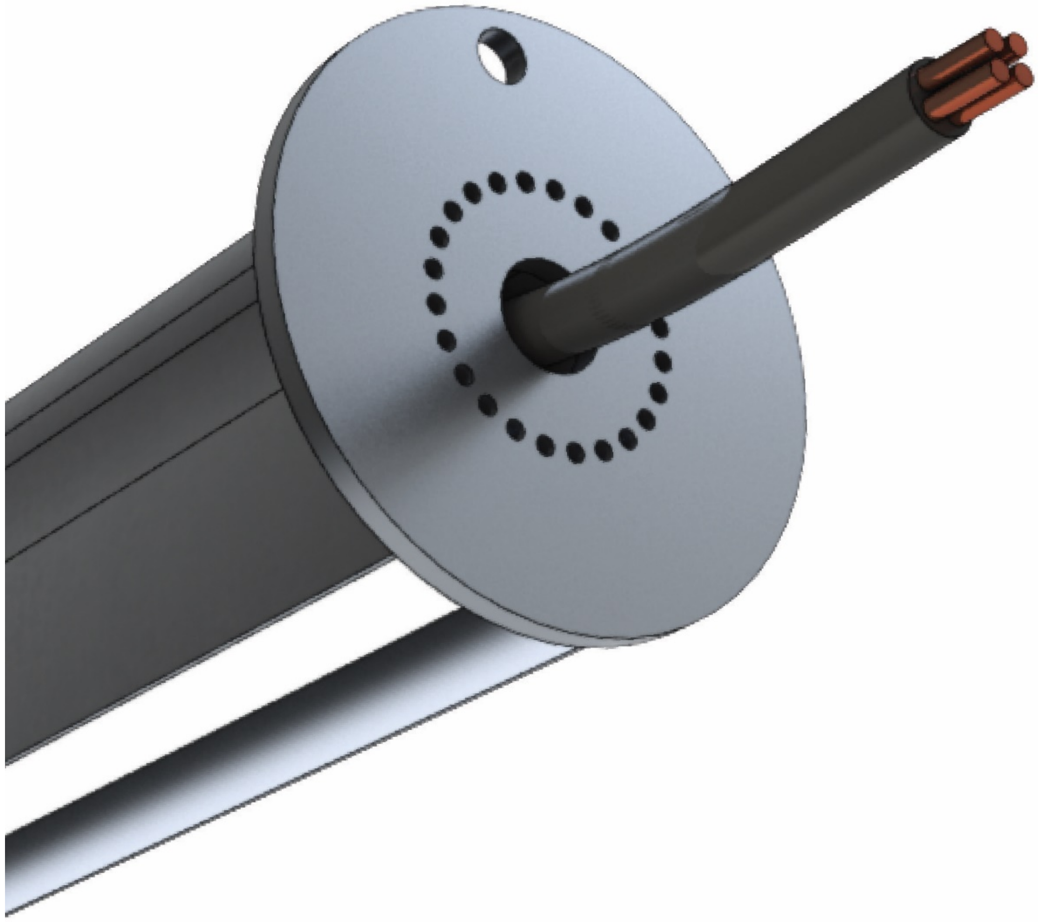
The first selected design method (Pahl & Beitz) couldn't be effectively applied since most of the detailed requirements were not defined by the client in the beginning of the project. This kind of implications or anomalies are described according to Jensen & Andreasen (2010). In this case the anomaly was created by the client not providing enough specification about important technical aspects of the design and left those to be defined in a later stage. Design thinking method, on the other hand, was much better in structuring this ill-defined problem where the outcome of the design work was not apparent in the begging of the project. Based on the design philosophy of doing design more than analyzing and calculating, many prototypes were created and tested. The design solutions came through this iterative process of trial and error. Tools such as the visual mind mapping and group brainstorming proved very effective in combining ideas and contributed significantly in the collaboration between the designers.

Physical Prototypes

Major design breakthroughs and solutions in the design came from the use of physical prototypes in this project. One of the most important would be the development of a robust simple and intuitive to use rotational mechanism. This happened due to the simplification of the mechanism for prototyping which proved to be functional and gave good results after testing. As an added benefit this solution reduced the complexity and the number of parts in the system, this simplification was warmly accepted by the customer. Another would be the identification of the interference of the connecting cable between the profiles and the interference during the rotation. In which physical prototyping and testing highlighted and later helped in identifying a solution. Physical prototypes played a key role in collaborating and communicating the design between the design team and during the presentation of the concepts to the client by the MP. These unexpected solutions together with the further optimization of the shape of the profile came from the creation of the physical prototypes and probably wouldn't have been thought if prototyping hadn't been implemented.

Systems innovation behind your brand





Systion LED **Multi**

Case study 3
Project H2O water filter

4.7. Case stud 3

Introduction

Client: N/A (INNGAGE internally developed project)

The purpose of this project was to develop material to include in the portfolio of projects of INNGAGE. This material would be used as a communication of INNGAGE's design services to potential clients. Also, since this would be an explorational project, it was used as an opportunity to advance the skills of the intern in presentation sketching and in more advanced prototyping methods.

Briefing

The vision of this project was to create a better water drinking experience. Through the development of a new line of water purifying systems that can provide clean and customizable water, depending the user's needs. This concept would enable the user to customize the water's flavor, and mineral content. For example: "if a user wants stronger bones can use this device to adjust the mineral content of the water by adding certain minerals that can improve bone mass". All concept should have the option of the user using cartridges with different mineral contents or different flavors.

The project more specifically required the development of three concepts:

- Home use, direct faucet attachment
- Home use, desktop stand-alone unit
- Professional use, large form factor machine

The concepts had to have a reservoir or a compartment were

*In the following pages is presented only the development of the faucet concept model. Due to time and resources constrains part of the prototyping process was completed outside of INNGAGE design studio after the internship.

Project Name: Project H2O

Project duration:

19 /2/2017 – 10 /2/ 2017 (Research, Ideation)

12/6/2017 – 16/6/2017 (Concept development)

15/6/2017 – 30/6/2017 (Development, Prototyping)

Design process overview

Although this project was not developed for an actual client the standard procedure of HCD approach was followed. Including all the steps from research and empathize with the user's needs, the definition of the desired features and appearance followed by ideation and prototyping. In this project considerable effort was put in the phases of ideation and prototyping. More specifically prototyping was used as a tool to refine and shape of the highly complex surfaces that the concept required. To do so the intern had to come up with his own workflow in combining RP and manual modeling techniques for prototyping.

