U.PORTO

Valorisation of recycled HDPE through the creation of toys - We Won't Waste You project

Dissertation for the Master Degree in Product and Industrial Design
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MDIP/**78**

To my parents and life partner, who always trusted me and supported all my decisions.

Resumo

Atualmente, é impensável vivermos sem os polímeros, vulgarmente conhecido como plásticos. Consequentemente, a abundância desta matéria incitou o descarte despreocupado, afetando nocivamente os recursos naturais, e ameaçando a vida selvagem e a saúde pública. O design desempenha um papel importante, uma vez que influencia todo o processo de produção e funcionamento do produto. Através da utilização de estratégias de design que procuram encerrar o ciclo de vida dos produtos, e incentivar a reciclagem, é possível reaproveitar a matéria e integrá-la novamente no ciclo de produção.

Considerando este enquadramento, no decorrer do Mestrado em Design de Produto e Industrial (MDIP) da Universidade do Porto (UP), os alunos foram desafiados a criar produtos a partir dos resíduos gerados localmente na cidade de Matosinhos. O projeto We Won't Waste You (WWWY), é um projeto de investigação que está em curso no Design Studio (DS) na Faculdade de Engenharia da Universidade do Porto (FEUP). Este projeto procura encontrar soluções para o desperdício, através do desenvolvimento de novos materiais ou produtos. Dentro deste projeto, surge uma colaboração com a Câmara Municipal de Matosinhos, e a oficina design que tem como objetivo encontrar soluções e desenvolver produtos desenhados pelos alunos do MDIP, para a divulgação da cidade. Este projeto tem ainda como objetivo ser produzido por um grupo social vulnerável. Durante o ano de 2017/2018, no âmbito do projeto WWWY foram desenvolvidos o conjunto Beach kit, com o intuito de proteger os pertences pessoais na praia, e o brinquedo Beach kids. Uma vez que o brinquedo Beach kids não preenche os requisitos desejados, o seu desenvolvimento foi prolongado até o ano seguinte.

Ambos os projetos foram fabricados a partir de polietileno de alta densidade (PEAD) reciclado, no entanto, o Beach kids foi feito exclusivamente com material 100% reciclado.

Paralelamente ao desenvolvimento dos produtos para o Beach kit e Beach kids, foram elaborados diversos testes e experiências aos resíduos de PEAD, para estudar as capacidades e propriedades do material. No âmbito do projeto WWWY foram experimentados diferentes processos de fabrico onde foram utilizadas ferramentas de baixa tecnologia que dispensam mão de obra especializada.

Palavras chave: desperdício; reciclagem; sustentabilidade; PEAD; eco-design; economia-circular

Abstract

Currently, it is unthinkable to live without polymers, commonly known as plastics. Consequently, the abundance of this material has driven carefree disposal, damaging natural resources, and threatening wildlife and public health. Design plays an essential role as it influences the entire production process and operation. By using design strategies that seek to close the product life cycle and encouraging recycling, it is possible to reuse the material and integrate it back into the production cycle.

Considering this framework, the students of the Master's program in Product and Industrial Design (MDIP) of the University of Porto (UP), were challenged to create products from wasted materials produced in the city of Matosinhos. The project We Won't Waste You (WWWY), is a research project that is underway at Design Studio (DS) at the Faculty of Engineering of University of Porto (FEUP). This project seeks to find solutions for waste through the development of new materials or products. Within this project, there is a collaboration with the Matosinhos City Council and the design workshop that aims to find solutions and develop products designed by MDIP students, for the dissemination of the city. This project also aims to be produced by a vulnerable social group. During 2017/2018, under the WWWY project, the Beach kit, which protects the personal belongings on the beach, and the Beach kids toys were designed. Since the Beach kids toy did not meet the desired requirements, its development was extended until the following year.

Both projects made from recycled high-density polyethylene (HDPE), however, Beach kids were made exclusively from 100% recycled material.

In parallel to the development of the Beach kit and Beach kids products, various tests and experiments were carried out on HDPE waste to study the capabilities and properties of the material. Under the WWWY project, different manufacturing processes were tried using low-tech tools to dismiss skilled labour.

Key words: waste; recycling; sustainability; HDPE; eco-design; circular economy

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I would like to take this opportunity and thank all my colleagues from MDIP for the fellowship and mutual help throughout the entire project.

A huge thank you, without your support, it would be impossible to complete this stage,
Camelia

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List of abbreviations

BPA - Bisphenol A

ESA - Environmental Services Association

EC - European Community

EU - European Union

FBAUP – Faculty of Fine Arts of Universidade of Porto

FEUP – Faculty of Engineering of Universidade do Porto

HDPE - High-density polyethene

IPD – Integrated Project Design

ISO - International Organization for Standardization

LAC - Life Cycle Assessmen

LDPE - Low Density Polyethylene

MDIP – Master in Product and Industrial Design

NGO- Non-governmental organization

PBL - Project Based Learning

PC – Polycarbonate

PE - Polyethylene

PEMD - Medium Density Polyethylene

PET - Polyethylene Terephthalate

PLA - Polylactic Acid

PMMA – Polymethyl Methacrylate

PP - Polypropylene

PS – Polystyrene

PU / PUR– Polyurethane

PVA - Polyvinyl Alcohol

PVC – Polyvinyl Chloride

SMR - Secondary Raw Materials

UP – Universidade do Porto

UV - Ultraviolet

WWWY - We Won´t Waste You

List of symbols

BTu - British thermal unit

cm - Centimeter

cm^2 - Square centimeter

cm^3 - Cubic centimeter

ºC - Degree Celsius

€ - Euro

g - Grams

GPa - Gigapascal

HV - Hardness - Vickers

kg - Kilograms

kg/m^3 - kilograms per cubic millimeter

kg/MJ - kilogram multiplied by megajoule

kJ/m^3 - Kilojoules per cubic millimeter

km - Kilometer

kN.m/kg - Kilonewton multiplied by meter per kilogram

kWh - Kilowatt

l - Liter

m - Meter

MJ/kg - Megajoule per kilogram

mm - Millimeter

mm/s - Millimeters per second

MN - Meganewton

MN.m/kg - Meganewton multiplied by meter per kilogram

MPa - Megapascal

Mt - Megaton

Pa - Pascal

% - Percentage

I. Introduction

In a world facing global challenges such as fast-growing population, food security and climate change, our societies need to choose and rely on the most efficient solutions in order to guarantee a sustainable development.

(Plastics Europe 2017)

1.1 Background - Theoretical framework

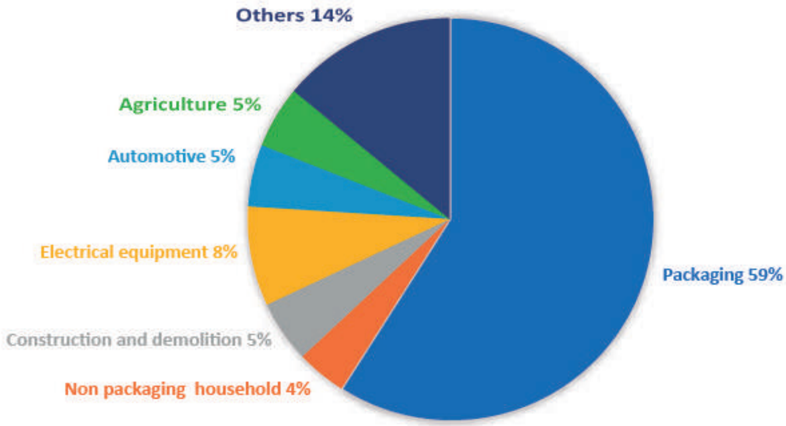
Polymers are a ubiquitous and essential material in our daily life and have been a subject of considerable public discussion, because of the negative impact of this material on wild fauna and flora. However, the detrimental factors are due to our inability to handle end-of-life polymers. Even though polymers are now considered villains, this material brought many advantages in fields such as industry, medicine and agriculture. The dependence of polymers has reached an extreme. The increasing demand and consumption of goods by the growing population encouraged the industry to produce and to extract more non-renewable raw materials.

Nowadays, it would be unthinkable to discard this material. Aspects such as their mechanical properties; its low cost; ease of production; its durability and resistance to environmental changes; encourage their exploitation and use (Ashby 2013b). Polymers have modified our relationship with products. The mass manufacturing, consequently affected the prices of the products, making them cheaper and accessible to all citizens (e.g. water bottles, cutlery, straws and disposable dishes).

However, available and inexpensive products have led to a high increase in waste. That ends up in waterways, rivers, seas and oceans, even in the most remote areas, away from human contact. Consequently, the plastic waste (about 80% of the marine debris) carried by the sea flow originates the floating trash "islands" shown in Figure 1 and Figure 2 (Plastics Europe 2018, 2017). In addition to the visual impact, approximately 75,000 or 300,000 tons of microplastics resulting from the abandoned polymer fragments have contaminated our Oceans and affect the lives of the animals living there.

Figure 1 (***a***) (left) Plastic trash in the ocean nearby Roatan; (***b***) (right) A diver as he gets ready to dive in the plastic wave along Roatan, an island off the coast of Honduras (source: Caroline Power Photography) (https://www.forbes.com/sites/trevornace/2017/10/27/idyllic-caribbean-island-covered-in-a-tide-of-plastic-trash-along-coastline/#2247449d2524)

This problem does not only affect our economy, but it also affects public health. The single-use plastic packaging has reached values of 59% of the trash generated at the European level (as shown in *Graphic 1*) which forced us to reconsider the products whose life cycle is so short.



Graphic 1 European Union waste generation in 2015 (adapted from European Commission 2018b)

For many years, the industry focused on the linear production model, whose goal was to extract, produce without any concern for their end-of-life and discard. Plastic Europe (2017) estimates that annually Europe generates 25.8 million tons of plastic waste. A few tons are recycled, and the rest is delivered to be incinerated or deposited in the landfill. It is fundamental to end this linear production and move towards a restorative economy through creativity and innovation (Ellen MacArthur Foundation 2017).

Plastic waste proved to be a complex and multidimensional challenge, and currently is one of the highest discussed topics worldwide. The European Union's (EU) industrial policy encourages the reduction of environmental impact. By implementing innovative and creative sustainable strategies that stimulate competitiveness, employee motivation and job creation (European Commission 2018b). To modify and improve such a complex value chain, it requires the efforts and cooperation of all stakeholders, from producers, retailers, consumers, and recyclers.

Design plays an essential role in the development of sustainable products. Their purpose is vital in defining a solid end-of-life product strategy so that the material can re-enter the industry and the market. To promote and to communicate the importance of recycling. Also, implementing many strategies which include closing the life-cycle, ease the dismantling of products, to simplify the maintenance/recycling, or prolongation of the useful life of the product.

Through creativity and innovation, the design has been responding to today's needs. Products in addition to reusing polymer waste at the same time communicate to society the value of the material, which should be used and not wasted. It is not just about teaching the need to recycle; it is essential to implement and to market more products that use recycled material.

To be able to implement recycled plastics in various sectors is a difficult task. Nevertheless, it is essential to study innumerable solutions efficiently reuse the material. There are more demanding sectors than others, such as health and food, which show a clear preference for raw materials. Another industry that gives priority to virgin material is the toy industry since it presents a series of standards and requirements that must be respected. However, the reuse of polymers is still a subject that is still under study. The use of recycled material in addition to redirecting plastic waste from landfills helps to extend the life of the content while raising consumer awareness and teaching the younger generation the importance of recycling.

1.2 We Won´t Waste You project

The WWWY (*Figure 2*) research project, which is underway in FEUP's DS, seeks to find solutions for waste through the development of new materials or products. From the partnership with the City Council of Matosinhos, the students were challenged to create products from wasted materials.

During MDIP, and particularly in the WWWY project, the Project-Based Learning (PBL) methodology was applied to allow students to face real-world problems, as the method entails (Efstratia 2014; Guerra, Ulseth, and Kolmos 2017).

Figure 2 We Won´t Waste You logo

Throughout this project, students were asked to explore the waste produced by the city of Matosinhos and to develop products that would help to promote the city and the circular economy. It was also necessary to consider the fact that the designed products must be manufactured under a low-scale production system, low-tech, easy to operate, thus dismissing skilled labour. The objective was to create employment for a socially vulnerable group of active unemployed adults, identified by the city's social care (Fernandes et al. 2018).

Within the scope of the WWWY project, there were already presented dissertations, where several wastes were explored, and a few products were developed, such as buttons created from polyethylene terephthalate (PET) bottles, and bottle caps (HDPE) (Freixa 2016); a beach backrest from polypropylene (PP) fishing nets (Monteiro 2016); a set of coffee grounds and polylactic acid cups (PLA) (Canavarro 2016); and a textile waste puff (Costa 2016). Underneath the WWWY project some products were developed, such as: Beach kit, a set of products that aim to protect the belongings from sand (HDPE and PP), a lamp made from eggshells, Obo Lamp, a dish made from algae, Algma Portuguesa, and another lamp from sugar and sand, the Sand Set (Fernandes et al. 2018).

Given a real context, the elements that participated in the project had the opportunity to experience the daily life of a designer. Also, the WWWY project demonstrated the influence that design has on society and the environment (Fernandes et al. 2018). The project overcame the pedagogical approach as the PBL methodology forced students to put all their knowledge into practice and simultaneously cooperate with team members in search of solutions to reduce environmental impact.

1.3 Objectives

The primary purpose of this dissertation is to continue the project previously developed within the WWWY project. That entails complementing the already developed project, Beach kids.

However, the main goal of this dissertation is to design and create a toy from recycled HDPE, using exclusively recycled material. Furthermore, other objectives were identified, namely:

i. use waste material from Matosinhos;

ii. promote the city through the products;

iii. investigate the use of HDPE at the end of life and reintegrate it as an input of value in the market, validating and encouraging the reuse of plastic waste for the design of new products;

iv. investigate a fast, easy to handle and inexpensive manufacturing process;

v. promote the connection between social reintegration (since the resulting products are intended to be produced by a socially vulnerable group in the city); innovation (through product development); and exploration of ideas and environmental concern (through the application of concepts such as circular economy, reuse and recycling of wasted materials produced in the city).

This dissertation aims to encourage the reuse of material and make people aware of the impact it has on the ecosystem, the economy, and the health of the wildlife that inhabits the planet. The intention is to promote the use of recycled HDPE and the development of new products with the help of the identified socially vulnerable group.

1.4 Methodology

The dissertation division has the theoretical and experimental component. It has four chapters, which are Introduction, State of Art, Case Study, and Conclusion. The theoretical component takes place during the first two chapters, the Introduction and presentation of state of the art and also in the last section. On the other hand, the practical component arises with the description of the experiments performed during the project development. *Figure 3* summarises the methodology adopted.

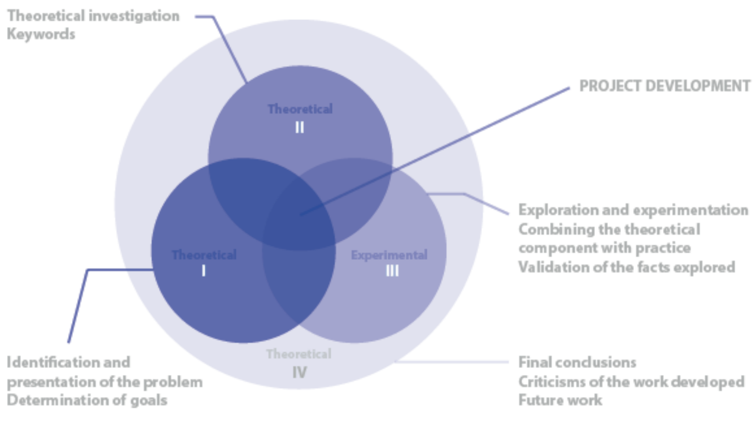


Figure 3 Scheme of the adopted methodology

The initial two chapters of the dissertation present the theoretical foundation. The first chapter, the Introduction, presents the problem, the theme, the motivation of the dissertation, the objectives, the Introduction of the WWWY project, the methodology, and the expected constraints during the project development.

Therefore, the next chapter, the State of Art, presents the scientific research on the topics and key concepts related to the dissertation. The first phase research was carried out through articles, to identify the current state concerning concepts such as waste; recycling; sustainability; HDPE; eco-design; circular economy. The survey covered official EU guidelines and reports, books, websites and communications. The information was acquired through publications on peer-reviewed scientific literature database platforms such as SCOPUS, Web of Science and Engineering Village. Finally, the research was validated by presenting some projects and products that demonstrate the viability of reusing end-of-life plastics.

The Case Study chapter aims to validate the knowledge acquired through experimentation. First, the previous projects developed within the scope of the WWWY project, as the Beach kit and Beach kids, are shown. The different production methods explored are presented before proceeding with the full development of the toys. The direct exploitation of the HDPE, the study of its properties, applications and various manufacturing process experimentations helped the project development. The material characteristics determine its design, format and the manufacturing process.

Finally, the Conclusion chapter features the final judgments. Throughout this chapter, an overview of the entire research and design process is presented, revealing final considerations about the results achieved, pointing out what can be improved and the prospects for the future.

1.5 Limitations

The constraints may occur during the development of the project conditioning the final solution. During the research, may arise some obstacles since this phase depends on the keywords chosen, as well as the research tools used. Either from the internet, books or dedicated software, the information must be filtered to present the most recent data that best fits the theme of the dissertation.

However, the experimental stage is more susceptible to the constraints since this stage depends on the material and equipment used. Considering that this dissertation aims to explore and investigate the reuse of HDPE, all the following processes are important and essential. The project budget has become a factor that has created several limitations, namely:

i. the collection, identification and classification of HDPE delays the development of the project, beyond which it is not always reliable;

ii. the adaptation of industrial manufacturing processes to a low budget;

iii. availability of the ceramic furnace and press.

II. State of art – bibliographic research

In this chapter, popular topics, such as circular economy, plastic waste, and recycling are presented, as well as the role and influence of design in this panorama.

i. Demonstration of some strategies outlined by the EU to make today's economy more competitive, circular, modern, innovative and climate friendly. Also, during this chapter are presented some design strategies and their role in this new economy.

ii. Then the polymers are presented, where the primary concern and focus is on HDPE. Which leads to the presentation of its properties, characteristics and applications. Also, during this chapter, CES Edupack (2018) software was used to compare the feasibility and impact on reusing this material in terms of energy expenditure and CO2 emissions.

iii. Afterwards, the different types of recycling are presented, as well as their limitations and benefits in HDPE specific recycling.

vi. Finally, during the market research, several companies and projects that recycle HDPE or other polymers in the manufacture of products are shown. This last subchapter aims to validate the viability of using recycled material to fabricate toys, furniture, footwear, and clothing.

2.1 Building a circular economy

There is a primary difference between the circular and the traditional linear approach. The linear strategies consume and depend on fossil fuels, take-make-use-dispose and do not care about the end of the products life. Regarding the growing concern about the environment was created this new circular economy with promising strategies. Unlike the linear approach, the circular business model relies on renewable resources, and viable ways to reuse the materials and the products. In 2015, the European Commission (EC) adopted an action plan for the circular economy. Measures have been taken to boost employment, growth, investment to achieve a competitive economy, carbon-neutral and resource-efficient (European Commission and Directorate General for Regional and Urban Policy 2019).

The transition to the circular economy has increased employment and revolutionized the organization of the industry giving priority to innovation, investment, and the development of new business models. Within the industry, efforts are being made to adopt sustainable measures by closing the product cycle and using resources efficiently (Preston 2012). A systemic approach along the value chain is now being adopted, and circular policies on plastics production, water management, food systems and resource-specific waste stream management are also being integrated (European Commission and Directorate General for Regional and Urban Policy 2019).

i. Circular Design and Production Processes

The circularity of products relies on design, insofar as circular thinking should always be present in the process of product development. The circular concept makes it necessary to think of each stage of the product, from the nature of its material, the manufacturing process, transport, use, disposal and recycling.

Considering the plastics case, the EC has highlighted several measures to transform the plastics industry into a sustainable and innovative sector where reuse, repair, and recycling are fully respected (European Commission 2018b). These series of factors will consequently bring environmental benefits, as the emission of noxious gases will be reduced, as well as dependence on fossil fuels. Given this, plastic products should be developed to enable durability, reuse and recycling at a high level.

As regards resource efficiency, the EU has implemented strategies such as the *Eco-design Directive* and the *Energy Labelling* or *Ecolabel Regulation.* To better articulate the various tools of EU product policy and their contribution to the circular economy, some alternatives are currently under consideration (European Commission and Directorate General for Regional and Urban Policy 2019). Including expanding the policy of eco-design that was successful for energy-related products and, product groups, as well continuing to support the repair sector in the EU (European Commission and Directorate General for Regional and Urban Policy 2019).

ii. Empowering Consumers

Changing citizens' consumption patterns is crucial. For the same reason, strategies have been implemented to increase the effectiveness of the *EU Ecolabel* providing consumers with accurate environmental information. Like *Energy labelling*, where each device gets a score depending on the energy expenditure. Currently, the EC is discussing the adoption of the same scoring system for the repair possibility that may affect consumer buying decisions.

iii. **Turning Waste into Resources**

From 2008 to 2016, there was an increase in the contributions of recycled materials. However, in addition to demonstrating improvement in waste treatment, there is still much to improve. The EC is trying to increase the visibility and understanding of the circular economy by implementing waste legislation. In addition to providing assistance and focusing on the Member States that face the greatest challenges in achieving recycling targets (European Commission 2018a). Following the review of the different waste-to-energy processes to avoid unnecessary loss of valuable resources through landfilling and incineration.

> *Environmentally sound management of waste, inside and outside the EU, is key to achieve a more circular economy.*
>
> (European Commission and Directorate-General for Regional and Urban Policy 2019)

iv. **Closing Loops of Recovered Materials**

One of the objectives of the circular economy's action plan is to increase the use of secondary raw materials (SRMs). General agreement and support among stakeholders for improving the traceability of substances and information flows. Harmonize the end-of-waste criteria, fair conditions between EU and third-country operators. Also supporting and reinforcing the circular economy aspects in instruments such as the *Eco-design Directive* (European Commission and Directorate General for Regional and Urban Policy 2019).

v. **A Systemic Approach: the EU Strategy for Plastics in a Circular Economy**

Plastic is currently one of the five priority areas of the EU circular economy action plan to increase resource efficiency and reduce dependence. The *EU Strategy for Plastics in a Circular Economy* (2018) is the first EU-wide policy framework adopting a material-specific lifecycle approach to integrate circular design, use, reuse and recycling activities into plastics value chains.

The *EU Strategy for Plastics in a Circular Economy* demonstrates a clear vision of the objectives to be achieved. The EU goals are to reduce the dependency on fossil fuel, cut the CO_2 emissions, make the plastics industry sustainable and innovative, drop-in waste generation; increase consumer awareness, avoid litter and ensure that waste is handled correctly, and use recycled plastic as valuable raw material. By 2030 the EU intends to replace the plastic packaging on the market with reusable or recycled packaging - which will increase the recycling levels of plastic waste (European Commission and Directorate General for Regional and Urban Policy 2019). Additionally, by 2030, modernization and increased sorting and recycling capacity is planned, creating 200,000 new jobs across Europe.

Through exemplary actions, particularly on single-use plastics, stimulate change across borders. As the EU is currently supporting the international incentive around the plastic agenda,through initiative, partnerships with organizations and help to combat the plastics pollution (European Commission and Directorate General for Regional and Urban Policy 2019).

However, the resolutions of the plastic pollution or waste problem (reduction of marine litter and cleaning the beaches and the sea), or plastics waste prevention could be a business opportunity.

***vi.* Accelerating the transition**

***vi.i.* Innovation and Investments**

During the transitional phase, it is necessary to innovate and adapt the industries (European Commission and Directorate General for Regional and Urban Policy 2019). To guarantee sustainable development, the *European Investment Bank*, together with the *Circular Economy Finance Support Platform*, has provided assistance and exploitation of synergies (European Commission and Directorate General for Regional and Urban Policy 2019; Enterprise Europe Network 2019).

***vi.ii.* Strong Stakeholder Engagement**

Stakeholder participation is essential for the transition, transporting it across sectors and borders, participation in joint circular economy missions, strengthening links between European institutions, NGOs, companies and relevant stakeholders in third countries (European Commission and Directorate General for Regional and Urban Policy 2019).

***vii.* Challenges**

The circular economy should become the backbone of the EU's industrial strategy (as well as other areas still unexplored). The goal is to achieve a more prosperous, modern, competitive and climate neutral economy. It is fundamental to create business models and encourage the use of renewable energy, improve the infrastructures and the recycling system, as well as modify consumption patterns, which lead to the reduction of emissions harmful to the environment (European Commission and Directorate-General for Regional and Urban Policy 2019).

The current circular economy is a global trend. Innovation becomes a fundamental concept for plastics value chain transformation, even extending the benefits beyond the EU borders. European companies need to invest in the future and affirm their leadership in modernizing the plastics value chain, by encouraging countries to cooperate, taking corrective action against accumulated plastic waste and preventing the flow of plastics to the oceans (European Commission 2018b).

2.1.1 Design for the circular economy

Currently, concepts such as eco-design and sustainable measures are gaining more reputation, due to the circular economy influence. The combination of design and the circular economy is increasingly evident since they combine design strategies that extend the product's useful life, decelerate and closure the flow of resources — generating a reduction of resources by product or service unit (Bocken, Bakker, and Pauw 2016; Rocha, Camocho, and Alexandre 2018).

2.1.1.1 Eco-design

Eco-design advocates further reflection on the product life cycle leading to consideration of all environmental aspects or associated impacts from the initial stage. Also implementing changes to optimise final results and significantly reduce harmful emissions to the environment (De Pauw et al. 2014; Rocha, Camocho, and Alexandre 2018; Vallet et al. 2013). While environmental assessment evaluates the environmental impacts of a product/ service, environmental improvement aims to find environmentally friendly solutions (Vallet et al. 2013).

Eco-design is also associated with the Life Cycle Assessment (LCA) which operates as a tool for evaluating the product life cycle, from the manufacturing process until the final disposal stage (Ashby 2013c; Romli et al. 2015). The LCA helps: to identify and improve the environmental aspects of products throughout the various points of their life cycle; planning, prioritising, designing or redesigning products or processes in the industry, governmental or non-governmental organisations; selecting relevant environmental performance indicators, including measurement and marketing techniques (e.g. an environmental statement, *Eco-labelling* scheme or environmental product declaration) (International Organization for Standardization 1997).

According to the ISO (1997), LCA can be applied qualitatively, to analyse different application scenarios and to discover, at an initial stage, possible areas of improvement (Hauschild, Jeswiet, and Alting 2004).

2.1.1.2 Closing the loop – Circular design strategies

The combination of the concepts generated by circular economics with the practice of eco-design has led to a series of policies designed to help build global and sustainable value chains and influence value management. Design plays a circular role, as it deals with all stages of product development, also influences its recycling, maintenance, repair, distribution, reuse, reform, and remanufacturing. Also, the design is responsible for analysing the environmental, economic and social impacts associated with the product.

As shown in *Figure 4*, tthe literature review illustrates the linear flow, then the narrowing (design for resource conservation), circular (design for recycling) and slowing loops (design for durability) (Rocha, Camocho, and Alexandre 2018). The resource flow patterns that characterise each business model dictate a big difference between "*cradle-to-grave*" flows (linear business model) and the "*cradle-to-cradle*" flows (circular business model) (Braungart e McDonough 2010). Within closed-loop systems, there are fundamentally two types of loops: "slowing resource loops" and "closing resource loops" (Bocken, Bakker, and Pauw 2016).

Consequently, the extension of the useful life of a product leads to the consideration of the sustainability of the materials, energy and water throughout the life cycle (Rocha, Camocho, and Alexandre 2018). Responsible innovation, production and consumption, together with the promotion of a well-being ecosystem and human health, are concepts that are put into practice and underpin sustainable development.

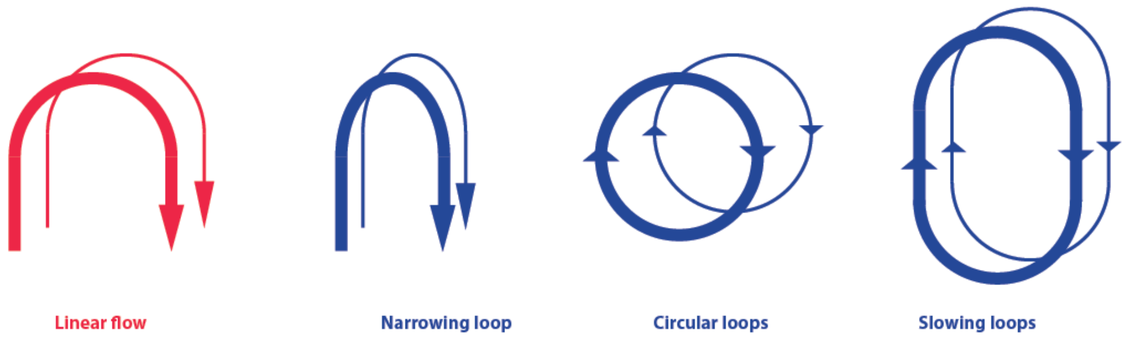


Figure 4 In the linear flow, resources are extracted, the products are manufactured, and discard when they become obsolete; The narrow loop uses low resource strategies and manufactures energy efficient products; The circular loop, recycling-related strategies to "close the material loop" after multiple reuses; The slowing loops, refers to strategies such as maintenance, repair, refurbishing and remanufacturing to encourage product reuse (adapted from Bocken, Bakker, and Pauw 2016)

The **narrow loop** advocates the minimum use of resources, material promotion, energy and water sustainability throughout the entire product life cycle. Unlike other circuits, narrowing does not involve service loops (e.g. repair). It does not influence the product flow speed, which can lead to faster linear resource flows, resulting in very little overall savings (Bocken, Bakker, and Pauw 2016).

2.1.1.2.1 Slowing resource loops

Slowing resource loops advocates extending the life of the product, creating durable, easy to maintain, repairable and modular products. To facilitate the upgrade/adaptation, as well as the development of services to support the product life extension, meeting the needs of the user with services. Extending the life of the product reduces the use of resources. Long-life products are motivated by design for attachment, trust (i.e. emotional durability), reliability and physical durability. The maintenance and repair; upgrading and upgradability; standardisation and compatibility; and dis- and reassembly are design strategies adopted to promote product life extension.

There are two design strategies for slowing resource loops, designing long-life products (Bocken, Bakker, and Pauw 2016).

Design for long-life products aims to reduce resource loops and ensure a long period of use of the product. The empathic and lasting partnership that blossoms between the product andthe user can also be called design for emotional durability (Bocken, Bakker, and Pauw 2016). This strategy develops designs for reliability-based, primarily on their physical durability. With high probability for the product running in a specified period without any failure when maintained according to the manufacturer's instructions.

Designing for product-life extension aims to reduce resource loops and promote the extension of the period of use of goods through the inclusion of service loops to extend product life. Requiring the reuse of the product itself, with maintenance, repair, technical upgrading, and the combination of these. These design for maintenance and repair strategies, allows to maintain the products with optimal conditions, as the introduction of the maintenance services (technical, administrative and managerial); repair that helps to restore the equipment, (the product returns to work without problems); upgrade through quality improvement, value, effectiveness or performance, to make sure the product continues to be useful.

2.1.1.2.2 Closing resource loops

Closing resource loops close the post-use loop and production through recycling, creating a circular flow of resources. The closed loop promotes the development of easily disassembled and assembled products to facilitate recycling. This strategy also creates reverse logistics services to recover after-use products maintaining the value of the material and/or components.

The "*cradle to cradle*" design is an ambitious circular approach to product design that advocates strategies for circular material flows (Braungart and McDonough 2010). There are only two possible long-term waste destinations: recycling/reuse, or dissipative loss (compatible with biological systems). There are three design strategies for closing resource loops, designing for: a technological cycle; a biological cycle; and disassembly and reassembly (Bocken, Bakker, and Pauw 2016).

Designing for a technological cycle is a strategy that provides continuity and resource flow. The waste should be recycled according to primary, secondary, tertiary or quaternary recycling (see section *2.3.1.2 Recycling process* chapter which explains the steps in a more advanced way) as shown in *Figure 5*. Unlike upcycling, downcycling involves reusing a re-processed material into a "low" value product.

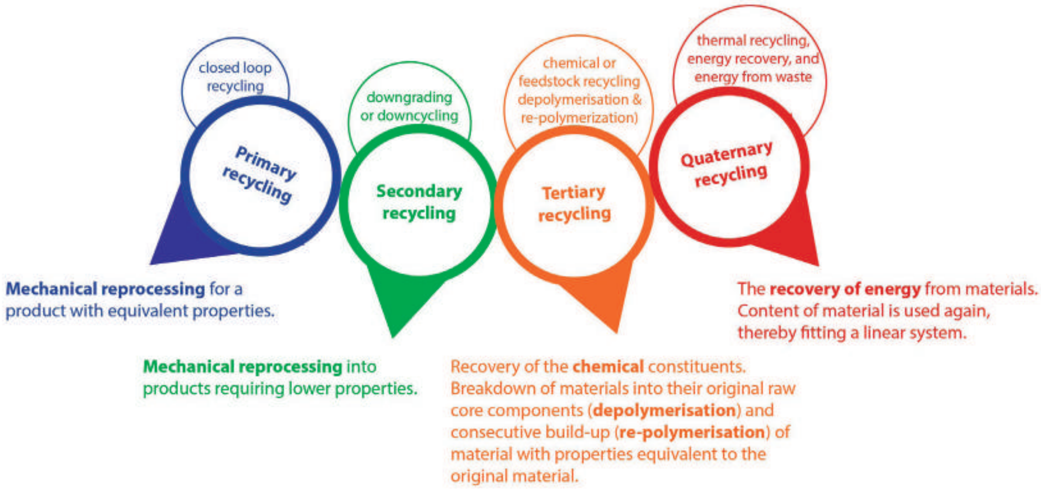


Figure 5 Overview of recycling definitions, based on plastic recycling terminology (adapted from Bocken, Bakker, and Pauw 2016)

Design for a biological cycle represents the consumer goods that are worn-out throughout their use, known as biodegradable materials (degradation by the biological activity of organic material biologically decomposed by microorganisms such as bacteria and fungi). Currently, in Portugal, companies such as LIPOR are studying the field of Bioplastics, Biocompostables and Biodegradables. However, their end of life remains uncertain, given the variety of biodegradable materials. The waste treatment infrastructures are not prepared for the treatment of this type of materials. (Composting is also considered tertiary recycling.)

Designing for disassembly and reassembly is a strategy that ensures that the parts of the products can be separated and reassembled quickly, to facilitate the separation process of the different materials to be able to enter different cycles.

2.2 Polymers a brief history

The materials have always played a fundamental role from decades since they denominated the ages of man (Ashby 2013a). From pre-history until nowadays, materials have made significant progress. From the beginning, our kind learned to take advantage of the resources provided by nature.

Polymers emerged as a human invention by combining carbon with oxygen, hydrogen, nitrogen and other organic or inorganic elements (Kumar, Panda, and Singh 2011). The polymer revolution began in the 20th century with the development of phenolic Bakelite in 1909, which triggered a fast growth of polymer science, as shown in *Figure 6*. Between, the 1940s and 1960s, the polymers that we currently use in our daily lives, such as polypropylene (PP), polyethylene (PE), polyvinyl chloride (PVC), polyurethane (PU), among others, were discovered.

Polymers, commonly known as plastics, a term derived from the Latin *plasticus* and the Greek *plastikos*, meant to describe something capable of being moulded or suitable for moulding (Plastics Europe 2018). Nowadays, is used to describe a large family of materials with different characteristics and properties. There are three types of polymers, namely thermoplastics, thermosets and elastomers.

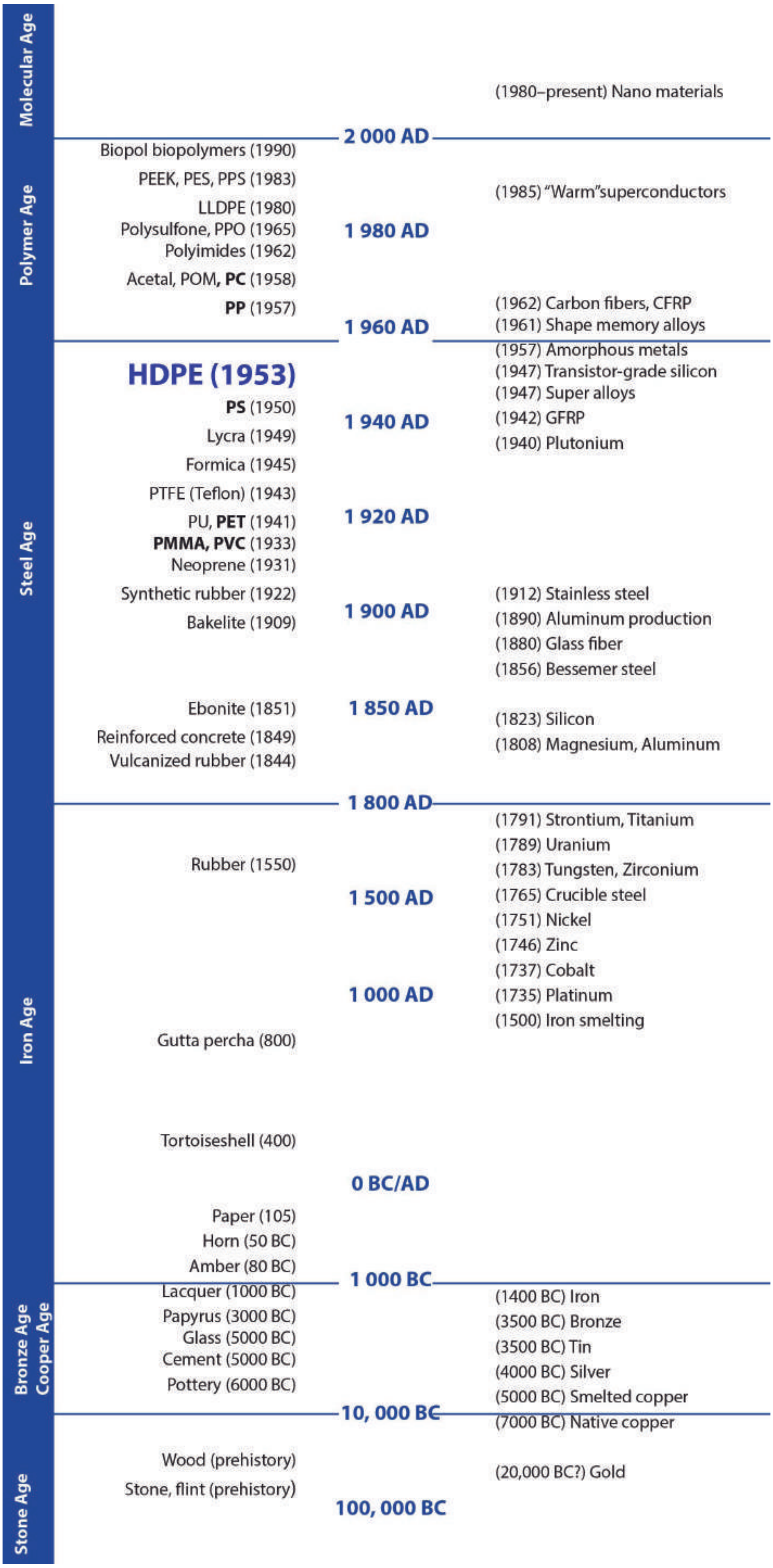


Figure 6 The material timeline with a nonlinear scale (adapted from Ashaby 2013)

Thermoplastics are the result of an aligned chain of the union of atoms and molecules from end to end in a series of long chains of carbon. There are three types of thermoplastics, the crystalline, amorphous or a mixture of both. They all share the same characteristics, in contact with heat soften and returning to their normal state when they cool down. These polymers enable the creation of composite materials to provide a wide range of physical, visual and tactile effects (to reduce sensitivity to sunlight or flammability respectively may be added, UV filters or flame retardants). The thermoplastics properties can be controlled by branching/chain length (measured by molecular weight), through mixing and plastification of the crystallinity degree (Ashby 2013f). The high molecular weight influences the strength and hardness of the polymer, increasing them and complicating the moulding process. Crystalline polymers are chemically resistant, more stable at high temperatures, and better creep resistance than those that are amorphous, such as, polycarbonates (PC), polymethyl methacrylate (PMMA), polystyrene (PS), and PVC. Its transparency characterizes the amorphous polymers. On the other hand, the semi-crystalline polymers such as HDPE, PET and PP can be translucent.