Empathize-Define

The project started with the empathize phase and tools such as market mapping mood board and trend research were used to identify the user's profile what are their needs. Based on those insights the design language was defined by the creation of moodboards (Figure 67) Since the appearance of a product is the first impression and affects the user in a visceral level a highly refined exterior design with complex surface was decide that would increase desirability of the product.

Figure 67:Tools used during the research phase.

Ideate

Based on the research the ideation phase started with a lot of sketching, having the aim to create a very curvy and highly refined form that resembles automotive design language. For this first draft sketches with fine-liner were created and later more refined presentation drawings were rendered with color (Figure 68). By the end of the ideation phase, a rough CAD model was created in Rhino3D to be used as a base for further optimization of the shape. Figure 69 provides a visual summary of the first design iteration.

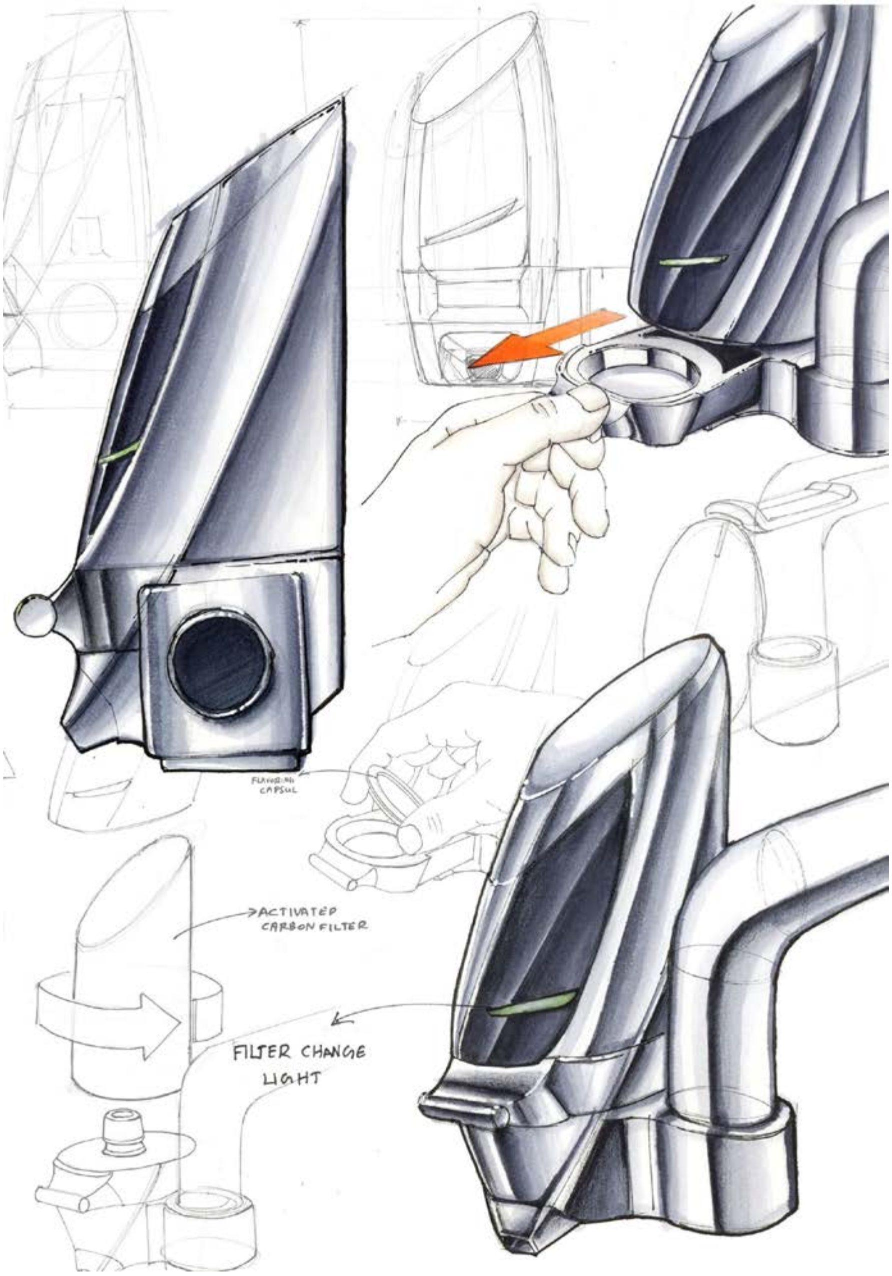


Figure 68:Water filter ideation and presentation sketches.