Thermosets, in contrast, are formed through intermolecular condensation. This type of polymers cannot be reformed once moulded. The chemical changes of the monomers on heating and convert themselves into an irreversibly infusible mass (Kumar, Panda, and Singh 2011). The most known and produced thermosets are polyurethane (PUR); polyesters (UR); epoxies and silicones (Ashby 2013f). Besides, being expensive compared to thermoplastics, thermosets cannot be recycled.

Unlike thermoplastics, and thermosets, *elastomers*, can deform when stretched, and return to their shape when released (Ashby 2013f). The footwear and tire industry makes extensive use of elastomers due to its high friction on rough surfaces, and since without harming its physical integrity can be easily manipulated.

The wide employment of the polymers is due to their versatility. They are low weight; excellent thermal and electrical insulation properties; corrosion-resistant, which increases its durability and makes it a suitable material for use in harsh environments; easily moulded into complex shapes (Plastics Europe 2018, 2017). This material can be developed with virtually any combination of properties to accommodate almost any application. *Figure 7* shows some implementations of the polymers and the European plastic converter demand by polymer types in 2017.

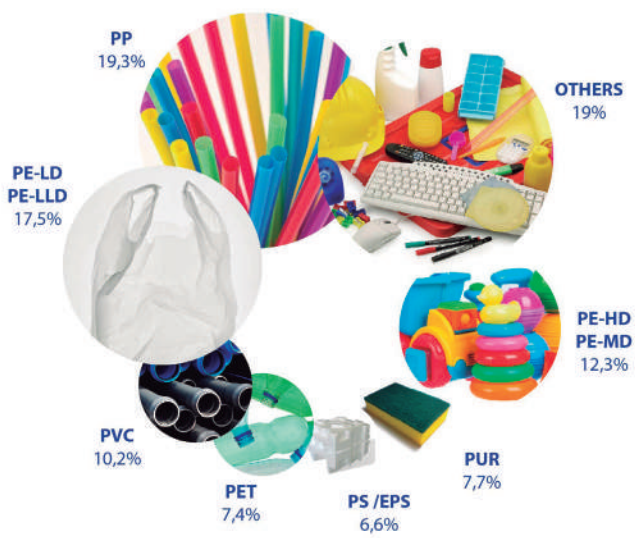


Figure 7 European plastic converter demand by polymer types in 2017 (adapted from Plastic Europe 2018a)

2.2.1 High Density Polyethylene (HDPE)

Polyethene (PE) is a non-biodegradable thermoplastic, that can be recycled and reused since thermoplastics can bear multiple cycles of heating and cooling. Also, it can be converted into energy, since it is obtained from the oil and has a high calorific value.

PE is produced by polymerisation by addition of ethylene. This polymer has a linear structure, where the size and distribution of the crystalline regions are determinants of tensile strength and stress cracking (Kumar, Panda, and Singh 2011). The lower the branching, the higher the intermolecular strength, which makes the polymer harder and opaque.

Until the 1950s, the only type of PE produced was low-density polyethene (LDPE). This polymer requires high pressure, dawning several branches during intermolecular and intramolecular chain transfer during polymerisation (Kumar, Panda, and Singh 2011). The main difference between LDPE and HDPE is related to the degree of branching that drastically modifies the mechanical properties.

Using the CES Edupack software, it was possible to analyse HDPE in detail. *Table 1* presents the physical, mechanical, electrical and thermal properties of HDPE. HDPE has versatile properties, and it is widely used due to its mechanical strength, low cost, excellent biocompatibility, accessible process capacity and resistance to chemical and biological attacks. It also has a low degradation rate, its mechanical and thermal properties depend on the relative amounts of crystalline and amorphous content present in the polymer, crystalline structure, molecular weight, and branching (Kadhim 2017). This material presents various colours and can be translucent or opaque.

Table 1 Physical, mechanical, electrical and thermal properties of HDPE (adapted from Ashaby 2013 and CES Edupack 2018)

Physical properties		
Density (Kg/m^3)	952	965
Mechanical properties		
Young's modulus (GPa)	1.07	1.09
Specific stiffness (MN.m/kg)	1.11	1.14
Yield strength (elastic limit) (MPa)	26.2	31
Tensile strength (MPa)	22.1	31
Specific strength (kN.m/kg)	27.3	32.4
Elongation (% strain)	1.12e3	1.29e3
Hardness - Vickers (HV)	8	10
Hardness - Rockwell M	31	35
Hardness - Rockwell R	45	55
Elastic stored energy (springs) (kJ/m^3)	320	442
Impact & fracture properties		
Fracture toughness (MPa.m$^{0.5}$)	1.52	1.82
Thermal properties (ºC)		
Melting point	130	137
Glass temperature	-125	-90
Maximum service temperature	113	129
Minimum service temperature	-82	-72

Processing properties		
Polymer injection molding	Excellent	
Polymer extrusion		
Polymer thermoforming		
Linear mold shrinkage (%)	1.5	4
Melt temperature (ºC)	177	274
Mold temperature (ºC)	30	50
Molding pressure range (MPa)	82.5	103

HDPE usually is used to manufacture (*Figure 8*): bottle caps, milk bottles, toys, film for packaging, blown bottles for food, plastic bags, containers, laundry detergent bottles, fuel tanks for vehicles, folding tables/chairs, chemical resistant/ geothermal heat transfer/ natural gas distribution piping systems, water pipes for domestic water supply, among others (Kumar, Panda, and Singh 2011; Ashby 2013f).

Recycled HDPE is typically used to make products such as toys, soda bottles, trash cans, plastic "wood" for street furniture (see chapter *2.4 Form waste to the material – Market research*).

Figure 8 HDPE containers (source: https://www.polytainer.com/pe-containers.php)

2.2.2 CES EduPack® software exploration

CES Edupack is a supporting resource for materials related courses across design, engineering and science. This tool is used in some schools and speciality graduate courses. One of its tools is the Eco audit tool.

This software was developed to be used in the design and to help introduce students to concepts around sustainability. Eco audit is fast and easy to use. Although its results are approximate, sufficient discrimination must be maintained to differentiate between alternative options. Eco audit is not a tool to calculate a full LCA; it focuses only on energy consumption and carbon dioxide emissions. The life phases are separated so that the dominant stages can be seen and acted on first.

For the Beach kids project, Eco audit was used to examine in which stage the product consumes more energy and causes CO_2 emissions. Also, the values obtained in the simulation of the manufactured toy of 100% recycled HDPE were compared, and the alternatives using 50% raw material and 50% recycled HDPE and, finally, the option to use only raw material. By using Eco audit, it was possible to verify the feasibility of using 100% recycled HDPE.

2.2.2.1 Eco audit

The Eco audit is used to estimate energy demand and carbon emissions throughout the life of the product (Ashby 2013e). This tool helps identify which stage is most damaging in terms of energy expenditure or CO_2 emissions. The phases identified by the Eco audit are material, transportation, manufacture, use, disposal and EoL potential.

The main purpose of an Eco audit is comparison, allowing alternative design choices to be explored rapidly (Ashby 2013e).

For the Beach kids project, this tool was used to verify the stage of its transformation that resulted in more energy expenditure or CO_2 emissions. When opening the software, the Eco audit tool appears in the initial frame, "**Databases**". Material, manufacture, end of life, transport, use and report are the steps to fill to evaluate the performance of the toy.

i. 1st step, Material, manufacture, and end of life

With each step, the software asks more and more data about the **Anémona** toy. The number of products to be manufactured (**100**); the product components and their material (**HDPE general-purpose, moulding & extrusion**); the percentage of recycled material (100%); the mass of the component (**0.1kg**); then the primary (**polymer moulding**) and secondary process (**cutting and trimming**); the percentage of material removed (**2%**); its end of life (**recycling**); and finally indicate the rate of material recovered at the end of its useful life (**100%**).

Regarding the end of life, the CES Edupack presents several options shown in the *Table 2*. At the end of life, when the option "none" (*Table 2*) is selected, the software considers that the components are discarded on the floor since it does not have end-of-life values.

Table 2 Components end-of-life options (adapted from CES Edupack 2018)

<table>
<tr><td>End of life option</td><td>Applicable materials</td></tr>
<tr><td>Landfill</td><td>All non-toxic materials</td></tr>
<tr><td>Combust (for energy recovery)</td><td>All organic-based materials with a heat of combustion value >5 MJ/kg</td></tr>
<tr><td>Downcycle</td><td>All</td></tr>
<tr><td>Recycle</td><td>All unfilled: metals / glasses / thermoplastics /TPEs</td></tr>
<tr><td>Particulate filled thermoplastics</td><td>1.12e3</td></tr>
<tr><td>Particulate & whisker reinforced metals</td><td>8</td></tr>
<tr><td>(All ceramics / thermosets / elastomers / natural organic / natu-ral inorganic materials and all fibre reinforced materi-als are marked as non-recyclable)</td><td>31</td></tr>
<tr><td>Re-manufacture</td><td rowspan="3">All</td></tr>
<tr><td>Reuse</td></tr>
<tr><td>None</td></tr>
</table>

Figure 9 demonstrates the above fields filled out.

Also, within the material domain, it is possible to specify joining (adhesives, cold curing/heat curing, fasteners, large/small, electric/gas, construction) and finishing processes (painting; electroplating; power coating). Then it can also be indicated the amount and the unit used to make the joining or finishes of the product.

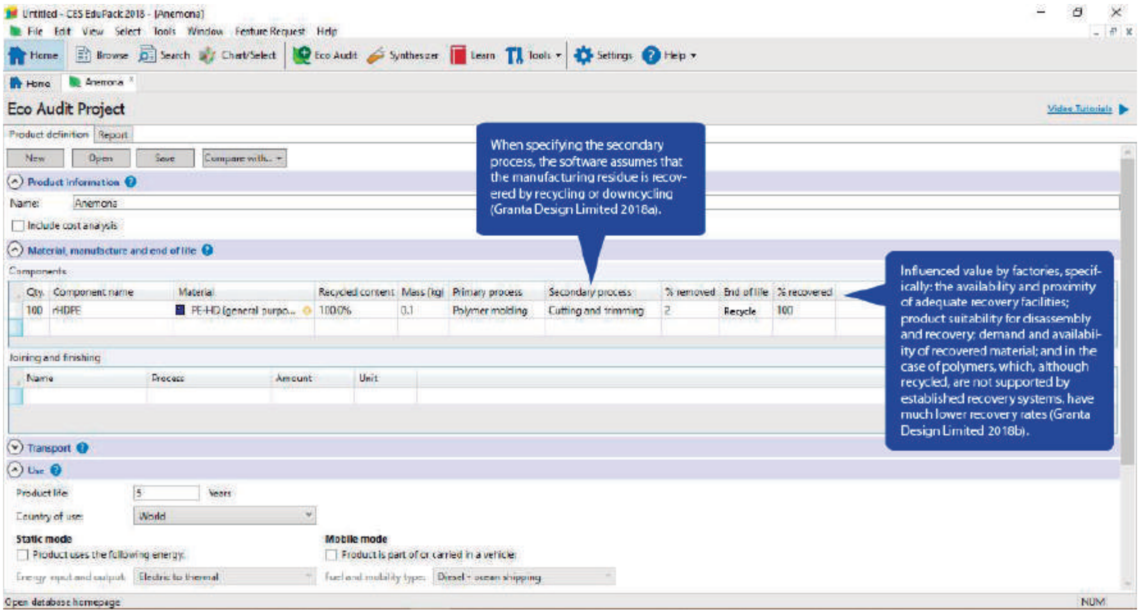


Figure 9 CES Edupack, material and end of life specifications for the Anémona project (CES Edupack 2018)

ii. 2nd step, Transport

This step concerns the finished product transportation, from the manufacturing source to the customer.

The Anémona does not need any of these actions. This stage was not completed, since the workshop and the sales outlet of the products has not yet been established. The *Table 3* presents the values associated with energy and CO_2 emissions.

Table 3 Transport types and values associated with energy consumption and CO_2 emissions (adapted from CES Edupack 2018)

	Transport energy (MJ/tonne/km)	**CO_2 footprint, source (kg/MJ)**
Ocean freight	0.18	0.072
Coastal freight	0.27	0.072
River / canal freight	0.40	0.072
Rail freight	0.35	0.072
55 tonne (8 axle) truck	0.71	0.072
40 tonne (6 axle) truck	0.82	0.072
32 tonne (4 axle) truck	0.94	0.072
26 tonne (3 axle) truck	1.1	0.072
14 tonne (2 axle) truck	1.5	0.072
Light goods vehicle	2.2	0.072
Air freight - long haul	6.5	0.072
Air freight - short haul	13	0.072
Helicopter	55	0.072

iii. 3rd step, Use

This last step concerns the usage stage of the product.

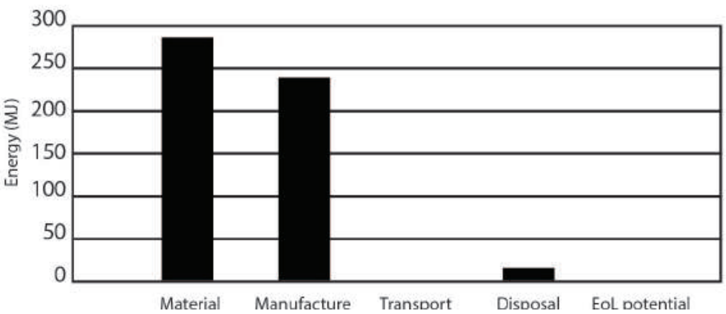
Concerning the product s life years, it was estimated to be used for more than 3 years. It is possible to select a country. However, it was left the default option, (**world**), since the city of Matosinhos has many tourists coming many places of the world. Besides, this selection field is not relevant for the product, because during its use this does not entail any energy costs or CO_2 footprint.

Finally, if the product is (static) (associated with stationery products that generally require energy to operate) or mobile (associated with transport systems where mass has a significant influence on energy consumption), both terms entail energy expenditure and CO2 emissions, for this project was selected the (**static**) option.

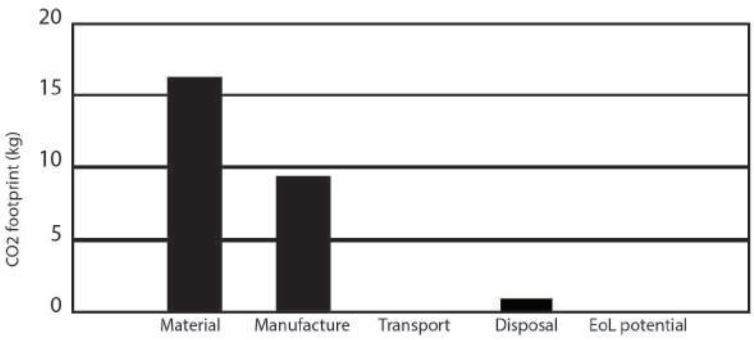
iv. 4th step, Report

Lastly, by selecting the summary chart, a graph window is opened for energy and CO_2 emissions made by the product throughout the stages of its life. More detailed information is displayed when the specific report option is selected. The values for energy consumption (*Graphic 2*) and CO_2 emissions (*Graphic 3*) are presented separately and together through graphics and tables. Also, it is possible to compare and identify in which stage it consumes more energy or emits more CO_2 going through the comparative chart (*Graphic 4*).

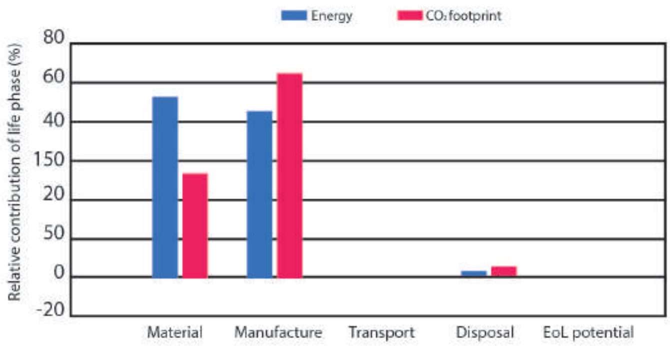
The graphics data is updated automatically when the product settings values are modified. *Graphic 2* shows that, in this project, material is the dominant life phase. Relatively to CO_2 emissions, *Graphic 3* shows that, in this project, manufacture is the dominant life phase.



Graphic 2 Anémona energy analysis (adapted from CES Edupack 2018)



Graphic 3 Anémona CO_2 footprint analysis (adapted from CES Edupack 2018)



Graphic 4 Anémona relative contribution of life phase (adapted from CES Edupack 2018)

2.2.2.1.1 Conclusion and analysis of results

Three possibilities were tested. First, the Anémona that only uses recycled material. Second, the Anémona 1 that uses 50% of virgin and 50% recycled HDPE and the last option the Anémona 2 made exclusively of virgin material.

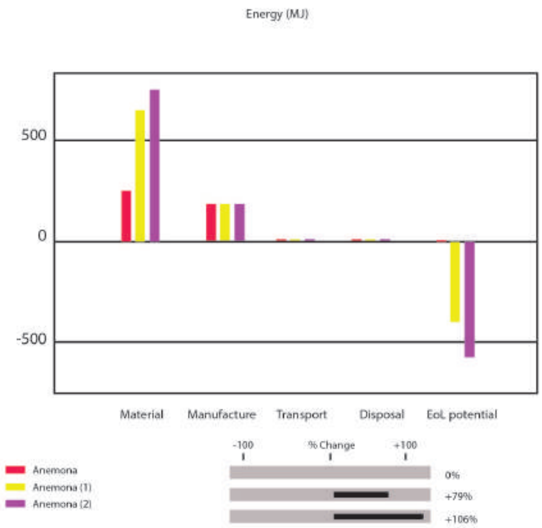
The most significant contribution to energy consumption drives from the production of the material (*Graphic 5*) and CO_2 generation drives mostly from the *manufacture* (Graphic 6). The lack of information regarding transport made it impossible to fill in this field, presenting a gap in the graphs. Also, the use field does not present data, since the toy dispenses energy to operate. The energy and CO_2 footprint associated with a product's end of life split into *disposal* and *end of life* **(EoL)** *potential*. *Disposal* includes the cost of collection of the material/component at the end of life and, where applicable, disposal in a landfill; and separation and sorting of the collected material, ready for reprocessing by the proposed end of life route.

EoL Potential represents the end of life savings or 'credits' that can be realized in future life cycles by using the recovered material or components (CES Edupack 2018).

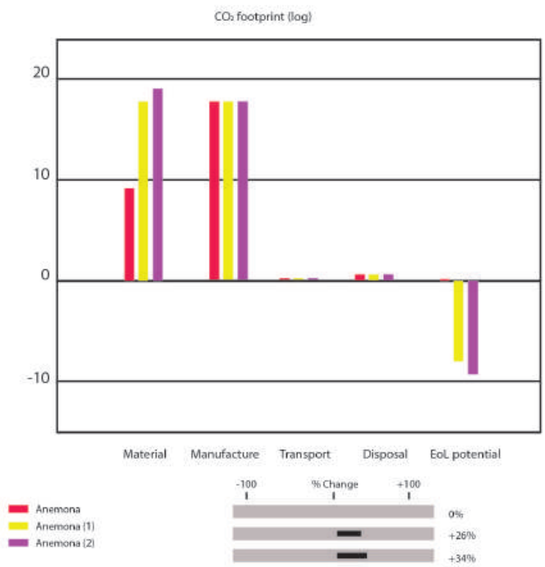
Re-manufacture/re-engineering is not a viable option for this project, as it does not require re-manufacturing or restoration. However, the reuse can be a viable measure, considering that the toy can be offered to another child. Still, this requires a market for the purchase and resale of articles.

There is a dramatic fall in energy associated with the *material*, illustrated in *Graphic 5*. Anémona 2 consumes about twice as much energy compared to Anemona, and Anémona 3 is the one that spends the most energy. *Graphic 5* shows that, in the tree examples of this project, Material is the dominant life phase. Also, the first life energy (not including EoL potential) is increased by 79% (Anémona 2) and, 106% (Anémona 3).

There is a corresponding fall in carbon emissions associated. *Graphic 6* sshows that, in the tree examples of this project, Manufacture is the dominant life phase. Also, the first life CO_2 (not including EoL potential) is increasing by 26% (Anémona 2) and, 34% (Anémona 3).