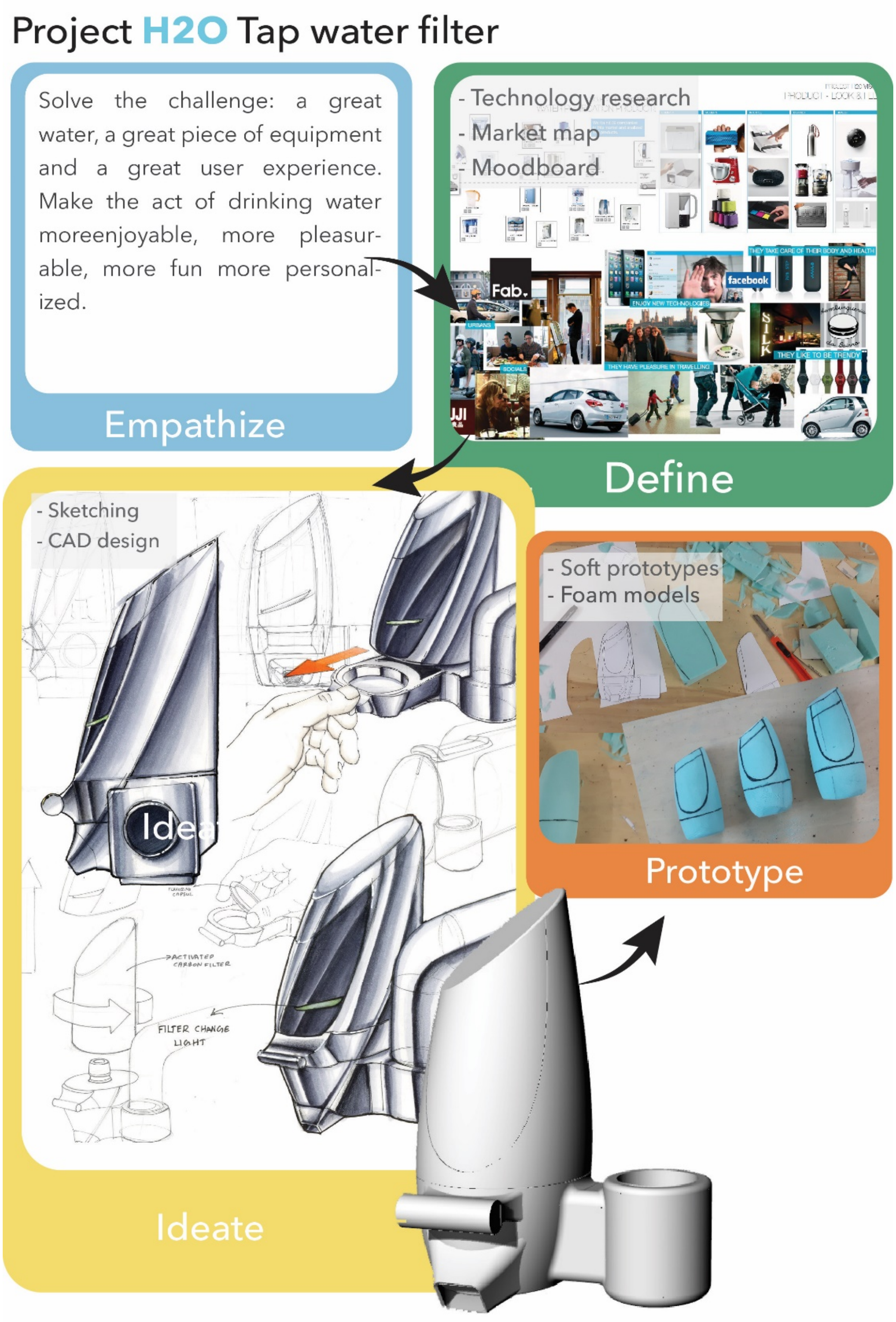


Figure 69:A visual summary of the first design iteration

Physical Prototyping in the design process

To make sure the water filter will have the correct proportions and will look right when installing at the faucet. There different sized soft models were constructed from expanded polystyrene sheets. The expanded polystyrene sheets are a cost-effective alternative to the PU foam boards. Moreover, they are much easier to source since they are a common construction material used as insulation in the buildings. For the construction of the soft prototypes first, 2D drawings were generated and printed in 1:1 scale. These were used as patterns to cut and shape the polystyrene board. For the joining of more than one sheets of polystyrene board white glue was used. The shaping was done using an x-acto knife and various grits of sandpaper, starting with 80 grit and finishing to 150 grit.

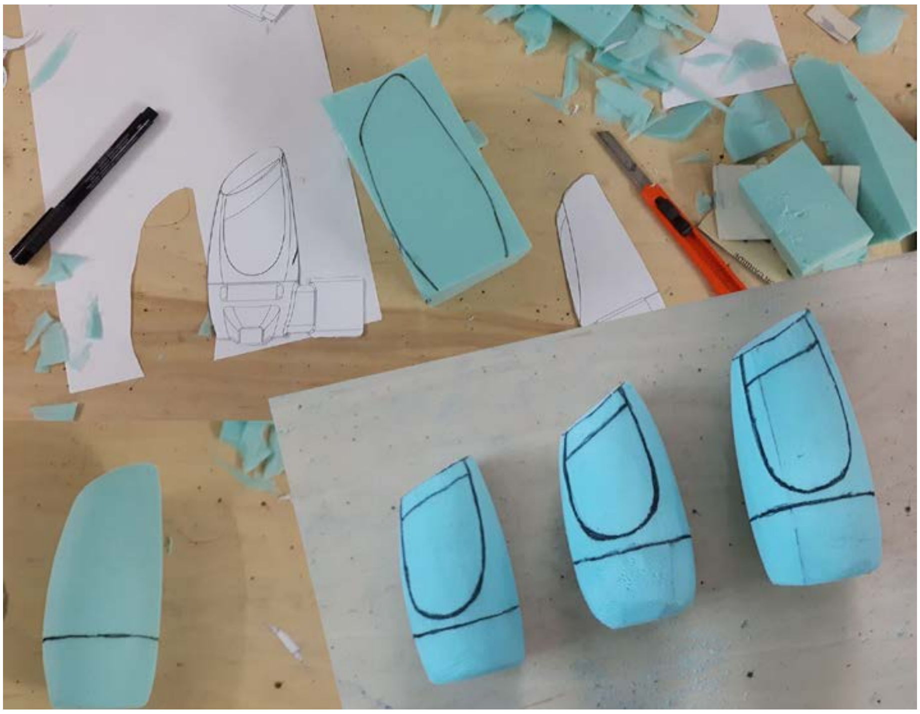


Figure 70: Soft model fabrication process.

Subtractive Rapid Prototyping (RP)

After establishing the correct size, a more accurate prototype was created using an RP subtractive fabrication, with CNC milling. A CNC mill was not available in INNGAGE, so this kind of work was done outside the design studio. This was possible since the intern had access to this kind of machinery. The fabrication of physical model with CNC milling is quite similar to other RP technologies. First we start with a CAD model then the toolpaths are generated, from the toolpaths the g-code is “posted”. This g-code is transferred to the machine which fabricates the part with no user intervention. For this purpose, Rhino CAM software was used to generate the toolpaths from the 3D model. Rhino CAM is a plugin for Rhino and is integrated into the Rhino interface. The workflow for creating a CNC milled foam prototype was the following.