Graphic 5 Comparison of values regarding energy consumption between Anémona (100% rHDPE), Anémona 1 (50% virgin + 50% rHDPE) and Anémona 3 (100% virgin HDPE) (adapted from CES Edupack 2018)



Graphic 6 Comparison of values for CO_2 emissions between Anémona (100% rHDPE), Anémona 1 (50% virgin + 50% rHDPE) and Anémona 3 (100% virgin HDPE) (adapted from CES Edupack 2018)

Both in the field of *manufacturing* and *disposal*, all three examples have the same values. Given the reasons mentioned above, *transport* and *use*, do not present values. However, *Graphs 5* and *6* show that the example which uses only the recycled material exclusively has lower rating concerning energy cost and CO_2 emissions.

2.3 The polymers end of life cycle

Polymers have revolutionised our lives due to their low cost, high mechanical efficiency, flexibility, high versatility and ability to endure bacterial and fungal penetration, which delays the prolonged natural process of biodegradation. There is an ongoing search for polymers, and this increasing demand has consequently led to a growth of urban and industrial waste.

However, due to the massive amount of plastic waste and environmental pressures, recycling has become a prevalent issue in today's plastics industry.

Half the plastic waste collected is sent abroad, and more than 85% of plastic waste is exported and shipped to China. But soon that will change, because China decided to ban the import action of certain types of plastic waste, thus creating opportunities for EU recyclers (European Commission 2018a).

There are several possibilities for the polymers end-of-life, such as landfills, combustion for heat recovery, recycling, re-engineering and reuse, represented in *Figure 10*.

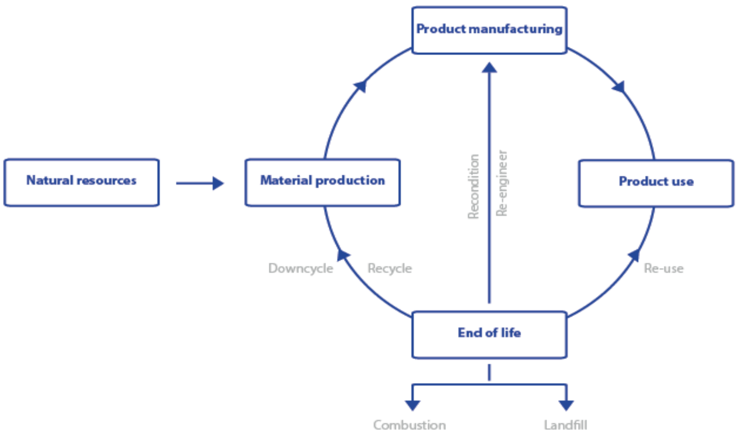


Figure 10 End-of-life options (adapted from Ashaby 2013d)

The landfill has been one of the most commonly used solutions over the years, even though some countries are crowded (Ashby 2013b).

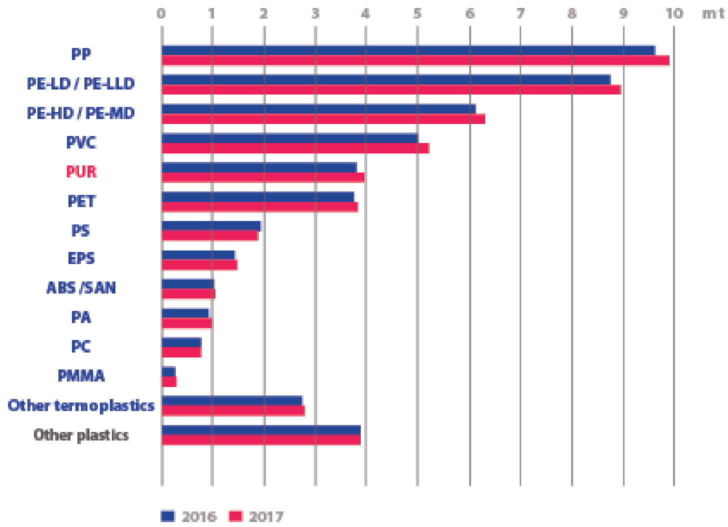
Re-engineering or refurbishment advocates the reform, modernisation and recovery of the components of some products (eg., cars, aircraft). Replacing or upgrading parts is viable, as it does not influence product performance. Reuse is the redistribution of the product to a consumer sector that is willing to accept it (even if it has already been used) and take advantage of its original functions (eg., second-hand car) or adapt it to another use (converting the car into a go-kart) (Ashby 2013d).

However, recycling is the only process that can return waste materials to the supply chain at a rate comparable to that in which waste is generated (Ashby 2013b). T). The recycling process itself involves many stages of energy consumption, and inevitably contamination. Th us may even limit the use of recycled material, so the value is approximately 60% lower than virgin material.

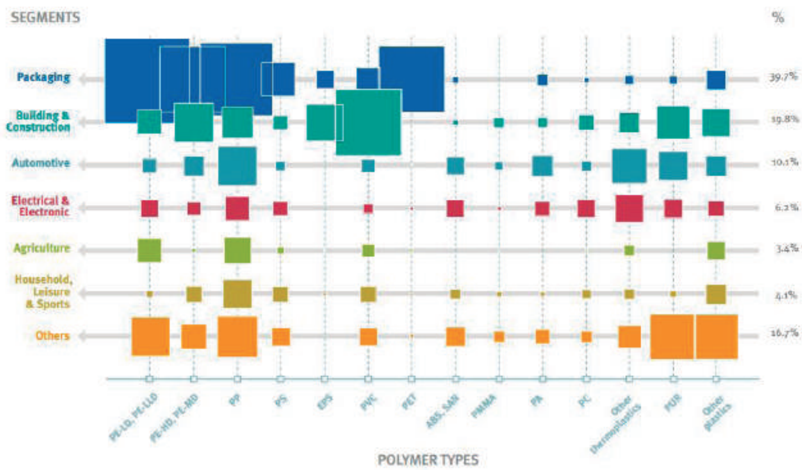
The reintegration of recycled material into the cycle depends on the content. When integrating a recycled material, a fraction of virgin material is usually added to avoid the accumulation of uncontrollable impurities.

2.3.1 Recycling HDPE

Fifty years ago, the production of the polymers was minimal, nowadays, is done in metric tons per year (*Graphic 7*) aand is unthinkable to dispense them from our lives. These materials have revolutionised the market, and are, nowadays, widely used in many industries illustrated in *Graphic 8*.



Graphic 7 Distribution of European (EU28+NO/CH) plastic converter demand by resin type in 2017 (adapted from Plastic Europe 2018)



Graphic 8 European plastic converter demand by segments and polymer types in 2017 (Plastics Europe 2018)

HDPE has been persistently used since its discovery and presents excellent characteristics as durability, flexibility, water tightness, corrosion resistance and ductility. HDPE is one of the most widely used polymers in the thermoplastic family, as shown in both *Graphic 7* and *8*. This polymer is mainly used to manufacture packaging (discarded after a single). The solution relies on the reuse of these residues that besides being in great abundance, preserve their mechanical characteristics (Kumar, Panda, and Singh 2011).

Currently, environmental concerns have been a recurring theme in our society. Changes in oil prices and long-term supply constraints are considered. Recycling has gained more importance since it is a vital role in the world economic dynamics, and financial viability of enterprises linked to plastic (TechDuto 2018).

2.3.1.1 The benefits of recycling

Recycling should be our top priority once the impact of plastic waste has affected the ecosystem. Recycled HDPE helps to preserve non-renewable fossil fuels, reduces energy consumption, as well as carbon dioxide (CO_2), nitrogen oxides (NOx) and sulfur dioxide (SO_2)

emissions. By comparing the production of virgin and recycled plastics, the production of a recycled polymer can reduce approximately 80 to 90% of energy consumption. Also, by using a ton of recycled plastic, it saves 5774 kWh of energy, 2604 l of oil, 98 million Btu of energy and 22 m^3 of landfill (Biron 2017). Redirecting HDPE from landfills or environment allows the reduction and accumulation of plastic waste.

The following marks, shown in *Figure 11,* were designed to improve and facilitate the separation of the different types of polymer. This way, the recycling facilities can dismiss expensive equipment like X-ray fluorescence or infrared spectroscopy (Ashby 2013b). There are several possibilities for identification, some products are identified with the full mark (triangle, number and name), others only with the name/number and, in the worst-case scenario, are not identified. Nevertheless, it is crucial and necessary to inform the users of the type of plastic of the product and, inform the correct way of disposal.

The main problem with using recycled plastics is the lack of information regarding the pos-

Figure 11 Common recycling marks present in polymers (adapted from Ashby 2013b)

sible presence of chemicals (e.g. flame retardants) (European Commission 2018b). That creates a significant obstacle for achieving higher recycling rates.

Refining plastics recycling can positively stimulate the environment and the economy. Through the cooperation of all participants in the value chain, it could be possible to achieve higher levels of recycled plastic. However, this requires addressing the challenges of production, consumption and disposal as business opportunities, where concrete strategies can be developed to realise the vision of a more circular plastics economy (European Commission 2015).

2.3.1.2 Recycling process

Optimising the recycling processes of the material has become the challenge of the century. Reconciling cost-effective with what is environmentally acceptable has proved to be a complicated task, due to the complexity inherent in the reuse of the polymers. Although it is a material used for various applications, as it is also one of the most discarded materials.

The recycling process is divided into four methods: primary, secondary, tertiary and quaternary (*Figure 12*).

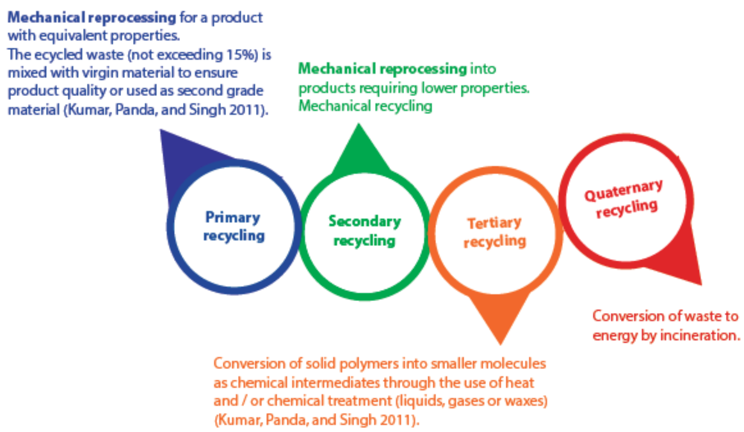


Figure 12 The four types of recycling

2.3.1.2.1 Mechanical Recycling

Mechanical recycling is the most widely used method for waste recycling. The steps of the process are shown schematically in Figure 13.

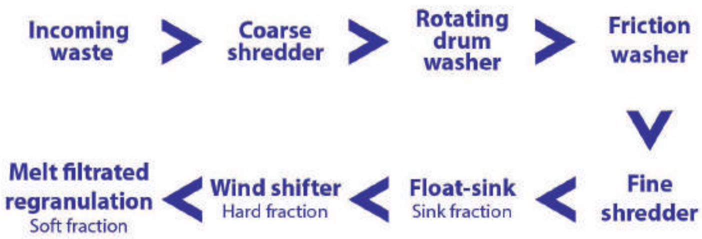


Figure 13 Mechanical recycling process (adapted from Ragaert, Delva, and Van Geem 2017)

First, the polymers collected are stored in a large warehouse. Subsequently, the material is classified and shredded with the coarse shredder aid. Afterwards, the material is washed with a rotating drum washer, to remove the impurities and the organic residues adhered to the plastics, being again re-washed with friction washers. Then, the float-sink separation test is performed. The sinking material goes through a strong suspended magnet (ferrous debris removal), after that the material is mechanically dried. The floating material goes through wind sifter (separation, based on mass). The material can be used directly by the converters, or it may still be subject to final re-granulation, followed by the extrusion process (Ragaert, Delva, and Van Geem 2017). And, the last fraction can also be reused as a raw material.

In spite of the benefits of recycling, during the recycling process, the material can experience some degradation due to heat, oxidation, light, ionic radiation, hydrolysis and mechanical shear (Ragaert, Delva, and Van Geem 2017).

2.3.1.2.2 Chemical Recycling

Currently, different strategies are being implemented to reduce the material in monomers or petrochemical feedstocks. These flows go through processes such as gasification, pyrolysis, fluid-catalysed cracking and hydrocracking. These strategies ideally methods for reducing volume waste and preserving limited resources (Ragaert, Delva, and Van Geem 2017). *Figure 14* demonstrates the various interventions to which the material, in this case, HDPE can be submitted.

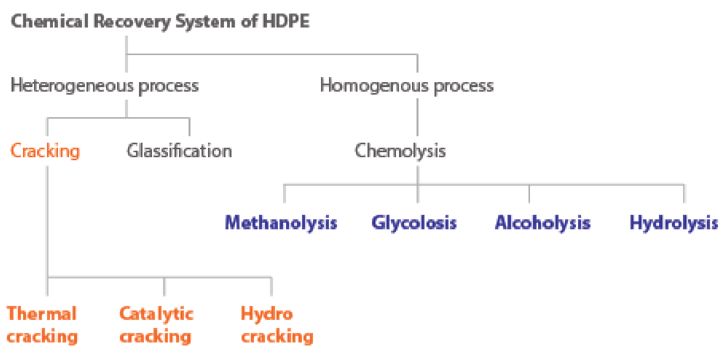


Figure 14 HDPE chemical recovery system (adapted from Kumar, Panda, and Singh 2011)

i. Chemolysis / Solvolysis

During this process, the polymers turn into monomers, through the catalysis of the chemical agents. This process is divided into hydrolysis; alcoholysis; glycolysis and methanolysis (Kumar, Panda, and Singh 2011). *Figure 15* summarises the operation of each step.

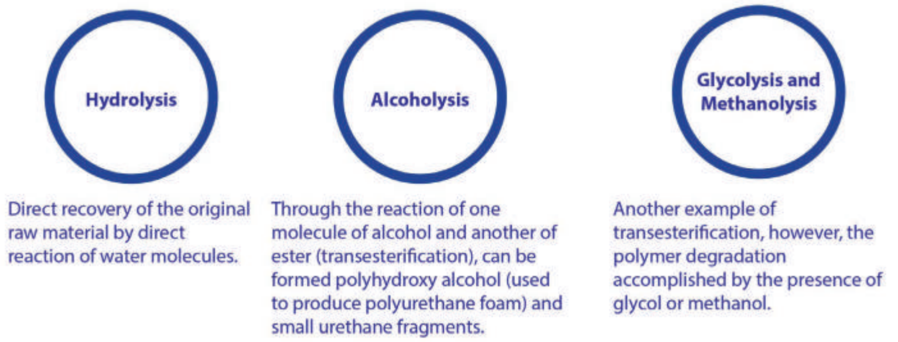


Figure 15 Chemolysis / Solvolysis process

ii. Gasification or Partial oxidation

Use of the gases and hydrocarbons mixture, through partial oxidation (using oxygen and/or steam) or gasification and casting system.

iii. Cracking

This process is still divided into thermal; catalytic; and hydro cracking (Kumar, Panda, e Singh 2011). *Figure 16* summarises the operation of each step.

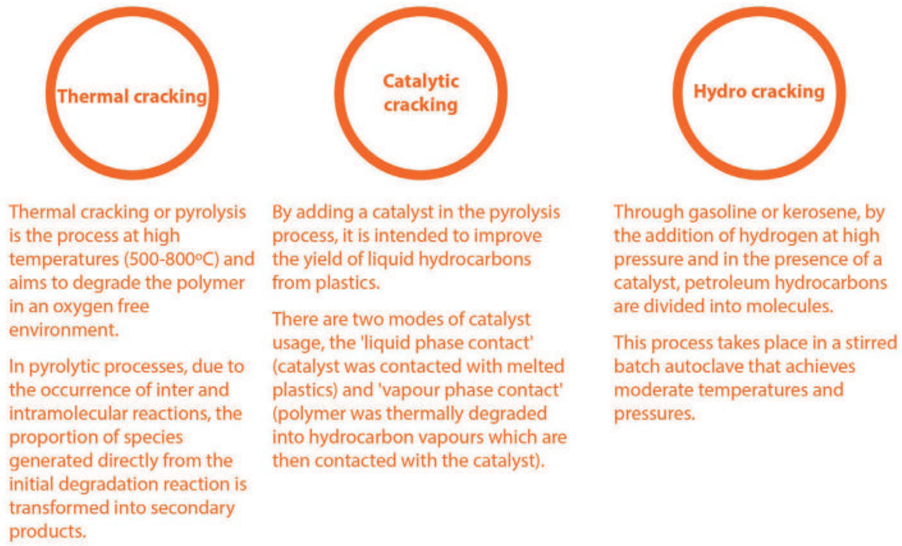


Figure 16 Cracking process

2.3.1.2.3 Energy recovery process

During this process, the waste goes through an incineration process, in which emissions comply with environmental legislation (although they have the potential to emit even low levels of toxic pollutants such as dioxins, acid gases and heavy metals) (Royte 2019). This process takes advantage of polymeric residues abundance and their high predictability and stability for energy production. The modern technology of the mills (if used correctly) can capture the compounds through sophisticated purifiers, precipitators and filters (Royte 2019).

Regarding the economic aspect, the electricity produced is insignificant (market cost). Although mechanical recycling saves more energy, what is valued is the environmental contribution of these facilities (Royte 2019). Apart from that, the electricity production through this strategy helps to achieve the national objectives of renewable energies production and decarbonisation of the economy (Agência Portuguesa do Ambiente 2018).

The construction and use of these facilities are expensive, and they charge more than landfills to dump the litter. Also, to ensure the efficiency of this type of treatment, it is often necessary to import residues from far away to ensure constant flow. Besides, the fact that the smell and smoke disturb people living in the neighbourhood of this type of facility.

There is a conflict between ideas about the conversion of polymers into energy. The opinions are divided since people like Rob Opsomer argue that this process cannot be considered cyclical, rather linear (Ellen MacArthur Foundation 2017). SSo, the extraction of fossil fuel and the plastics production and subsequent incineration to produce energy is not viable. On the other hand, the director of the Environmental Services Association (ESA), Jacob Hayler claims that this is a more acceptable strategy than to deposit the waste in the landfill (Harrabin 2018).

2.3.1.2.4 Summary and analysis of the types of recycling

Mechanical recycling still has some challenges to face. As the contamination or mixing of different kinds of plastics, which may influence the quality of the product, generating limited economies of scale and floating price of recycled materials (Ragaert, Delva, and Van Geem 2017).

Chemical recycling, although it is still slightly utilised, it has brought great interest. This strategy can transform heterogeneous and contaminated waste (residues whose separation is not economically viable or is not entirely technically feasible).

The energy recovery process, in addition to stirring much controversy, also presents significant challenges, since this method is not capable of producing large amounts of energy.

With this in mind, *Table 4* analyses the different types of recycling, their respective advantages and challenges. Any of the strategies presented remains preferable to landfill, since these types of recycling may be complementary paths for the closure of the polymer circuit.

Table 4 Comparison and analysis of the different recycling systems (adapted from Ragaert, Delva, and Van Geem 2017)

Recycling process		Technique	Advantages	Challenges
Mechanical recycling	Sorting	Floating (sink-float)	_ Well-known technology _ Cost-effective _ Particle size	_ Efficiency determined by density differences plastics _ Mainly limited to binary mixtures
		Melt filtration	_ Useful to remove non-melting contaminants _ Additional melt pressure	_ Potential pressure fluctuations in production
		FT-NIR	_ Post-drying not required _ Well-known	_ Black undetectable _ Plastic should be dry
		Tribo-electric (electrostatic) separation	_ Efficient for various plastics _ Small particle sizes allowed	_ Pre-treatment
		Froth flotation	_ Efficiency	_ Precursor step required _ In development for recycled plastics
		Magnetic density separation	_ Improved density-based technique _ Multiple polymer fractions in a single step	_ Density overlaps remain
		X-ray detection	_ Accuracy _ Useful for PVC	_ Cost-effectiveness
	Reprocessing		_ Thermal-mechanical degradation	_ High value recycling
			_ Challenging for complex mixtures	_ Well-known technology
			_ Miscibility of polymer blends	_ Straightforward
Chemical recycling	Chemolysis		_ Generates pure value-added products _ Operational for PET	_ Requires high volumes to be cost-effective _ Mainly limited to condensation polymers
	Pyrolysis		_ Suitable for highly heterogeneous mixtures of plastics _ Simple technology	_ Complexity of reactions _ Requires high volumes to be cost-effective _ Low tolerance for PVC _ Stable waste supply
	Fluid Catalytic cracking		_ Narrow product outcome _ Less stringent reaction conditions lead to favourable economics	_ Deactivation of catalyst _ Absence of suitable reactor technology
	Hydrogen technologies		_ Suitable for mixtures of plastics _ High predictability and stability of energy production contrasts with other disruptive renewable energies	_ High cost of hydrogen _ High investment and operational costs
	Gasification		_ Syngas is a valuable intermediate _ Cost of air _ Well-known technology _ Syngas is a valuable intermediate _ Cost of air _ Well-known technology	_ Amount of noxious NOx _ Specific drawbacks of air _ Amount of noxious NOx _ Specific drawbacks of air
Energy recovery process	Incineration		_ Environmental contribution _ The abundance of waste _ Plastic has is more energy-dense than coal	_ Little amount of electricity _ The process emits even low levels of toxic pollutants such as dioxins, acid gases and heavy metals _ Location of this type of facility _ Expensive process _ Charging an electricity tariff to invest in advanced waste treatment _ Charge more than landfills to dump the litter.