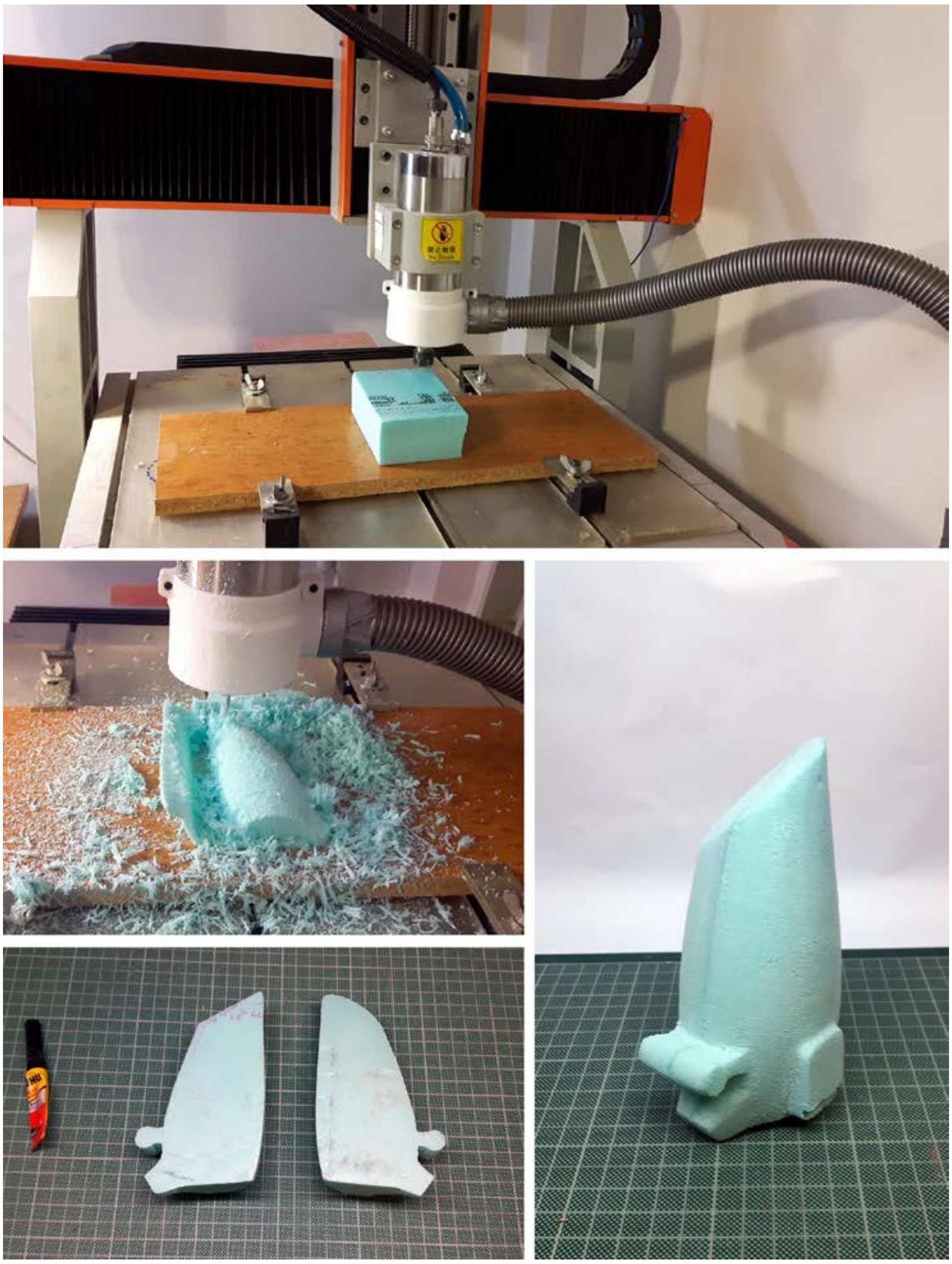


Figure 71: RP with CNC milling machine and polystyrene foam.

First, the appropriate tool was selected, in this case, was a tapered ball endmill of 2mm in diameter. Then the desired machining approach was defined. Two machining operations operation were required for the fabrication of this prototype Roughing and Parallel finishing. After completing the simulation and verification of the toolpaths, the generated g-code was "posted" and transferred to the CNC machine (Figure 72). For the machining of the prototype, the model was split into halves and after the completion of the machining operations the two halves were joined together with white glue to form the full 3D model (Figure 71). This method of RP is very fast and cost efficient since the raw material is very cheap. It is more suitable for simple models with no undercuts and usually medium to large models, were 3D printing would be impractical since it would require too much time.

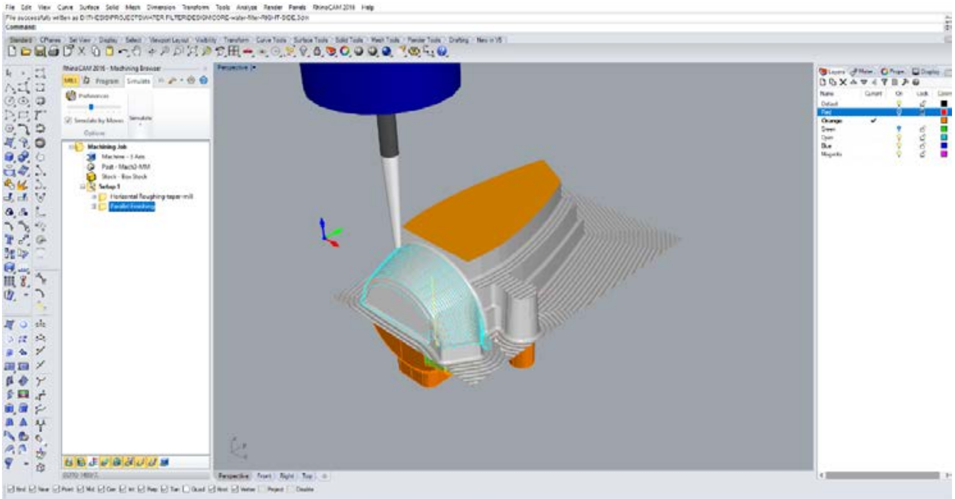


Figure 72: Screenshot from the toolpath simulation with RhinoCAM plugin for Rhino3D.