2.4 Form waste to the material – Market research

The transition of the EU to the circular economy aims to boost global competitiveness, promote sustainable economic growth and create new jobs. It is essential to review our relationship with non-renewable materials and adopt sustainable measures to ensure that the economy becomes stronger and circular. It is necessary to intervene in the production of products and through the design aid to close their life cycle. Recycling is a vital measure for the reuse and valorisation of materials and can be a potential business opportunity.

The industry to meet the demand for legislation has been launching eco-conscious products on the market. However, this may be a marketing strategy as it touches a community concerned about environmental issues. Few products show the percentage of recycled material used, and few that care about the environment. An eco-friendly product advocates a sustainable and conscientious practice during all processes by which the product goes, and throughout its life cycle.

Throughout this research, it has been found that many products on the market aim to use fully or partially recycled plastic in new products. In some cases, the mixture of various polymer resulted in several product ranges. These composites deflect polymer waste from landfills. However, this strategy lacks planning for the future as it is very likely that this type of material at its end of life will end up in the landfill.

If the goal is to promote recycling and demonstrate the value of HDPE or any other polymer, it is necessary to explore the material and implement it in products, so that people can appreciate the material value. The creation of products that use recycled material promotes the economics circularity and awareness of the population.

To conclude this second chapter, some examples of products that use recycled HDPE to manufacture products for children, furniture and other products are presented — followed, by some companies that reuse various plastic waste.

2.4.1 Reusing HDPE
2.4.1.1 Products intended for children

The research was focused on toys that use recycled HDPE. Not many examples were found, in part due to the stigma that people still have of recycled materials.

There are currently only a few companies that fabricate products intended for children made from recycled material. However, they do not specify the quantity. Two companies use **100% recycled HDPE** to produce furniture and toys for children. Both companies are determined to change the mindset of people who associate recycled plastic with a greyish, dull and unattractive material (Green Toys 2018).

***i.* ecoBirdy**

Recycling plastic toys seems to be an absolute necessity since it is one of the industries that intensively use plastic. The problem with toys is that they are manufactured and made of various types of polymers (or other materials), which determinates them as general waste, leaving them in the landfill.

The company ecoBirdy developed a solution to recycle these toys made of plastics, contributing to a circular economy that generates less waste (ecoBirdy 2019). Each toy collected is manually analysed (intensive process; however, it brings ecological benefits), and dismantle to remove the unwanted parts (batteries and fabrics). After that, the material is taken to the professional recycling centres, where plastics are shredded, washed and passed through an automated and accurate classification.

From the patented polymer binding formula and the primacy of classifying polymeric waste, emerge ecothylene®, a high-quality material consisting of **100% recycled HDPE** (ecoBirdy 2019). Each produced piece has a unique characteristic since the dotted pattern is different in all the chairs (*Figure 17*). Mainly, the chair is presented in a single part to ensure high strength and robustness, besides being light, easy to clean and 100% recycled.

In addition to its role in giving a new destination to plastic waste, this company collaborates with the local sheltered workshop in the effort to create social added value (ecoBirdy 2019).

Figure 17 ecoBirdy process (ecoBirdy 2019)

ii. **Green Toys**

The California-based company offers eco-friendly children's products in the local market. Green Toys use 100% recycled post-consumer plastic, a strategy that in addition to redirecting the material from the landfills, helps reduce harmful emissions to the environment (Green Toys 2018).

The old can give way to something new, and Green Toys demonstrates this through their toys that in the past life were bottle caps, milk jugs or yoghurt cups. Usually, the company mainly uses HDPE, or on some occasions, LDPE or PP, all **100% recycled** materials. The toy's packaging is 100% recycled cardboard, and the company goes further by printing the brand and specifications of the toy on the packaging with soy ink.

The close local supply chain of material together with strict quality processes guarantee the production of high-quality products. The manufacturing processes also go according to the ecological motto of the company. The plastic collected by waste management is subsequently cleaned, shredded, reprocessed and mixed with food-based dyes. The 100% recycled material undergoes a variety of tests throughout all production steps to ensure that they meet the safety standards (Green Toys 2018).

Through these toys (*Figure 18*), the company intends to raise awareness about sustainability and, at the same time, deliver unquestionably safe products (Green Toys e 2018).

Figure 18 Green Toys process (Green Toys 2018)

2.4.1.2 Various applications

i. Precious Plastic

In 2013, Dave Hakkens started the Precious Plastic project that involves a global community spread all around the world. They share the same goal of finding a solution for the plastic waste that hunts our environment.

> *At Precious Plastic we want to show the world the incredible opportuni¬ties of plastic waste in order to eliminate plastic pollution, reducing the demand for new virgin plastic and closing its materials loop while creating better livelihoods for people around the world. Precious Plastic is, above all, a cultural tool to change the way society perceives plastic.*
>
> (Precious Plastic 2017)

This community began by finding a place where people that share the same goals could work and create new products from collected plastic waste. *Figure 19* shows the manufacturing steps. At Precious Plastic, there is a need for having plastic to create new products. Given this, there is a collection made by visitors or pedestrians who leave the plastic into the containers distributed in the community.

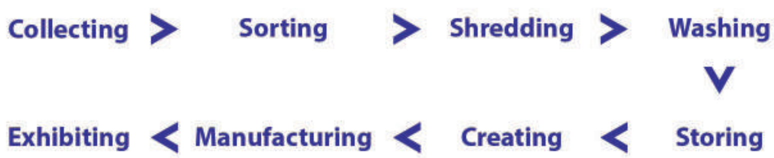


Figure 19 Precious Plastic manufacturing flow

Collecting is the first step, followed by another critical step, sorting. The precise and efficient separation apart from distinguishing the different plastic also helps in organising the workspace. Then, the material is shredded and washed (5 to 10 times), to remove the impurities that the material has acquired. After drying, the material is stored and, it is time to be creative, through the machines also developed by Precious Plastic (shredder; extrusion machine; injection machine and; compression machine). The possibilities are endless. In the end, the final product is photographed and displayed (*Figure 20*), once the purpose is to sell the product all around the world.

This independent community keeps on developing new technics, machines, and products that are available online at https://preciousplastic.com.

Figure 20 Precious Plastic machines (left), and (right) products (Precious Plastic 2017)

> *The machines are designed based on traditional industrial concepts but on a much smaller scale so that costs and knowledge's entry level can be kept to a minimum. This inclusive approach increases accessibility and adop¬tion worldwide.*
>
> (Precious Plastic 2017)

The machines developed are easy to manipulate, reproduce and repair as they use basic, easy to find technology and materials. The machine's components can be easily replaced since all of them are modular.

Their motto is that everyone can begin, and everyone can contribute to this cause. This community keep on trying to recruit more people interested in the fight against plastic pollution.

ii. Studio Smile Plastics

The Studio Smile Plastics through a simple, versatile and functional design demonstrates the beauty and value of the materials. The manual production and exploitation of different colours and patterns from different waste streams originated unique pieces (*Figure 21*). The imperfections and variations tell a different recycle history (Smile Plastics 2017).

Figure 21Smile Plastics creation process and applicability (Smile Plastics 2017)

iii. Intectural - Metem Plastics Product Line

TThe company Intectural has launched the Metem Plastics, a line of panels in a variety of colours, produced from **100% recycled polymers** such as HDPE. Metem Plastics can be applied both inside and outside (*Figure 22*), has UV stabilizing additives, is BPA Free and is maintenance-free (Intectural 2019).

Bisphenol A **(BPA)** is an industrial chemical used to produce certain plastics (polycarbonate and epoxy resins). BPA can seep into food or drinks, which can affect our health.

Figure 22 Exterior (2nd image left) and interior (1sr image left a de middle image) application as well as the Metem Plastics material detail (Intectural 2019)

iv. Mummy Vessel 3 by Marcel Sigle

Mummy vessel designed by Marcel Sigle was created from the joining of HDPE plastic bags and glass bottles of various dimensions. The bottles wrapped in the HDPE layers give different thickness and transparency (*Figure 23*). The random pattern of construction is enhanced by the light that comes from behind or inside the vessel (designboom 2005). The designer unleashes the public's perception of recycled products and the way we use them.

The main focus of the design was to change the inherent value of the material being used. (…) By retaining the essential look and feel of the plastic bag the design challenges our perceptions of recycled products and the way in which we use them, helping develop consumer awareness about the recycling process.

Marcel Sigle (2019)

Figure 23 Mummy Vessel by Marcel Sigle (designboom 2005)

v. Beach slipper, buttons and necklaces by Flávia Freixas (MDIP, DS at FEUP)

Within the scope of MDIP, the designer Flávia Freixas presented in her thesis three product proposals made from PET and **HDPE** waste. Freixas presented the plan for a pair of beach slippers produced from PET (plus silicone), buttons and collars (plus biodegradable thermoplastic - PLA) produced from residues of HDPE (*Figure 24*) (Freixa 2016). Out of the three products, the most viable is the buttons one, since it is the only one that was produced entirely from recycled HDPE, which makes it easily recycled.

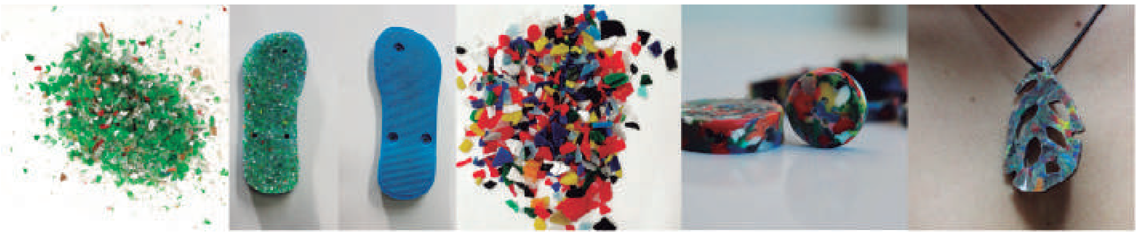


Figure 24 Shredded PET (1st image left) and Beach slipper (2nd image left); Shredded HDPE (middle image) and buttons and necklaces (right images) by Flávia Freixa (Freixa 2016)

2.4.1.3 Furniture

i. Gibada Stool by Axel Silva (MDIP at FBAUP)

Also, within the scope of MDIP, the designer Axel López Silva explored HDPE waste and designed the tripod stool "Gibada" (*Figure 25*). Gibada seat was designed and manufactured in recycled HDPE and oak wood legs. Through its elegant and modular form, Gibada aims to be a project that helps promote and value the reuse of thermoplastics and deployment in furniture.

The designer also argues that a recycled product should promote long-term consumer use in contrast to the short life of current packaging applications (Silva 2018).

The key aspect of this furniture is transmitting the positive outcomes of creating products that implement recycled thermoplastics in their components.

Axel Silva (2018)

Figure 25 Gibada Stool by Alexandro Axel López Silva (Silva 2018)

ii. 'prolong' by Charlotte Allen

The multidisciplinary Charlotte Allen collected for one month its own trash (recyclable) that later originated the 'prolong' stool (*Figure 26*). Cardboard junction and PVA (polyvinyl alcohol) created the legs, and melted HDPE originated the bench top.

> *I gave myself the brief 'prolong' where I wanted to prolong people's relationship with their waste.*
>
> Charlotte Allen (designboom 2018)

Figure 26'prolong' stool by Charlotte Allen (designboom 2018)

iii. Müll by Carter Zufelt

The abundance and depreciation of the bags attracted the designer Carter Zufelt attention, how transformed these wastes into a collection called müll (*Figure 27*). The collection has tables organisers, cubes and stools. Zufelt pieces showcase intricate patterns, swirls, and colours that appear to be carved in marble (Goodner 2015).

> *The manipulation involves multiple baking sessions, twisting, folding, and compressing, (…) the trick is the right amount of heat coupled with the right amount of pressure.*
>
> Carter Zufelt (Goodner 2015)

Figure 27 Müll collection: cubes (right); the stool set (middle); and the stool (right) (Goodner 2015)

2.4.2 100% Recycled polymers

In addition to mixing the various polymeric wastes, the so-called "plastic wood" contains UV protectors and stabilisers to improve product quality. Although this material helps reduce the consumption of natural resources, it is impossible to recycle.

i. Decoverdi

Decoverdi produces profiles called "plastic wood" from **100% recycled plastic**. This high quality, resistant, durable and versatile material emerges from the double extrusion of mixed plastics from urban and industrial waste.

The plastic wood has a diversity of colours (dye incorporated in the polymer mixture), is anti-slip, antibacterial, robust, and the dimensions can be varied. However, there is a limitation as to the geometry of the section that can be round, square, rectangular (Decoverdi 2016). Regarding functional qualities, the material is easy to work mechanically; versatile and customizable; anti-vandalism; anti-graffiti; anti-static; no maintenance required; chemical and biological resistance (Decoverdi 2016). Also, this material helps to reduce the consumption of natural resources.

Since this material is impermeable and resistant to extreme temperatures, is used for the construction of public spaces (*Figure 28*), garden areas, environmental requalification, urban furniture or construction of green roofs.

Figure 28 "plastic wood" section (left) and application in Santo André Lagoon, Santiago do Cacém (righy) (Decoverdi 2016)

ii. Extruplás

Extruplás has established a solution for mixed plastics waste at the national level. Through the recycling, collection and recovery of the mixed plastics from which the company produces urban furniture (*Figure 29*) (Extruplás 2018). Similar to Decoderdi, Extruplás also provides a material that: resists corrosion; does not rot; anti-vandalism; anti-graffiti; supports shock, rupture, and abrasion; no maintenance required; low installation cost; non-slip; resistant to temperatures and burners; is unassailable by parasites and fungi; and easily machined.

Figure 29 Profiles storage (left) and urban furniture (righy) (Extruplás 2018)

Through its concept of sustained growth, Extruplás intends to value and encourage recycling through innovation, research and internationalisation of the manufacture of quality products (Extruplás 2018).

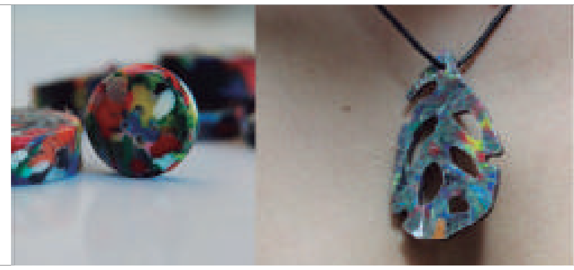
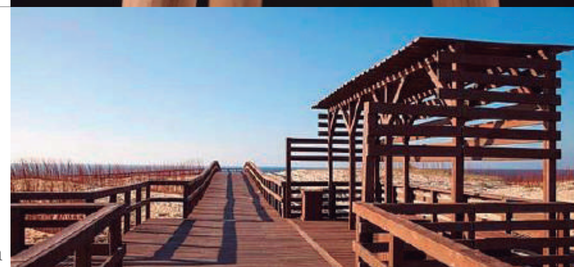
2.4.3 Summary and analysis table of products made from plastic waste

Table 5 summarises and analyses the information relating to all the examples mentioned above. The products are followed by the company, the waste used, as well as the process of transformation adopted.

Some companies choose not to reveal the transformation process they use, due to the fact that some of them have patented processes. Still, it is possible to identify a constant in all examples; the collected material is always washed (eliminate impurities) and shredded (facilitates the melting process). The steps followed depend on the infrastructures of the company and the product intended to be manufactured.

Table 5 Comparison and analysis of the different products made from waste and exploitation of the transformation process

Company/ brand/ Designer	Waste	Process of transformation	Application	
ecoBirdy	recycle these toys (HDPE)	From polymeric waste and the patented technology of the improved binding formula for polymers, emerges ecothylene®.	Furniture	 ***Figure 30*** ecoBirdy (eco-Birdy 2019)
Green Toys	bottle caps, milk jugs or yoghurt cups (HDPE; LDPE; PP)	The plastic collected by waste management is subsequently cleaned, shredded, reprocessed and mixed with food-based dyes. The 100% recycled material undergoes a variety of tests throughout all production steps.	Toys	 ***Figure 31*** Green Toys (Green Toys 2018)
Precious Plastic	PET; HDPE; LDPE; PP; PS	Collecting, sorting, shredding, washing, storing and creating.	Tiles, jars, modular desktops, covers for mobile phones, jewellery, handles, beakers, photo frames, beams, bricks.	 ***Figure 32*** Precious Plastic (Precious Plastic 2017)
Smile Plastics	Thermoplastics (e.g. HDPE, PET, HIPS; PVC), sea plastic, credit cards, electrical cables, christmas decorations, wellington boots, paper, textiles and organic materials like tea, spices and coffee grounds.	Depending on the requirements, different mixtures of materials, textures, colours, and even mixing between various materials are explored. Before manufacturing the final product, a sample is produced to verify if the material presents the desired properties.	Store and exhibition design; tabletops, shelving, seating, bathrooms; product and furniture design (from jewellery to homeware, both indoor and outdoor); bathroom panels, counter tops, splashbacks, cabinet doors, furniture and shelving; playgrounds, swimming pools and spas.	 ***Figure 33***Smile Plastics (Smile Plastics 2017)
Intectural - Metem Product Line	HDPE	Unknown process.	Commercial playground structures; bathroom partitions; skate park construction; and exterior cabinetry.	 ***Figure 34*** Metem Plastics (Intectural 2019)
Mummy Vessel by Marcel Sigel	100% recycled HDPE plastic shopping bags, and varying sizes glass.	HDPE bags wrapped and melted around the glass bottle.	Vessel	 ***Figure 35*** Mummy Vessel (designboom 2005)

Beach slipper/ flip flops, buttons and necklaces by Flávia Freixa	PET; HDPE	The slippers were produced through the junction of PET shredded with transparent silicone. The buttons were made of 100% recycled shredded HDPE. The jewellery combined the shredded and recycled HDPE with the PLA.	Beach slipper/ flip flops, buttons and necklaces		*Figure 36* Buttons (Freixa 2016)
Gibada Stool by Axel Silva	HDPE	The top was produced through the recycled shredded HDPE, which was moulded, machined and CNC cut so that the wooden (oak) legs could be placed.	Stool		*Figure 37* Gibada Stool (Silva 2018)
'prolong' by Charlotte Allen	One-month household waste.	Cardboard and PVA (polyvinyl alcohol) originated the legs, and the shredded HDPE originated the benchtop.	Stool		*Figure 38* 'prolong' stool (designboom 2018)
Müll by Carter Zufelt	HDPE bags	Process of multiple baking sessions (at controlled temperatures), twisting, folding, and compressing, which gives it a marble-like appearance.	Stool, cubes, table organizers.		Figure 39 Müll stool (Goodner 2015)
Decoverdi	Mixed plastics from urban and industrial waste	This "plastic wood" emerges from the double extrusion of multiple plastics.	Construction of public spaces, garden areas, environmental requalification, urban furniture or construction of green roofs.		*Figure 40* Santo André Lagoon, Santiago do Cacém (Decoverdi 2016)
Extruplás	Mixed plastics				*Figure 41* Urban furniture (Extruplás 2018)

III. Case study - Development of a project from HDPE waste

Throughout state of the art, it was verified that by closing the product's life cycle, it is possible to guarantee the reuse of the material as valuable input. The third chapter intervenes in favour of the validation of the subjects discussed in the previous section.