Advanced prototyping combination of Manual and RP tools

As seen in the literature review even in today's product design process where there is an abundance of digital tools available, for highly complex surfaces designers still choose to work with clay to prototype and refine their idea especially in automotive design studios. Since this concept required to have a very complex automotive inspired surface it was an excellent opportunity to apply a combination of manual and RP model making tools using oil-base clay as a medium. For the creation of the 1:1 clay prototype first the base which would provide the support for the clay had to be crated. For this, a foam core was created by a CNC milling machine. The foam core was split into two half's and secure with double-sided tape on the CNC bed so it could be machined. The foam core was made 10mm smaller so there would be sufficient space for a layer of clay to be deposited. The clay used for this project was automotive grade oil-based clay "Tech Clay" and was provided as a free sample from Kolb-Technology. This type of clay is quite hard at room temperature, so it can be shaped by CNC or by hand with metal slicks. After the completion of the foam core, clay was deposited on top. The clay was first warmed to 70 C in an oven to be more easily pliable and a layer of at least 15mm was built on top of the foam core. After the clay has cooled to a room temperature of about 20°C the shape of the model was CNC milled on the clay. The same process was followed for the other half of the model. After the completion of these process, the two halves were joined together with superglue and screwed to a 3D printed base. This was done so the clay model could be later refined by hand (figure 73).

Figure 73: Prototyping process using RP CNC milling machine and automotive grade oil-based clay from Kolb-Technology.

Hand finished and reshaping of clay model

After the CAD model was prototyped on clay the model's surface were reshaped manually using steel metal slicks and thin strips of vinyl tape as a guide. Oil based clay is a very flexible material to work with since extra material can be easily added or subtracted. This level of flexibility enables the designer to ideate in 3D and to create faster and more intuitively complex surfaces than using CAD tools. (Figure 74).

Figure 74:Progress photos of the clay model's surface refinement manually

Digitalization of the hand finished prototype

After reshaping the clay model by hand, the form of the concept had to be "capture" digitally, this process is called digitizing. It enables the creation of 3D models from point cloud data. To accomplish this there are many available methods some of which utilize very expensive equipment. Instead, a more cost-effective method was chosen called Photogrammetry. With this method, the digitalization of the object is made through a series of photographs. For this process, a simple set up was used with two diffused lights and a smooth featureless background. A total of 56 photographs were taken around the object. These photographs were then loaded to the photogrammetry software ReMake from Autodesk. After processing and comparing the pictures a point cloud data is created and an STL mesh is produced. The first try didn't yield acceptable results due to lack of features on the smooth clay surface. Since photogrammetry relies on small features on the model to complete the 3D reconstruction. To overcome this, black paint was splashed to the model to create small black spots and provide sufficient references for the software to complete the model reconstruction. The process was repeated, and the second set of photographs was loaded into the software generating an STL mesh of the model. This model was used later as the reference to reshape the 3D model, so it resembles accurately the clay prototype.

Results

The need was to create a water filter with modern appearance automotive inspired appearance, which require complex surface design. To achieve this goal a mix of traditional and digital prototyping tools were used throughout the process. In the beginning, the use of manually created prototypes with soft models helped to define fast and inexpensively the correct proportions and size of the concept. In the later stages, the combination of hand modeling methods and digital RP tools helped to create complex surfaces faster. The use of a flexible medium such as oil-based clay has the unique ability that can be both machined both by RP tools such as a CNC mill and by hand. This enables the designer to modify and experiment with the design directly without the need to pass the idea through the CAD software. The combination of manual and digital tools on the same model allowed to achieve the goal of very fluent and aesthetically pleasing lines in the design. The overall evaluation of this method are highly positive. The workflow presented here can serve as a guide for students and professional when very complex surface are required in the design (figure 75).

Shape refinement workflow visualized

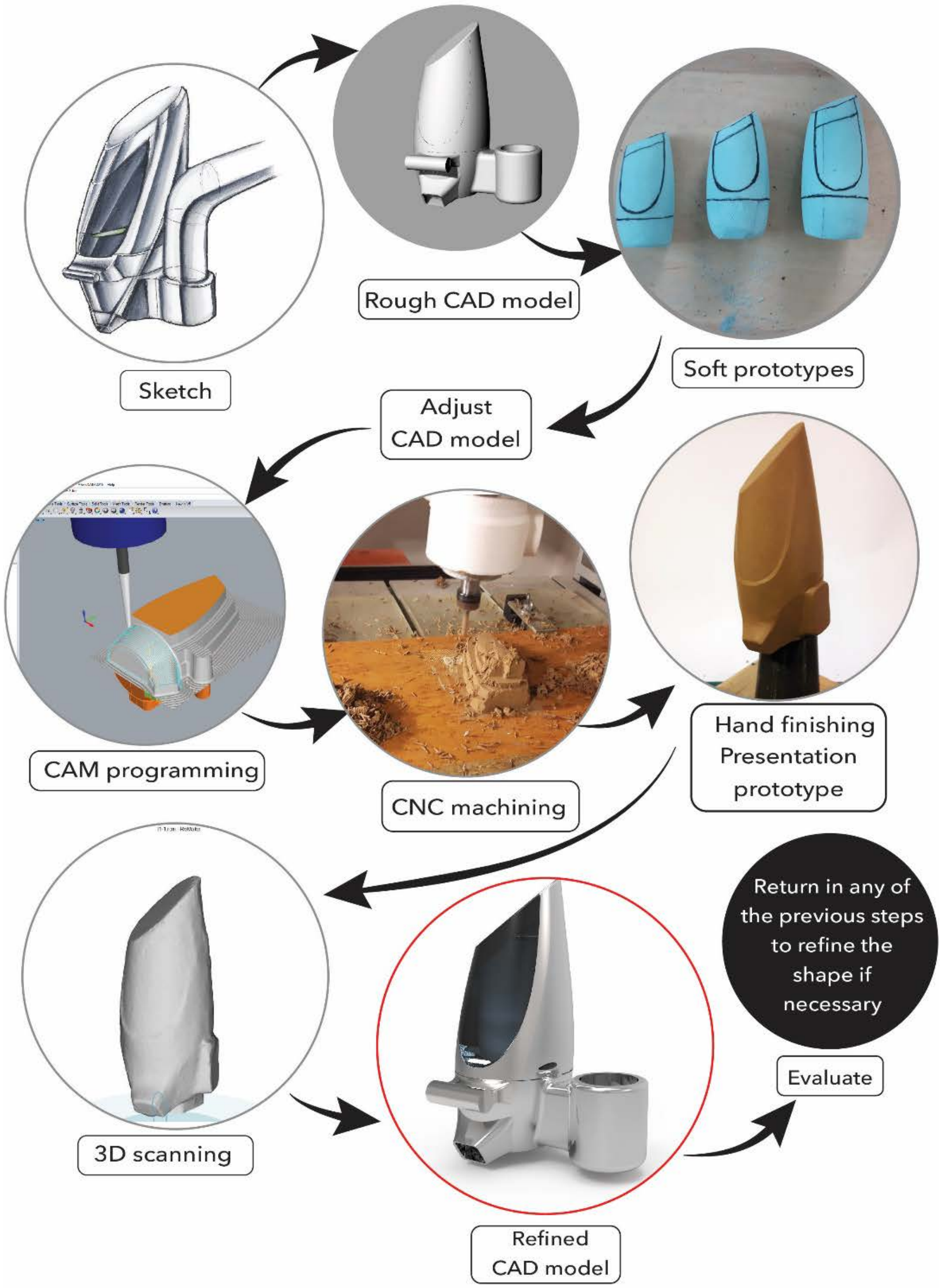


Figure 75:Form refinement process combining manual and RP tools

Project H2O

Faucet water filter

4.8. Main findings

The main findings from the five-month internship working as a full time industrial designer intern at the INNNGAGE design studio are summarized here. During these five months considerable knowledge was gained and there was an immense advancement in skills and professional attitude that is somehow difficult to summarize in the text bellow. The main findings are divide into three sections **Design process methods, Physical Prototyping** and **General professional product design skills**.

Design process methods

Using a systematic design approach to structure the design process was highly beneficial and was appreciated both within the design studio by the MP and by the clients. A systematic design approach was found to be helpful in many levels. First it helped the designer to structure the design process and provided a way of thinking on how to approach the problem in a better way. By sharing and presenting the design process it helped to communicate and justify the design decisions made during the design process. Also, by sharing and presenting the thinking behind each design decision the designer could get better feedback and more easily merge new ideas or new insights to create a better concept in the next iteration. On most of the projects during the internship the Design thinking method was used which is a HCD. This allowed to work in short design iterations and to explore and define the problem more accurately and faster by continuous prototyping and testing. Following such approach provides more confidence to the designer since feedback was received early in the design process.

Physical Prototyping (PP)

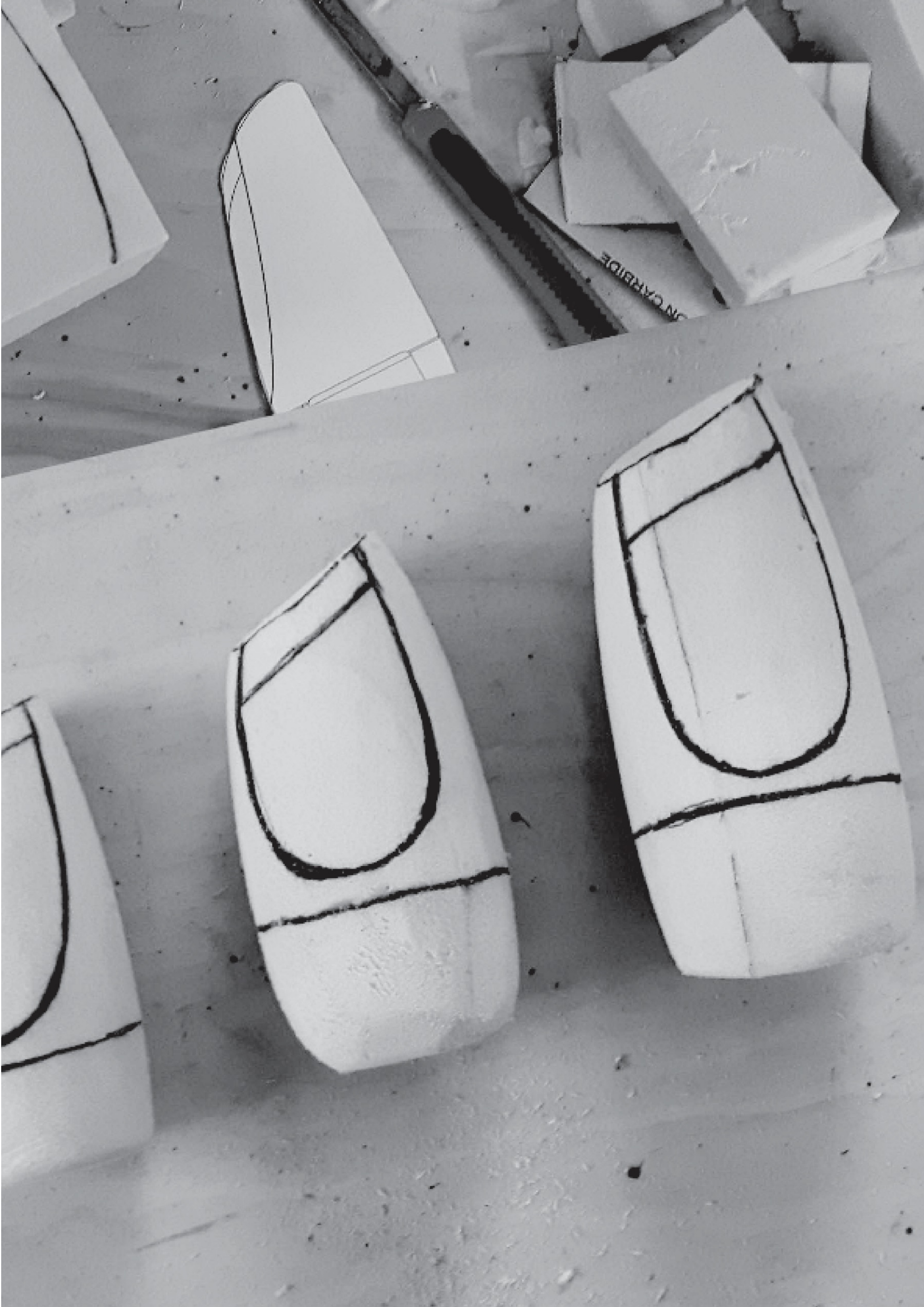
During the internship an attempt was made to use a variety of model making techniques for prototyping. This was done to gain as much practical and theoretical knowledge as possible on how to use physical prototyping (PP) in the design process. In all projects PP played a key role in advancing the design. Soft models were used in the beginning of the design process where the ideal solution was largely unknown. For the creation of soft model manual model making techniques were used predominantly, this meant that the design could progress fast since the possible solutions could be implemented directly to the model and tested on the spot. It also proved as shown in the case study of Solzaima wood stove *"naked"* soft model and PP helped to "break" the design fixation to a specific design solution and helped to think more "out of the box" by generate more concept ideas. Presentation models were used when the model needed to function like the intended final product for this kind of prototypes the use of RP tools was indispensable. The ability to create accurate physical models directly from the CAD without any user input during the fabrication process shortened the design process immensely and lightened the workload of the designer. These models were used for testing and provided insights that could have not been predicted without. This was especially true as seen in the case of Systion LED "Multi", where multiple interference between components were found after prototyping and during testing, like the cable passing through the led fixtures. Also due to PP it was developed the rotational indexing mechanism. When required to create highly complex surface as in the case study of *"project H2O" ,*tap water filter the use of a combination of manual model making and RP fabricated prototypes helped accomplish this task in a faster and more intuitive way. Since the modification could happen directly to the model and then digitalized back to the CAD software. This approach main advantage over additive RP with FDM 3D printers, is that the medium used can be oil-based clay. Which can be easily "worked" by hand whereas PLA or other polymers that are commonly used by additive manufacturing RP systems are much harder to work by hand. Presentation models proved very effective in communicating the design and were highly accepted by all stakeholders. It has to be noted here, that in some projects it was requested by the client the concepts to be presented only by physical models, since it is much easier to understand test and "feel" the design than relying on text documentation or renderings. Physical prototyping played a key role on all the projects within this work and considerable knowledge was gained for the intern on **why** to and **how** to use PP together with invaluable **practical** experience.