During this chapter is presented the entire development of the design project within the scope of the social project WWWY (see chapter *1.2 We Won´t Waste You Project* and *3.2 WWWY Project development*), whose purpose is to ally social action, innovation and environmental concerns (Fernandes et al. 2018).

First, the Beach kit and the Beach kids products are presented, both developed during the WWWY project throughout MDIP 2017-2018 academic year. However, as the toy designed for the Beach Kids did not meet the desired requirements, the project was prolonged for the following academic year (2018-2019), which originated the theme of this master dissertation.

That said, in this chapter is presented the Beach kids toy made of **100% recycled HDPE**.

3.1 Methodology

Figure 42 shows the different steps used throughout the Beach kids toy development. After

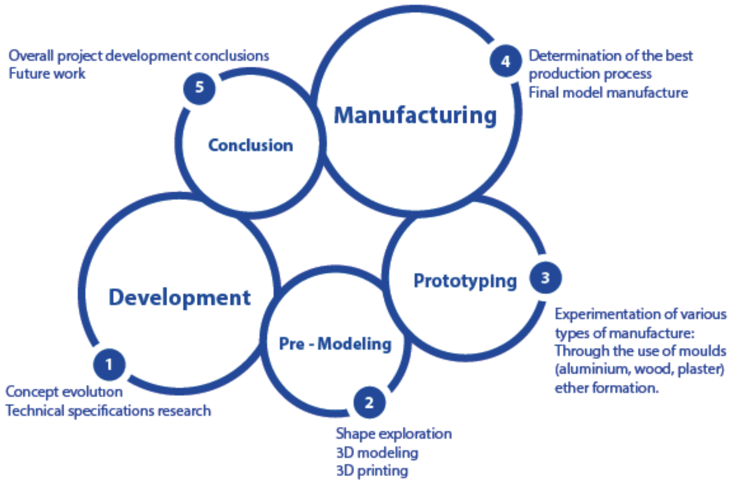


Figure 42 Beach kids toy development

the end of the first academic year of MDIP (2017-2018), a survey was made of the aspects to be improved in the Beach kids project. The project has undergone drastic changes.

i. During the first stage, the elements to be improved were reviewed, as well as further study of safety requirements and technical specifications.

ii. TThe research influenced the modelling stage, a process in which several changes occurred. Several 3D models were printed to verify and analyse the toy's shape. Which proved to be an essential step since it helped to achieve the intended final form for the toys.

iii. After that, the prototyping stage, where various experiments were performed with different materials. Also, throughout this stage, different manufacturing processes were performed (through the use of moulds in aluminium, pine, plaster, thermoforming process). Each procedure was adapted and designed with rudimentary and low-tech tools.

iv. After the experiment phase, it was possible to determine the most appropriate process for the production of the Beach kids' toys.

v. And finally, an overview and conclusion of the whole process and the final result was made.

3.2 WWWY Project development

3.2.1 WWWY Project

The WWWY project /design workshop has created a link between society, environment and innovation (Fernandes et al. 2018). In addition to promoting tourism of Matosinhos (through products made from the city's waste), the WWWY project promotes a circular economy, recycling and extending the materials life cycle. Each product developed under the scope of this project had to be manufactured with a low-tech, and, easy-to-operate system, in order to dismiss skilled labour. As the project progressed, there was the possibility of creating jobs for the active, unemployed adults from a socially vulnerable group identified by the city's social services (Fernandes et al. 2018).

The project training took place under the workshop frame in an environment similar to a design studio (Fernandes et al. 2018). In this context, the teacher helped the students to relate their objectives to the general expectations of the project (Graaff and Kolmos 2003; Reigeluth and Carr-Chellman 2009). TThe students were organized in teams of 4 to 5 elements. Each group developed creative solutions based on experiences (made at home or FBAUP and FEUP workshops), local visits and scientific research (from reliable sources, as articles, books, software and official websites). During the weekly meetings, each team presented the work progress to the teachers and colleagues. Through these meetings, a cooperating atmosphere among the whole class was created, as all commented, criticized and presented alternatives for the project development.

At the final stretch, each team had the opportunity to present their products to the heads of the city council social team of Matosinhos. And some of the products, such as the Beach kit, were selected for future production.

3.2.1.1 Beach kit

Matosinhos is known for the vast beach that covers the west of the city. Besides being an essential and emblematic area, it influences the local economic development. However, the amount of litter, mostly plastic, found at the beach is visible and worrying (*Figure 43*), and has motivated the team in charge to find a solution for the plastic wastes.

Figure 43 Matosinhos beach

The team began studying and testing the collected polymers. Several experiments were carried out, were some unlikely materials such as silicon, sand, fishing nets and potato starch were mixed, among others. After some failed attempts, the team realized that the best way for joining the plastic is through melting. Soon it was conceded that the most suitable material for the Beach kit products was HDPE, from the bottle caps. HDPE has versatile properties, is produced in various colours and, is widely used due to its: low degradation rate; mechanical, chemical and biological attacks resistance; low cost; and excellent biocompatibility (Kumar, Panda, and Singh 2011; Kadhim 2017).). On the other hand, the PP was also chosen due to his versatile properties, such as low cost, colour variety, easy moulding, good chemical resistance with moderate impact resistance, good thermal stability, low moisture absorption, non-toxic and good flexural strength (Jmal et al. 2018).

During the product development stage, the team separated, and each member chose to develop its product. However, the team was aware of each project development, since there was an environment of cooperation and criticism among teachers and colleagues in the group or class. As presented in *Figure 44*, the Beach kit product line is composed by a phone case

Figure 44 Beach kit

(HDPE), a cardholder (HDPE), a bracelet (PP) and a glasses case (HDPE). This collection of recycled products inspired by the beach was developed to guarantee the protection of the belongings (Fernandes et al. 2018). The glasses case and the bracelet were manufactured from 100% recycled material, the phone case and the cardholder have a small percentage of virgin material to help in the production process.

In addition to the material, the manufacturing process also influenced the final shape of each piece. However, one of the most significant obstacles felt was; to adapt and simplify the manufacturing process, as the WWWY project implied. The manufacturing process of the products was inspired by the basic construction equipment available on the Precious Plastic website (https://preciousplastic.com). Given the lack of conditions and equipment, the casting, sealing, moulding and compression processes were adapted according to the accessibility of FBAUP workshop equipment. In chapter *3.4 Experimental plan* and *3.5 Prototyping* (the *3.5.1.1 Aluminium mould*), the different strategies and processes used during this first year of experiments are detailed.

3.2.1.2 Beach kids

At the beginning of the following semester, the students had the opportunity to continue developing the prior project or begin a new one. Since the Beach kit was selected for future production, the idea was to expand the collection with new products.

The Beach kit gave way to the Beach kids, a set of toys developed for a younger audience to play on the beach. In order not to compromise the health and safety of children, the design of the toy had to consider: the size of its parts, to reduce the risk of suffocation or airway obstruction; to avoid protrusions or sharp points; and to prevent fractures or deformations, that can cause physical damage (European Parliament and Council of the European Union 2009; Diário da República 2017). AAn in-depth investigation is presented throughout the chapter *3.3.2 Legal requirements for toys for children - standards imposed by the EU*.

From de beginning of this toy project, the idea was to preserve some similarities with the previously developed project. The Beach kids' toy was also designed as a link between the environmental concern (by using **100% recycled HDPE**) and by representing one of the most known sculptures of Matosinhos. The toy shape intended to resemble the emblematic Anémona sculpture, as shown in *Figure 45*.

Like the previous project, the Beach kids toy production process was also inspired by Precious Plastic equipment. However, both the shape, as well as the production process, were not satisfactory. The shifting thickness and the straight walls not only made it difficult to extract the toy from the mould but also make it difficult to reproduce the shape in the sand. Besides, the surface had traces of aluminium foil, as well as very sharp edges. Its surface had traces of aluminium foil, besides having too sharp edges. The chapter, *3.5.1.2 Wood mould* describes this process in detail.

For these reasons, the Beach kids toy development was continued and became the subject of this dissertation.

Figure 45 Beach kids: Anémona and the sand silhouette

3.2.2 Project analysis

Since Beach kids had some aspects that could be improved, it was decided to continue and enhance the project. The features to improve are divided and presented in Table 6. From all the five topics, the most concerning and underdeveloped elements are the design/form and the manufacturing process.

Table 6 summarizes the aspects that needed to be improved during the development of the new toy. Besides, *Table 6* also outlined some features to consider during the development of the new project (highlighted in blue text).

Table 6 Aspects of Beach kids to improve and things to consider when developing the new project

Material	Research	Design/Form	Final Treatments	Manufacturing process
- explore different colours mixtures of HDPE.	- legal requirements for toys; - Matosinhos monuments; - explore the beach toys market.	- improve the representation of monuments; - use rounded edges; - explore more perspectives of monuments; - simplify the parts; - exclude unnecessary detail.	- improve final end treatments; - clean and shiny surface (no trace of aluminium foil).	- achieve a uniform thickness; - improve the production process; - mould angles (to extract the part easily); - determine the exact amount of material to be used (avoid wasting material);
- use only recycled HDPE	**- anthropometry and ergonomic measurements of the children hands;**	**- representative of the city of Matosinhos;**	**- explore efficient methods for the cutting of excess material;**	**- explore new manufacturing processes.**
	-appropriate age for these kinds of toys.	**- adapt the measurements;**	**-make the touch nice;**	
		-simplify the geometry.	**-lightweight toy.**	

3.2.2.1 Evolution of the concept

The beach is considered one of the cities´ main attraction and is daily visited by tourists and locals, to surf or relax. Although it is a place where people like to visit, it is also a place where people leave trash, such as water bottles, plastic bags, among others. This factor motivated the team to explore and find a solution for plastic waste. The chosen concept was the beach. Thus, the Beach kit collection was born from a summary of the belongings that people take to the beach (*Figure 46*).

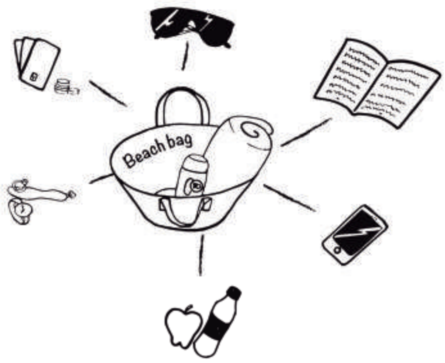


Figure 46 Belongings that people usually take to the beach

This strategy influenced and determined the development of the phone case, the card-holder, the bracelet and the glasses case.
In the following semester, it was intended to continue the Beach kit. However, as previously said, some changes were made specifically to the target audience and a slight variation in the product name. Instead of the Beach kit, the product was called Beach kids. The idea was to create something for a younger public since the children love the beach, and when they are not in the water, they play and do activities on the sand.

In order to preserve some resemblance to the previously developed set of products, it was decided to choose the same material, HDPE. Different ideas came across, as shown in Figure 47. What caught the attention was the possibility of creating a link between the city and the toy. The best way for the toy to connect to the city of Matosinhos is through its most emblematic monuments/buildings. By assigning the shape of the monuments to the toy, the users may perhaps remember the city of Matosinhos.

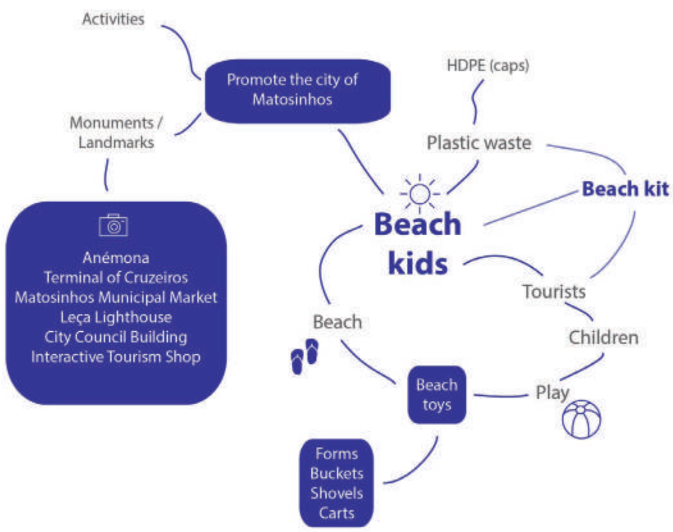


Figure 47 Brainstorming of ideas for the Beach kids project

3.2.2.2 Gathering ideas - Similar products

Market research has provided references regarding measurements, materials, toy typology, shapes, recommended ages and shapes. Predominantly, the most widely used material on the market, is, without a doubt, plastic, except for the examples 7,8 and 9 from *Table 7* and *Figure 48*. Regarding the dimensions, the weight and the prices widely vary. The measurements presented in *Table 7*, along with the measures introduced in the chapter 3.3.1 Anthropometric and Ergonomic issues relative to the design project, helped to define the appropriate dimensions for the Beach kids' toy.

Table 7 Similar products

No.	Product	Manufacturer	Material	Age recommendation	Dimension (cm)	Weight (g)	Price (€)
1	Sand Play Set	Green Toys	100% recycled HDPE	18 months - 5 years	25,4 x 25,4 x 22,9	476	19,40
2	SANDIG	Ikea	PP	12 months and up	17 x 17 x 17	280	6,17
3			PE		14 x 10 x 20	120	
4					14.5 x 12.4 x 9.7	181	
5	Kidami	-		24 months and up	9 x 9 x 6	267	10,50
6	Castle Wall Sand Mould	Spielstabil	PP	2.5 and up	2.4 x 3.1 x 7.5	100	4,50
7	Sand play set	Ekobo animo	Bamboo fibre	36 months until 10 years	12.2 x 7.1 x27.4	380	25
8	Beach Toys	Zoë b Organic	Biodegradable material, made from corn sugar	-	14,2 x 14,2 x 14	408	17,64
9	DuneBug's Sand Truck	Sprig	Recycled wood and reclaimed plastic	3 and up	22 x 19.6 x 9.4	381	13,38
10	Soft Boomerang	Tribord	Foamed PU	8 and up	16,5 Ø	65	5
11	OLAIAN		40% PP 60% LDPE		27 Ø	175	10

Figure 48 Beach toys available in the international market related to the *Table 8* (**1** Green Toys, 2018); (**2, 3, 4** https://www.ikea.com/pt/pt/search/?query=brinquedos); (**5** http://kidami-ent.com/proView.asp?ID=12) (**6** https://www.amazon.com/Spielstabil-Castle-Wall-Sand-Mold/dp/B01HDG8D2K); (**7** https://by-ekobo.com/en/beach-sand-toys.html); (**8** http://news.bio-based.eu/zoe-b-organic-introduces-worlds-first-biodegradable-beach-toys-finally-toys-cean/); (**9** https://themomedit.com/review-action-packed-ecofriendly-sprig-toys/); (**10, 11** https://www.decathlon.pt/C-1406326-jogos-na-praia)

3.3 Technical specifications

3.3.1 Anthropometric and Ergonomic issues relatively to the design project

Anthropometric is the study of the human body and its movement, often involving research into measurements related to people. It also involves collecting statistics or measurements relevant to the human body, called anthropometric data, that is usually displayed as a table of results diagram or graph.

Ergonomics is the study of people and their relationship with the environment around them. The measurements, also known as anthropometric data, are applied to designs and products to make them more comfortable to use. The application of measurements to products in order to improve their human use is called ergonomics.

> *Ergonomics tells us that what must be considered above all else during the design process is the user. Whether you are designing a tool, product, task, or environment, ergonomics dictates that the user's needs, interests, skills, and comfort come first. In this case, the users are children. Playground designers must, therefore, put children first and address age-related factors. …but any dimension critical to children's safe use of play equipment should have an anthropometric basis.*

(Roderick 2004)

Children change and grow quickly both psychologically and physically, but usually, are described according to their age (Lueder e Rice 2008). The developmental stage of the age group for which the toy is intended is crucial, as children are unable to anticipate the consequences of their decisions to use their skills in such equipment (Roderick 2004).

However, the growth rate varies during childhood. The physiognomy of children changes with growth and variations between the same age group (Lueder and Rice 2008). The hands help perform complex tasks in their daily lives; in turn, these activities require grip strength and manual dexterity that the children developed during the growing phase (Omar et al. 2018).

Although anthropometry is useful, it can cause unintentional design problems. Since the anthropometric surveys do not always follow standardized protocols to name and define variables. To avoid doubts is necessary to know how they are obtained.

Measurements were taken from the children's hands, relative to length, breadth (Dreyfuss 2003). In some cases, it was possible to obtain the sizes of the 3rd finger length; dorsum length; and thumb length (*Figure 49*) (Tilley and Associates 1993). Measures include children from 3 to 14 years of age (*Table 8* and *Figure 50*).

The measures shown in Table 8 include children from 3 to 14 years of age.

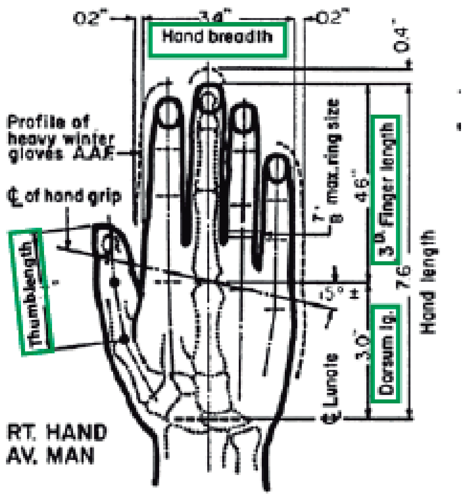


Figure 49 Measurements presented in Table 8 (Dreyfuss 2003)

Table 8 Measures of the hand of toddlers between 3 and 14 years old (all measurements are in mm) (adapted from Tilley and Associates 1993 and Dreyfuss 2003)

Years	3	4	5	6	7	8	9	10	11	12	13	14
Hand length	105	113	119	130	132	142	143	150	160	161	168	178
Hand breadth	50	54	55	58	63	64	65	68	71	70	79	79
3rd finger length	-	-	-	74	-	81	-	-	89	-	-	102
Dorsum length	-	-	-	56	-	61	-	-	71	-	-	75
Thumb length	-	-	-	46	-	51	-	-	56	-	-	61

As children are quite vulnerable, it is necessary to balance their curiosity and need to explore, learn about the environment and play (Lueder and Rice 2008). Ergonomic incompatibilities between the physical dimensions of the objects with which the children interact may inflict pain, which may influence the learning behaviour of children health (Cheng et al. 2018)

3.3.2 Legal requirements for children toys - standards imposed by the EU

Toys can help a child's development since their use presupposes specific skills, and characteristics are related to the age and stage of development. Various accidents are associated with design flaws, which can interfere with toy handling and use, facilitating ingestion of parts, causing suffocation, cuts or intoxication or a problem with the material used, which can cause serious incidents, even lead to the death of the child. Toy safety is an essential part of product development. Currently, the toy industry can only launch toys that pass the rigorous product evaluation test (Mak and Lau 2013). However, injuries and deaths still occur due to unsafe toys.

To reduce risks and protect citizens, the EC has brought together a set of product safety regulations to suit as the *European Standard* for the production of toys. The EU has developed a series of restrictions described in *Table 9*, as well as in ISO 8124 (International Organization for Standardization 2018).

Table 9 Toy Safety Standards Around the World (International Council of Toy Industries 2017)

Region	Standard(s) and Regulations
European Union	EN 71-1. Safety of toys - Part 1: Mechanical and physical properties. EN 71-2. Safety of toys - Part 2: Flammability. EN 71-3. Safety of toys - Part 3: Migration of certain elements. EN 71-4. Safety of toys - Part 4: Experimental sets for chemistry and related activities. EN 71-5. Safety of toys - Part 5: Chemical toys (sets) other than experimental sets. EN 71-8. Safety of toys - Part 8: Activity toys for domestic use. EN 71-12. Safety of toys - Part 12: N-Nitrosamines and N-nitrosatable substances. EN 62115. Safety of electric toys.
International	ISO 8124-1. Safety of toys. Part 1: Safety aspects related to mechanical and physical properties. ISO 8124-2. Safety of toys. Part 2: Flammability. ISO 8124-3. Safety of toys. Part 3: Migration of certain elements. ISO 8124-4. Safety of toys. Part 4: Swings, slides and similar activity toys for indoor and outdoor family domestic use. ISO 8124-5. Safety of toys. Part 5: Determination of total concentration of certain elements in toys. ISO 8124-6. Safety of toys. Part 6: Certain phthalate esters in toys and children's products. ISO 8124-7. Safety of toys. Part 7: Requirements and test methods for finger paints. ISO/TR 8124-8. Safety of toys. Part 8: Age determination guidelines.