General professional skills

The aim of this work was also to get experience in the work environment and introduce the author to the labor market. The acquisition of professional work experience is highly appreciated and most of the time is set as a prerequisite when applying for a product design job position. From these five-month internship some worth noting results were found. Good sketching skills were very important and were highly appreciated. Having the ability, to communicate an idea quickly with a presentable and understandable sketch had huge advantage. Since it helped in the interactions with other designers and stakeholders to communicate the design very fast. In contrast using CAD software and then create renderings and presentations which slow down immensely the process. Good concept sketches can be sent to the client for concept selection early in the design process before any work is committed to CAD, rendering or prototypes, saving time and money. Last but not least good interpersonal relations in the work should be pursued and not be dismisses as secondary importance. Such relations are built by doing simple routines such as taking coffee brakes all together and having lunch at the same table. These human factors should not be underestimated for their importance and how they can positively or negatively affect the quality of work. Working in a good working environment has a direct and positive effect in creativity and as a result on the quality of work.

Part V. Main findings & Conclusions

In the final part of this work the final consideration and conclusions are presented, together with discussion material and recommendations for future research.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Part V. Final considerations & Conclusions

5. Final Considerations

This work was done with the aim to deepen the theoretical knowledge in design methods and physical prototyping (PP) used in the design process, and, at the same time, acquire practical experience in a professional environment. These topics are widely perceived as very important in the product design process.

For the success of this work first, it was important to develop a good theoretical background about the main areas that affected this work which were the design studio environment, industrial design process, design methods and physical prototyping. This knowledge was applied on real cases of product development. For this, it was crucial to get permission to share this process here and exhibit the results from founder and managing partner of INNGAGE André Gouveia

Although it was clear from the beginning that PP would play a key role in the design process, it was important to test this, on real cases of product design.

Taking into consideration the vast size of the areas chosen to research, considerable time and effort were necessary to accomplish this task. But this was considered necessary to get a holistic and deeper understanding of the subject.

During the five-month fulltime internship, a great amount of work was done. More specifically on all projects a systematic design approach was followed, using different design methods. Moreover numerous prototypes were constructed during the design process, with different modelmaking techniques, including: manual modelmaking, additive RP (FFF) , decremental RP (CNC milling) and a combinations of them.

Due to the company's policy, it was not possible to have direct contact with stakeholders outside the design studio. Feedbacks from users or clients during each stage of the design process, was received from the managing partner André Gouveia. Although a direct contact of the designer with the stakeholder would be preferred, this was not considered to have affected the outcome of this research.

This work ads to the already existing knowledge with more practical evidence that PP used together with the design thinking methodology can be very effective in structuring the creative process of product design.

5.1. Conclusions

In order to guide this Final Work, research questions were refered in the beginning and accordingly answered in its course.

What is the role and contribution of Physical Prototyping (PP) in the real-world design process?

PP plays a key role in the design process. Although this is common knowledge, this work provides more practical evidence. More specifically PP was used as a learning tool and as an excellent communication medium. The designer should be aware and choose consciously which kind of prototype should employ during the different design stages. In the first phase of the design project, creative thinking is most important, but the designer might be overwhelmed by the projects requirements. This can create stress and anxiety that could limit the creative output of the design process. Since it is well documented that modelmaking and handcrafts have a positive effect in reducing stress and anxiety (Wilson, 2015). We can argue that by engaging in physical prototyping and manual model making in the very early stages of the design can help the designer be in a more relaxed state, as a result enhance the creative thinking. This can lead in more innovative solutions. During ideation phase, rough prototypes (soft models) are an excellent tool to generate new ideas and can be used to "break" design fixation as seen in the project "Naked wood stove" for Solzaima. Prototypes proved invaluable in identifying unseen problems such as in the eg. Systion Project: LED multi where the cable connecting the two profiles would interfere with its rotation. Presentation models found to be the best way to communicate the design and were highly appreciated by the clients in all developed projects. Hard models such as in the case of Project H2O there were employed when only a very detailed exterior appearance was relevant with no working or functional components. This work ecologies the indispensable value of prototyping in the design process and underlines that manual modeling methods should not be overlooked over RP methods. For a successful design approach, a mix of manual and RP methods is recommended with manual modelmaking playing a significant role early in the design process.

How can highly complex surface that elicit a more emotional response to the user can be designed in a more intuitive way?

The appearance of the product plays a key role in the emotional response of the user and can strongly influence desirability. This is highly pursued amongst companies operating in the consumer market since having a better more desirable design can create a competitive advantage and lead to increased sales. The product's appearance affects the user at the visceral level, where subconsciously is formed the first impression of a product which is mostly affected by aesthetics and the look and feel of the product. When required highly complex surface similar found to automotive design required to use a more special modeling approach because the creation of such design can be challenged with the common approach working directly in CAD software.