ISO 8124-1: 2018 has several requirements that apply to toys and any product designed for use by children under 14 years of age. ISO 8124 is divided into eight parts, where each document presents the requirements with respect to (*Table 9*): safety aspects related to mechanical and physical properties; flammability; migration of certain elements; swings, slides and similar activity toys for indoor and outdoor family domestic use; determination of total concentration of certain elements in toys; certain phthalate esters in toys and children's products; requirements; and test methods for finger paints; age determination guidelines.

Part 1: *Safety aspects related to mechanical and physical properties*, the document specifies acceptance criteria for the structural characteristics of toys, such as shape; size; contour; and spacing. Criteria for maximum kinetic energy values for projectiles with non-resilient tips and minimum tip angles for certain ride-on toys are also presented (International Organization for Standardization 2018). In addition, requirements and methods for children's toys of various age groups are presented in this document, and the requirements for a particular age group reflect the nature of the hazards and the expected mental and/or physical abilities of the child (International Organization for Standardization 2018). PProper instructions for using the toy are also required; however, this may vary by country.

The EC, published for the first time, in 1988 the approximation of the laws of the Member States on the safety of toys (European Parliament and Council of the European Union 1988). To be marketed, the toys had to meet the 1988 (essential) safety requirements for toys. The toy was (and still is) required to bear the CE marking, as well as the name and details of the manufacturer's address, and to provide a list of precautions to consider when using the toy (European Parliament and Council of the European Union 2009; European Parliament and Council of the European Union 1988; Diário da República 2017). In order to obtain the CE marking, toys must meet the criteria established in the *Toy Safety Directive*. If toys do not comply with the *Directive*, they are removed from the market (European Parliament and Council of the European Union 2009).

These requirements are still applied today, although recurring rectifications are made to the various physical, mechanical, electrical, flammability, chemical, hygienic, and radioactive hazards that the toy may present. Recently, particular attention has been given to certain chemicals substances.

The *Toy Safety Directive* sets out a list of requirements that toys must meet regarding their physical and mechanical properties, flammability, chemical properties and electrical properties, hygiene and radioactivity (European Parliament and Council of the European Union 2009). Currently, this Directive is being applied and adapted to the laws of each EU member state.

3.3.2.1 Particular safety requirements for the Beach kids

The review of the *Toy Safety Directive* requirements has directly influenced the development of Beach kids. *Table 10* discriminates the aspects to consider relative to the physical and mechanical aspects; flammability; chemical properties and hygiene.

Table 10 Particular safety requirements for the Beach kids (International Council of Toy Industries 2017)

	Standard(s) and Regulations
Chemical properties	- The contact between the material and the skin cannot present a health risk; - The toy must be designed and manufactured in such a way as not to affect human health by exposure to the chemicals of which the toy is composed or which contain.
Hygiene	- Meet hygiene and cleanliness requirements, to avoid any risk of infection or disease; - Facilitate washing.

Physical & mechanical	- Mechanical strength required to withstand the stresses which toys are subjected during use without breaking down or being susceptible to distortion, causing physical injury; - Avoid the risk of injury by eliminating sharp edges, ropes, cables, and anchorages; - Must not present a risk of strangulation, asphyxiation or closure of the airflow as a result of obstruction of the external airways to the mouth and nose; - The toys must be large enough to prevent their intake and not to obstruct the airways; - The packaging shall not present the risk of strangulation or suffocation; - The maximum and minimum temperature of the toy surface cannot cause damage and injury when touched; - Specify the minimum age of use.
Flammability	- The toys should not constitute any dangerous flammable element; - Cannot burn in contact with the flame; - They should not be easily flammable; - If they ignite, the toy must have a low rate of flame propagation.

3.3.3 3D Modeling

Anthropometric data and market research helped defining the measures, just as regulation helped to create a safer toy. The simplified forms of the monuments (as the Anémona sculpture, the Terminal of Cruzeiros and the Matosinhos Municipal Market in *Figure 50*) were transported to a 3D file, designed in Solidworks 2017 software. Each toy has been developed to represent the monument in a simplified way, with rounded edges, lightweight and ideally sized for children. Even so, these aspects were changed throughout the project development.

The prototypes were printed with a PLA filament at a 1:1 scale on the Anet A6 printer. As a result of this process, three toys were conceived.

(All the blue sheets can be found in *Appendix I*).

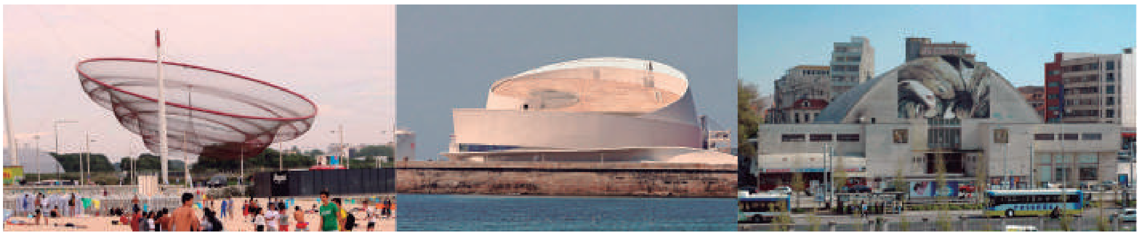


Figure 50 Chosen monuments of Matosinhos; Anémona, Terminal of Cruzeiros and the Matosinhos Municipal Market (https://www.cm-matosinhos.pt/pages/482?image_gallery_id=25)

3.3.3.1 Anémona

Since the previously Anémona did not meet the desired characteristics, the project was repeated. As shown in *Figure 51*, the shape of the Anémona has undergone some changes. Since the Anémona developed last semester (1st form on the left) represented the side view of the sculpture, and the following describes the sculpture seen from below.

Figure 51 The evolution of Anémona's design, chronologically presented

The prototype presents a revolution geometry, constituted by three circumferences with different diameters. However, after printing the 3D model, there was noticed a particular difficulty in picking up the part due to its angle (middle image from *Figure 52*). Another negative aspect was the reduced top size, which made it difficult to reproduce in the sand, as the difference between the three levels was not very significant (*Figure 52*).

Figure 52 Revolving geometry (left); Angle of the wall (centre); Reduced top (right)

The top of the following prototype was increased, and the centre of the circumferences was shifted to the side (*Figure 53*). Besides, the wall angle has been adjusted to make it easier to pick up. However, the negative aspect of the prototype was due to the shifted geometry, which eventually deviated from the sculpture's reference.

Figure 53 Front view (left); Angle of the wall (centre); Improved top (right)

Finally, the third prototype connected the positive aspects of past experiences (*Figure 54*). The final prototype combined the revolution geometry, adapted of *Figure 51*, the size of the top, and the inclination walls for easy handling of the toy adapted from *Figure 53,*

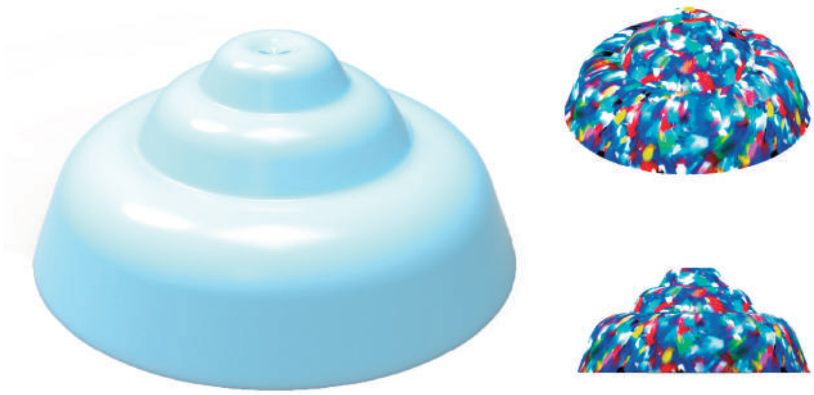


Figure 54 Anémona's final 3D prototype

3.3.3.2 Terminal

Since through the last 3D model of Anémona the wall angles were validated, the development process for the Terminal of Cruzeiros was relatively fast. The shape of the monument was simplified until it was reached the 3D model shown in *Figure 55*.

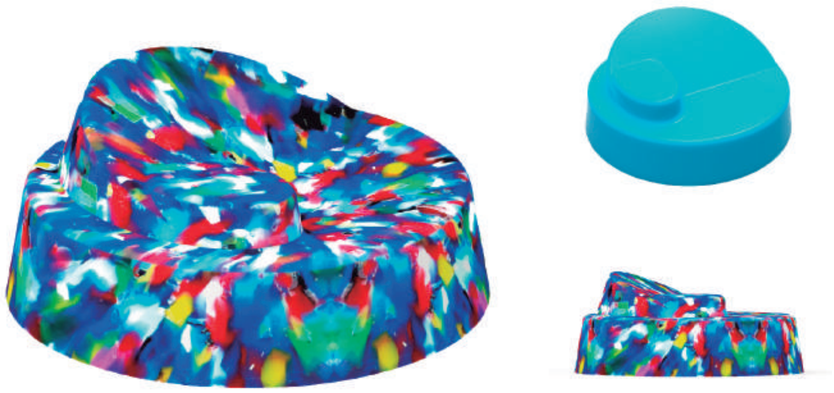


Figure 55 Terminal's 3D final prototype

Only the size of the elliptical shape was rectified since the first model presented a reduced size (left image from *Figure 56*.Later, the elliptical shape was increased (middle and right image from *Figure 56*).

Figure 56 The first (left) and the second (middle) prototypes; Angle of the wall (right)

3.3.3.3 Market

During the development of the Matosinhos Municipal Market, it was necessary to make some significant changes. The first prototype featured small side grooves, as well as the shape in general. Also, the 3D prototype featured sharp edges (*Figure 57)*.

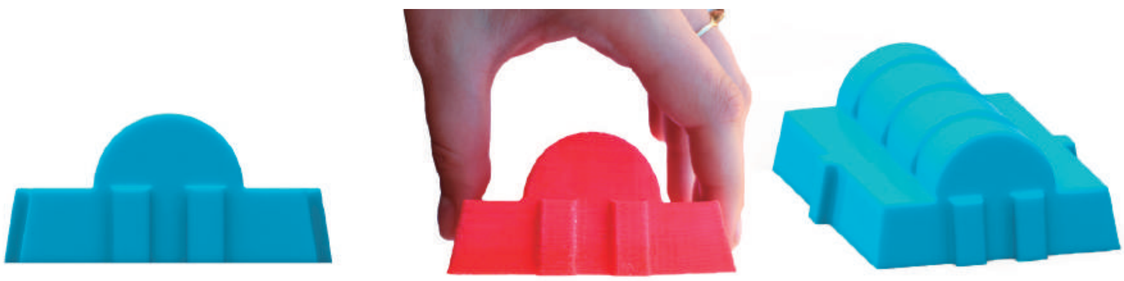


Figure 57 Sharp edges (left); Angle of the wall (middle); Small side grooves (right)

The length and width of the 3D model were considerably increased. The edges were rounded, and the side grooves, as well as the radius of the cylinder that follows the 3D model, were also increased (*Figure 58*).

Figure 58 Rounded edges (left); Angle of the wall (middle); Large side grooves and increased size (right)

The Market's final prototype (*Figure 59*), measures were once again reduced to create familiarity between the three toys. Finally, also the rounded edges, the size grooves and the cylinder were proportionally reduced for the final prototype.

Figure 59 Market's final 3D prototype

3.4 Experimental plan

To better understand the material, some experiments were performed to test the various tools and manufacturing processes (*Figure 60*).

The experimentation phase began with the exploration of various materials where silicone was the binding agent (*3.4.1 1st phase - Exploring the different materials* chapter). During the second phase of experiments, Precious Plastic helped to better understand thermoplastics through their identification (*3.4.2 2nd phase – Precious Plastic, polymer identifi cation* chapter). A crucial factor for the development of the third phase, where HDPE was explored *3.4.3 3rd phase – Melting experiments* chapter).

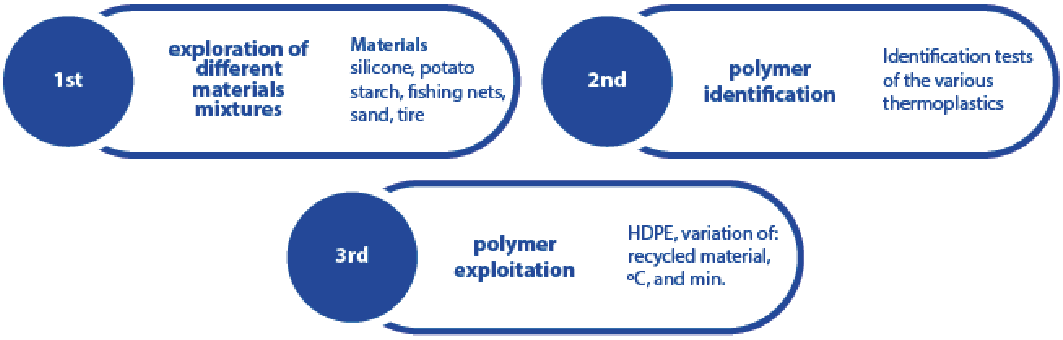


Figure 60 The three phases of experimentation

3.3.1 1st phase – Exploring the different materials

During the first stage, several different experiences were performed with different materials.

Composites were explored and created with silicon, potato starch (*Figure 61*), fishing nets (*Figure 62, Figure 63* and *Figure 64*), sand (*Figure 65* and *Figure 66*), shredded tires (*Figure 67* and *Figure 68*), among others (*Table 11*).

During this phase, different materials mixtures between different materials were explored; however, none of them had the potential to be thoroughly explored. In this first phase, the samples presented are the result of inexperience. That also led to the use of more virgin material (silicone and potato starch) than the actual waste (fishing nets, shredded tire) or materials from Matosinhos.

Table 11 Description of 1st experiences

Tools	silicone and potato starch
Materials	50% transparent silicone 50% potato starch
Descriptions	All materials were mixed until the silicone and potato starch mixed.
Conclusions	Very flexible sample, bending resistant, yet heavy.
Improvements	Only virgin material was used. Add some residue.

Figure 61 Sample 1 (silicone and potato starch)

Tools	silicone, potato starch and shredded fishing net
Materials	30% transparent silicone 50% potato starch 20% shredded fishing net
Descriptions	All materials were mixed until the silicone, potato starch and shredded fishing net mixed.
Conclusions	Stiff, heavy, and by handling the sample, the fishing nets particles disintegrated.
Improvements	Mostly virgin material was used. Use the whole fish nets.

Figure 62 Sample 2 (silicone, potato starch and shredded fishing net)

Tools	silicone, potato starch and fishing nets
Materials	30% transparent silicone 40% potato starch 30% fishing nets
Descriptions	Sandwich sample with two layers (top and bottom) of potato starch, silicone, and a sample of fishing nets that was placed in the center.
Conclusions	Fragile yet flexible. The sample easily disintegrated.
Improvements	Mostly virgin material was used.

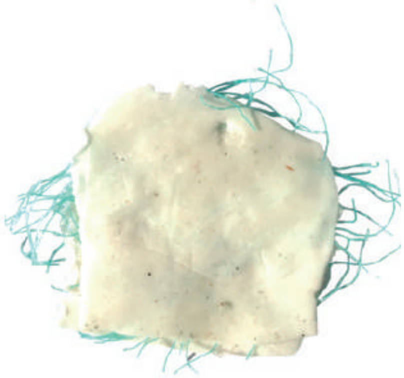


Figure 63 Sample 3 (silicone, potato starch and fishing nets)

Tools	silicone and shredded fishing nets
Materials	50% transparent silicone 50% fishing nets
Descriptions	All materials were mixed until the silicone and shredded fishing nets.
Conclusions	Fragile yet flexible. The vivid colour stands out.
Improvements	The percentage of virgin material used is still quite high.

Figure 64 Sample 4 (silicone and shredded fishing nets)

Tools	silicone, potato starch and sand
Materials	40% transparent silicone 40% potato starch 20% sand
Descriptions	All materials were mixed until the silicone, potato starch and sand.
Conclusions	Texture similar to the sandpaper. Fragile, yet flexible.
Improvements	Mostly virgin material was used. Use more sand.

Figure 65 Sample 5 (silicone, potato starch and sand)

Tools	silicone and sand
Materials	50% transparent silicone 50% sand
Descriptions	All materials were mixed until the silicone and sand.
Conclusions	The samples had a texture similar to the sandpaper. The samples fragility varied according to the percentage of silicone added (+ silicone = more flexible and resistant, - silicone = brittle material). Rough texture Sample too fragile
Improvements	Explore others materials.

Figure 66 Sample 6 (silicone and sand)

Tools	silicone, potato starch and shredded tire
Materials	35% transparent silicone 30% potato starch 35% sand
Descriptions	All materials were mixed until the silicone, potato starch and shredded tire.
Conclusions	The samples disintegrated by handling.
Improvements	Texture too rough. Sample too fragile.

Figure 67 Sample 7 (silicone, potato starch and shredded tire)

Tools	Silicone and shredded tire
Materials	55% transparent silicone 45% sand
Descriptions	All materials were mixed until the silicone and shredded tire.
Conclusions	By using more silicone, it was possible to improve the flexibility of the sample.
Improvements	More flexible sample, however the sharp texture, coupled with the visual effect did not meet the requirements.

Figure 68 Sample 8 (silicone, potato starch and shredded tire)

However, what revolutionised the course of the project was the visit to Matosinhos beach. The long beach was covered with sand, bags, bottles and plastic containers. This sad panorama has aroused the need to find a solution to the problem of unwittingly abandoned plastics. That said, some of the beach waste was collected and explored.

3.4.2 2nd phase – Precious Plastic, polymer identification

Along the beach, polymeric residues such as bottles, lids, bags, cutlery and packaging were visible. Firstly, the polymer recycling process was researched. The Precious Plastic project was found, which taught to identify the polymers (through the tests mentioned below). Precious Plastic also presented a set of low-budget equipment for transforming.

Once collected, the plastics were separated by the recycling marks. However, different identifications techniques for those who did not have any identifying mark, different identifications techniques were applied (Precious Precious 2017).

Floating - Each material has a specific density that will cause it to float differently in liquids. The liquid can be saltwater, alcohol, vegetable oil and glycerine. It can be very tricky, because the additive inserted in the plastics mixture can interfere with its density, making this test uncertain. In the case of HDPE, it fluctuates (*Figure 69*).

Figure 69 HDPE floating in water

Fire - In the presence of flames, plastics have different reactions, and it is possible to recognise: the smell; if the plastic melts; the colour of the flame; and if it prospers or it stinks. HDPE has a bright yellow-tipped flame, burns slowly, and the drops continue to burn after falling, also has the scent similar to paraffin (candle wax) (*Figure 70*).

Figure 70 HDPE in contact with the flame

Smashing - The plastic deforms differently when violently crushed by the hammer. Some break into many pieces, others break into larger pieces. Even if it does not present the most reliable results, this test is used, on some occasions. Under these circumstances, the HDPE only deformed and did not break (*Figure 71*).

Figure 71 Smashing one HDPE lid with the hammer (before, during and after)

Sound - When plastics are dropped purposely, they produce a peculiar sounds. The PS case has a very distinct and sharp sound. On the contrary, the HDPE presents a muffled sound/ medium clatter.

Scratch - Through this technique, the difference between the family of polymers can be easily identified. While thermoplastics are easily scratchable (for HDPE, as shown in *Figure 72*).

Figure 72 Scratching test on HDPE lid with the nail (before, during and after)

Type of object - Sometimes, objects are produced in certain specific materials such as PET bottles, PS CD cases, HDPE jerrycans, or bottle caps.

From the collected waste stands out the amount of PET bottles as well as their caps (PP, but especially HDPE). After identifying the polymers, an in-depth study was followed to understand the capabilities and properties of these materials. Even so, special attention was paid to the bottle caps (HDPE), due to the amount and diversity of colours that this material presented.