The combination of manual modelling methods, using clay and RP decremental technology, proved to be highly effective. More specifically working in CAD and then prototyping with RP with CNC milling on oil-based allowed the refinement of the surface at a very high level in a faster and more intuitive way. Since the changes would happen directly on the clay model without the need to use CAD and then to prototype again. This approach is recommended when the designer needs to refine a from and experiment with many possible aesthetic approaches fast and in an intuitive manner. The disadvantage is the requirement of considerable more investment in equipment and higher technical expertise in successfully following this approach. This work provides a useful guide for designers or other professionals that would like to experiment with this technique of modeling.

What was the practical experience using different design methods in the design process?

In all the projects a systematic design approach was followed.

Depending on the project type, different design methods were applied. The Pahl & Beitz and the design thinking method. It is widely accepted that the Pahl & Beitz design process method is one of the best examples of the systematic design approach. It is also considered as "the bible" of the design process. Based on this it was selected to guide the designing of the project LED multi for Systion due to the project's engineering nature.

The implementation of this method can sometimes feature some serious implications or anomalies, as described by Jensen & Andreasen (2010). In this project, very little was defined from the side of the client and there was no authority given to the designer to specify. This unforeseen anomaly in real-life product development processes was caused because the designer and the client didn't work at the same pace. In this situation, the designer had to start the design process without important specifications stated by the client, those specifications were left to be defined at a later point. In no point, a diminishing of the importance of the Pahl & Beitz method is attempted, but it is questioned its suitability for structuring the very early stages of the design process of innovative products were most if not all the specification are unknown.

In contrast, design thinking method could "cope" better with such uncertainties due to its iterative nature. Where the designer prototypes and test and learns along the design process. This method proved able to structure the design process of the project when very little info was given as input from the client, leaving the potential outcome of the solution extremely board and undefined. More specifically, it proved a valuable tool in structuring the design process without confining or constraining creative thinking. Since the design activity is divided into logical steps, but no explicit order is defined, or specific requirements are made before advancing to the next step. The designer is encouraged more to iterate and test than to elaborate and calculate. This trial and error method, with fast iterations, was found to be way more effective in defining and solving the problem than research and analysis trying to predict what would be the desired solution. This in combination with PP and especially RP additive manufactured prototypes enables the designer to solve a wide range of problems faster.

As seen from the literature review someone can observe that over the years as the methods have evolved there is a constant shift from more defined methods "heavyweight", to less defined "lightweight" and more abstract. These methods can be better defined as a way of thinking or values (e.g. Design thinking, Agile). These methods focus more in human factors of the user that is applying the method and provide tools that can help the designer by taking into consideration the limitation of the human nature such as cognitive ability, time management the ability to focus and concentrate.

Focusing more in providing a way of thinking to aid the designer in learning and exploring the problem along with time management and collaboration tools and workflows. Also, there is a shift from linear progress methods (e.g. Waterfall) to the realization that iterations and feedback are very important for the successful development of a solution (e.g. Front-end process, "V" model, Design thinking, Scrum). The use of design methods to structure the design process is widely accepted that is beneficial in the design process. But it is up to the designer's to select the appropriate one, according to project needs, culture, team composition and personal preference.

Can designer-client relation be improved by the PP approach?

It is well documented that prototypes could help to communicate an idea. According to Kelly (2001), if an image is worth a thousand words, then a prototype is worth a thousand images. Product design is a complicated procedure and during the product development there are always multiple stakeholders involved. The communication between all of them is crucial for the development of the correct product in a timely manner and within budget. PP proved to be highly effective, in communicating the design and physical prototypes when they were used in meetings between the design team and the client. It is recommended as the preferred way in communicating the design.

What sort of teamwork skills can we achieve involving Physical Prototypes processes?

Physical Prototypes are the centerpiece of most team meetings and group decision processes. Moreover, prototypes are used as a stimulus to enrich the group ideation processes, such as in brainstorming and mind mapping. Having a tangible object, helps all team members to understand and evaluate the design at a much higher level than relying upon 2D images or text. Also, the ideas and solutions can be easily visualized, working within the group with simple materials such as cardboard. PP is recommended to be used as much as possible with in the design team as early as possible, throughout the process of product development.

5.2. Discussion

The development of RP technologies in the late 80s and especially the development of AM technologies was one of the main factors of product development time reduction as seen in the (figure 22). This can be linked to the development and wider popularization of more iterative design methods. Someone can argue that the rise of highly iterative methods is possible due to the developments of RP, since the time and cost required to test a design solution is minimal. Thus, there is less benefit of spending the time to calculate and try to predict instead of doing and finding along the way with trial and error.

What is the cultural aspect of different design methods? According to Marcella & Rowley (2015), projects in the creative industries are struggling with a tension between project management and creative process. Why is this happening? One explanation, according to Berube & Gauthier (2017), is that management plans and control, as an iterative approach, looks messy and unpredictable to the project manager. Someone can argue that in a way, more traditional systems engineering methods try to be as detailed as possible to predict pitfalls and avoid failure. They exhibit as such a high degree of uncertainty avoidance. In contrast more recent methods the designer is encouraged to act prototype and test "a bias towards action ". Failure is embraced and is used as a tool to learn and develop the solution faster.

As mentioned in the bibliography, systems engineering methods such as the Waterfall model were developed for projects were changes in the later stages would have a great economic impact, and thus detailed specifications and criteria are made at each step so that more mistakes could be prevented. This is true in the current state of the art of our mass production system where the tooling for the production bears a significant cost, and as soon as this investment is made, changes are not possible to be done or bear an extremely high cost (Figure 16). But how are future advancements in manufacturing affect the design methods such as tool-less manufacturing? How are design methods going to be affected when making changes to a production item are minimal? Will this lead to the development or wider adoption of less defined and more flexible design methods?

5.3. Recommendation for future studies

This work only scraps the surface of two of the largest and more important areas of product design. Design methods and Physical prototyping play a key in the design process and over the years have continuously evolved and will continue to evolve. It is interesting to study the relation between cultural factors, technology and design methods. How these areas affected each other and how this area will shape and form the future or the product design.

5.4. Dissemination

The results and the process of this work will be used to in the elaboration of a final document that will be available for consultation by any person or entity that so wishes, through the Library of the Faculty of Architecture of the University of Lisbon or online. The dissemination of the work will also take place through the oral final examination presentation, before the jury for obtaining a Master's Degree in Product Design.

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