3.4.3 3rd phase – Melting experiments

Thermoplastics, when heated, they melt, and when cooled, preserved the formed shape, which facilitates their deformation and moulding and, when cooled, keeping the desired shape. For most samples, a Kilper ceramic furnace (*Figure 73*) and stainless-steel plates were used. For each sample, the furnace was preheated at 200 ° C for approximately 20 minutes. At the end of the furnace heating time, the stainless-steel plates containing the shredded HDPE (*Figure 74*) were placed in the ceramic furnace. The temperature and the timing vary throughout the experiments of this phase as the aim was to explore the material and its properties.

Figure 73 Kilper ceramic furnace

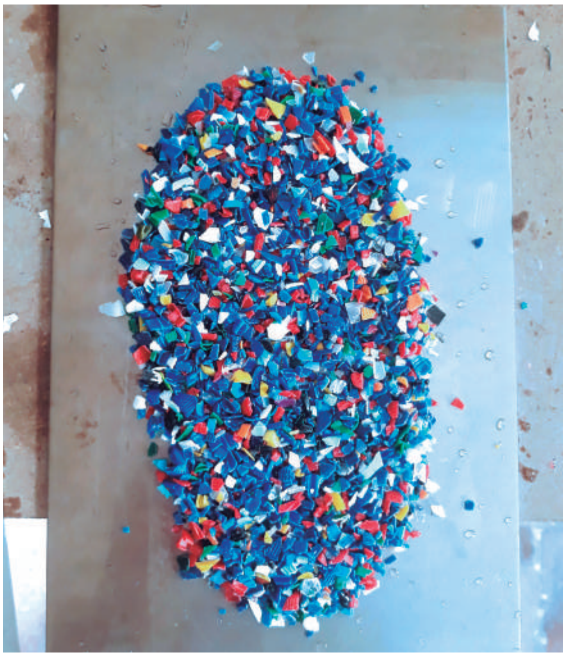


Figure 74 The shredded HDPE on top of the stainless-steel plate

Throughout *Table 12* are presented some samples made with different: temperatures (ºC); periods (minutes); percentages of raw or recycled material (*Figure 76, Figure 78* and *Figure 80*), etc.

Table 12 Experiments with the collected polymers

Tools	HDPE bottle caps, fishing net, ceramic furnace and stainless-steel plate	
Materials	90% Recycled HDPE	10% fishing nets
Descriptions	**Ceramic furnace**	200ºC
		20 min
	The raw HDPE and the fishing nets were placed on top of the stainless-steel plate and inserted on the furnace.	
Conclusions	The high temperature eventually melted until the HDPE burned a little, unlike fishing nets. Sharp texture due to fishing net.	
Improvements	Decrease the temperature.	

Figure 75 Sample 1 (HDPE bottle caps and fishing net)

Tools	Raw and recycled HDPE, ceramic furnace and stainless-steel plate	
Materials	30% Raw HDPE	70% Recycled HDPE
Descriptions	**Ceramic furnace**	150 ºC
		10 min
	The raw and recycled HDPE were placed on top of the stainless-steel plate and inserted on the furnace.	
Conclusions	Solid and impact-resistant sample. Raw HDPE melted faster than recycled. Soft and smooth texture.	
Improvements	Vary the percentage of raw material.	

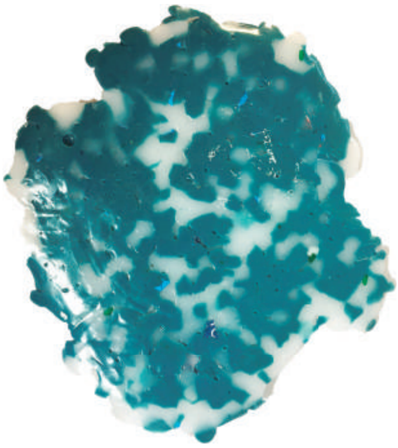


Figure 76 Sample 2 (Raw and recycled HDPE)

Tools	Recycled HDPE, ceramic furnace and stainless-steel plate	
Materials	100% Recycled HDPE	
Descriptions	**Ceramic furnace**	120 ºC
		10 min
	The HDPE bag was cut into pieces and placed on top of the stainless-steel plate and inserted on the furnace.	
Conclusions	From a bag of HDPE was cut a piece and placed in the furnace. The sample easily melted. The sample, although flexible, has a sharp texture and some fragility because of the holes it presents.	
Improvements	More material.	

Figure 77 Sample 3 (HDPE bag)

Tools	Raw HDPE, fishing nets, ceramic furnace and stainless-steel plate	
Materials	60% Raw HDPE	40% Fishing nets
Descriptions	**Ceramic furnace**	170 ºC
		20 min
	The raw HDPE and the fishing nets were placed on top of the stainless-steel plate and inserted on the ceramic furnace.	
Conclusions	Raw HDPE melted faster than recycled. Soft and smooth texture.	
Improvements	Decrease the percentage of raw material.	

Figure 78 Sample 4 (Raw HDPE and fishing nets)

Tools	Recycled HDPE, cork, ceramic furnace and stainless-steel plate	
Materials	90% Recycled HDPE	10% Cork
Descriptions	**Ceramic furnace**	145ºC
		40 min
	First, the recycled HDPE was placed on top of the stainless-steel plate and inserted on the ceramic furnace. The cork particles were added when the HDPE was melted.	
Conclusions	The sample was placed at a lower temperature so that the cork would not burn. Solid and impact-resistant sample.	
Improvements	Exclude cork as it adds nothing to the material.	

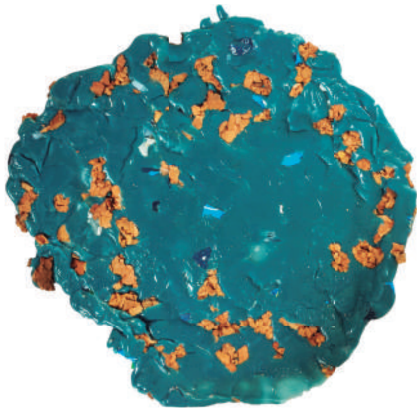


Figure 79 Sample 5 (Recycled HDPE and shredded cork)

Tools	Raw and recycled HDPE, ceramic furnace and stainless-steel plate	
Materials	90% Recycled HDPE	10% Raw HDPE
Descriptions	**Ceramic furnace**	190 ºC
		25 min
	The raw and the recycled HDPE were placed on top of the stainless-steel plate and then inserted on the ceramic furnace.	
Conclusions	Features similar to the previous show. Therefore; solid and impact resistant sample; soft and smooth texture.	
Improvements	Increase the temperature and decrease the time in the furnace.	

Figure 80 Sample 6 (Raw and recycled HDPE)

It was considered feasible to use 100% recycled HDPE since the material preserved the mechanical properties (Kumar, Panda, e Singh 2011). This phase was very enriching, as the experiences promoted a better understanding of the material as well as its limitations.

3.5 Prototyping

The prototyping with vaseline was crucial during the development of MDIP. This chapter describes the different approaches taken, namely the adaptation of manufacturing processes using accessible materials and technologies (*Figure 81*).

Throughout the development of the Beach kit, an aluminium mould was used to produce the phone case. During the same year, a pine mould was used to create the first Beach kids' toy. And lastly, the following year, various techniques were used, namely plaster moulds and the thermoforming process.

For all processes mentioned below, the HDPE used was previously collected, selected, shredded, washed and dried. Regarding temperatures and timings, as well as other relevant data to production, all were studied and specified for each manufacturing process.

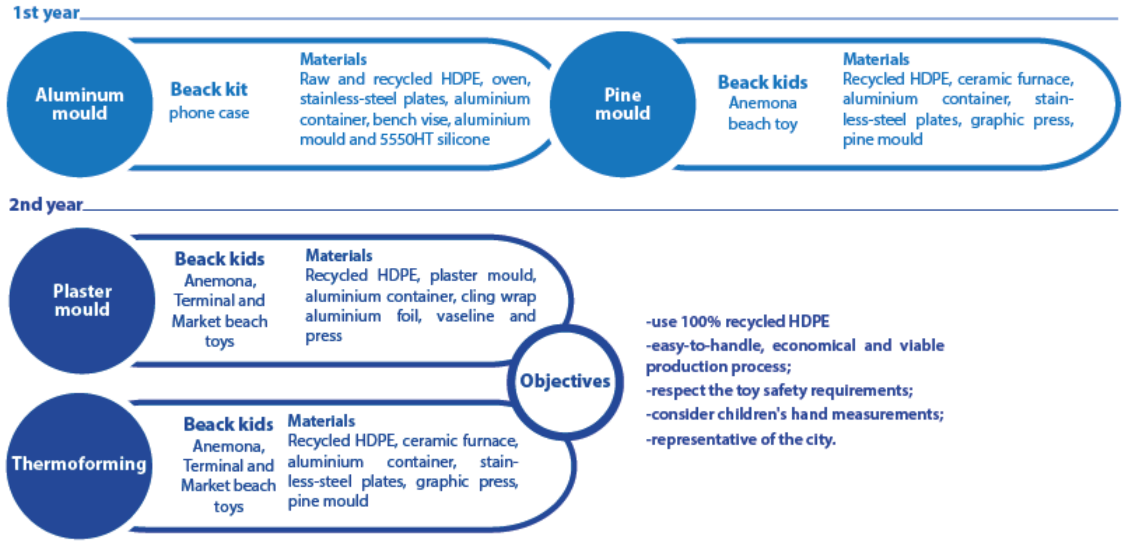


Figure 81 Chronological order of project development along MDIP

3.5.1 Mould experience
3.5.1.1 Aluminium mould

Even though it is a significant investment, the metal moulds are the best to work with, because of its durability and improved ability to conduct heat (more energy efficient). They also pay off in the long run as it is possible to create a higher number of models with good quality.

The idea of experimenting with metal moulds came from the Precious Plastic project, as they use and adapt metal containers (cans, tubes, among others), according to the project needs. During the development of the Beach kit phone case, efforts were made to adapt the manufacturing process to the equipment and materials available at the FBAUB workshop.

Regarding the material, it is well known that it would be HDPE. However, the sides of the cover could not be made of the same material. Hence alternatives were researched.

Fortunately, by contacting and explaining the project to the company Rangel - Industria Metalurgica, located in Campo, Valongo, they offered to produce the mould for the phone case. The mould they created was made of aluminium and consisted of three different parts, two half moulds and an insert of the same shape as the telephone (*Figure 82*).

All the data relative to the production can be seen in *Table 13*.

Figure 82 Aluminium mould

Table 13 Beach kit phone case prototype

Tools	Raw and recycled HDPE, oven, aluminium container, stainless-steel plates, bench vise, aluminium mould and 5550HT silicone	
Materials	90% Recycled HDPE 10% Raw HDPE 5550HT silicone	
Descriptions	**Oven**	250ºC
		20 min
	Bench vise	60 min
	Machining	40 min (cutting and drilling)
	Time inside the mould	30 min (silicone solidification time)
	1st	The (shredded) raw and recycled HDPE was placed in the oven at 250 ° C (previously heated to the same temperature) in an aluminium container.
	2nd	After 20 minutes, the molten material was poured onto a stainless-steel plate, and another was placed on top.
	3rd	Then was used a bench vise, to compact the material evenly (2 mm).
	4th	Subsequently, the cooled HDPE was removed between the plates. Cut into the desired shape, and perforated at the ends to aid bonding between the plate and the silicone.
	5th	After machining, the HDPE plate was placed in the mould where the 5550HT silicone (Custóias, Matosinhos, called 'HBK') was injected.
	6th	The final prototype can be seen in *Figure 82*.
Conclusions	The molten polymer in contact with the cold surfaces of the stainless-steel sheets helped to obtain a smooth surface, as well as speeding up the material cooling process. Prototype with good finish, smooth and resistant surface.	
Improvements	Strategies to decrease cooling and machining time.	

Figure 82 Phone cover final prototype

3.5.1.2 Wood mould

The geometry of the Beach kit toy made it challenging to build an aluminium mould. Instead, a pinewood mould built with cut, screws and glued pine slats (*Figure 83*).

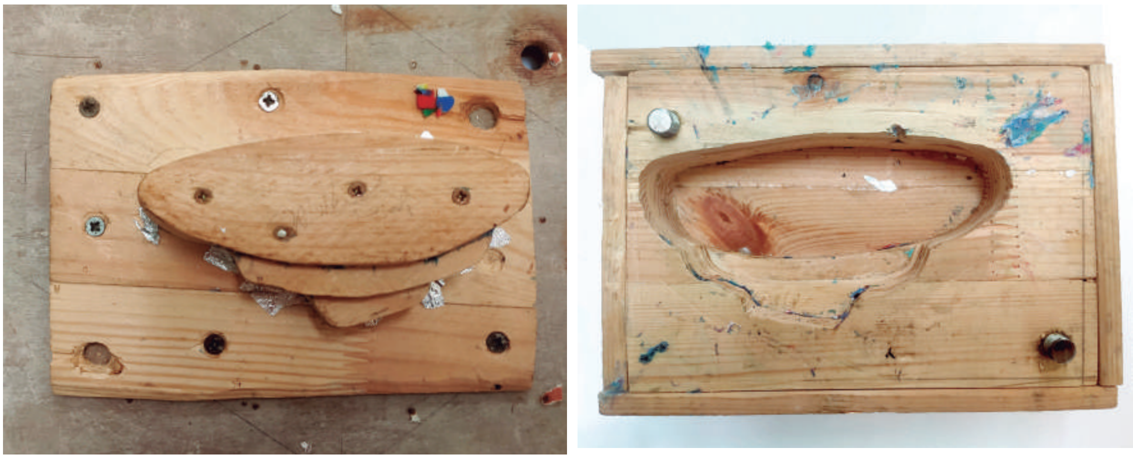


Figure 83 Pine mould

Table 14 Beach kids first toy prototype

Tools	Recycled HDPE, ceramic furnace, aluminium container, graphic press, pine mould	
Materials	100% Recycled HDPE	
Descriptions	**Ceramic furnace**	200ºC
		20 min
	Time inside the mould	50 min (silicone solidification time)
	Graphic press	45 min
	Machining	40 min (cutting and drilling)
	1st	As in the previous project, the ceramic furnace was preheated to 250 ° C for approximately 20 minutes.
	2nd	The shredded HDPE was placed in an aluminium container was then placed in the oven at 200 ° C for approximately 25 minutes.
	3rd	Before removing the material from the ceramic furnace, the mould was covered with aluminium foil so that the material would not damage or stick to the mould (*Figure 84*).
	4th	Then the melted HDPE was poured into the mould and then quickly aligned with the other part of the mould, and the whole set was placed on a graphic press at the FBAUP workshop.
	5th	When the material was cooled, the prototype was removed from the mould and was machined to remove excess material (*Figure 85*).
Conclusions	Besides being an economical process, the pine mould can reproduce the desired shape. However, this method still has some flaws.	
Improvements	Speed up the process when HDPE is poured into the mould (recycled HDPE is more doughy than raw HDPE, which ties and makes the whole process difficult). The final prototype with traces of aluminium. Inconsistent thickness. After producing 5 prototypes, the mould is damaged.	

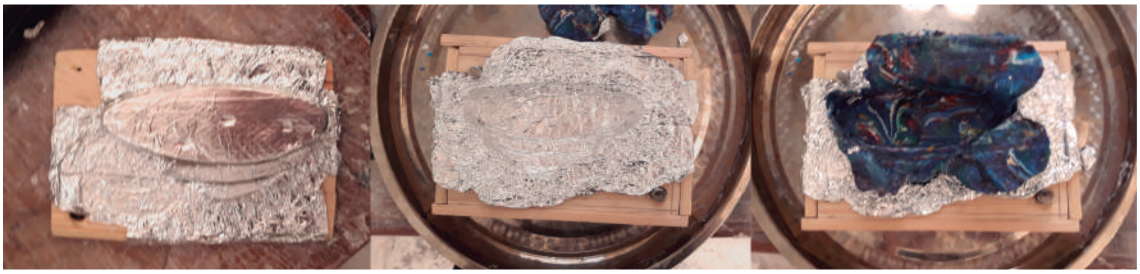


Figure 84 Preparing the pine wood mould by covering it with the aluminium foil (left and middle); after removing the mould from the press (right)

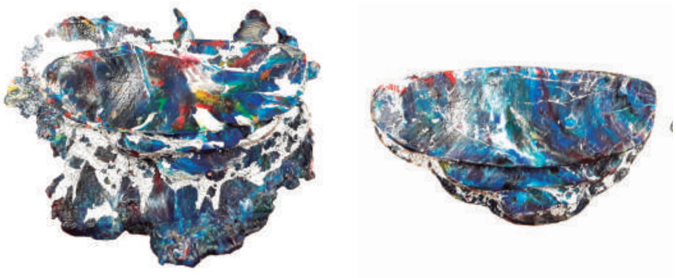


Figure 85 The prototype extracted from the mould (left) and after cutting the excess material (right)

The mould served to produce five prototypes until it was damaged. Yet, from this method, it was possible to create lightweight prototypes of the desired shape, despite inconsistent thickness and traces of aluminium foil (*Figure 86*).

Figure 86 Anémona, the final prototype for the Beach kids project

3.5.1.3 Plaster mould

During the first year of MDIP, different moulds and techniques were explored, in the second year, during the development of Beach kids, the plaster moulds were studied. Compared to other materials, plaster is easy to work with, as it does not require much technique or specialized equipment.

However, before producing the moulds, it was necessary to print the 3D prototype and only then it was possible to manufacture the moulds of the toys. The 3D files got printed on the Anet A6 printer (*Figure 87*), with PLA filament (*Figure 88*). Then each toy was coated with an epoxy resin to obtain a smooth surface. From the resin-coated prototype, it was possible to produce the moulds.

Table 15 Parameters used to generate for printing the pieces to produce the moulds

Print setup parameters for Anet A6 printer	
Material	PLA
Lenght (per roll)	400 m
Colour	pink, red and blue
Diametro	1.75 mm ± 0.1 mm
Printing Time (with brackets)	1h 10 min (Anémona) 2h 05 (Terminal) 2h 40 min (Market)
Printing temperature	190ºC
Table temperature	50ºC
Layer Height	0.3mm
Flow	100%
Print Speed	90 mm/s
Build Plate Adhesion	skirt

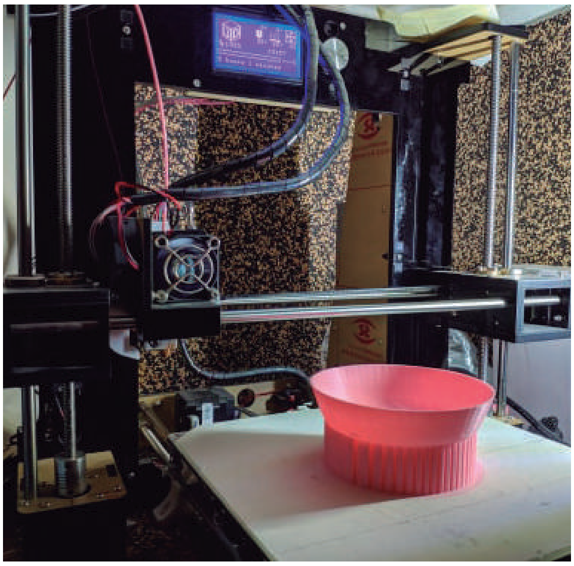


Figure 87 Printing the 3D model of Anémona

Table 16 Plaster mould manufacture

Tools	plaster, water and epoxy resin	
Descriptions	**Epoxy Resin Drying Time**	30 min
	Gypsum drying time	72 h
	Put the plaster in a container and add water until it creates a consistent paste.	
	Then place the 3D model in the paste and let it dry.	
	Remove the 3D model as soon as the plaster solidifies and allow to dry (*Figure 89*).	

Figure 88 3D model covered with epoxy resin

Inevitably, the force of compression degraded the moulds. The moulds that showed the highest longevity were those left in the same container where they were mixed. The container was made from an extendable aluminium flexible tube, which aided in adhesion with the plaster while preserving the integrity of the mould.

Figure 89 Market´s plaster mould

3.5.1.3.1 Plaster casting moulding: 1st experience - mould coated with cling wrap

The whole process is outlined in *Figure 90*. *Table 17* presents the overall results obtained during this first phase of the experiments, while *Table 18* shows the detailed data of each experiment.

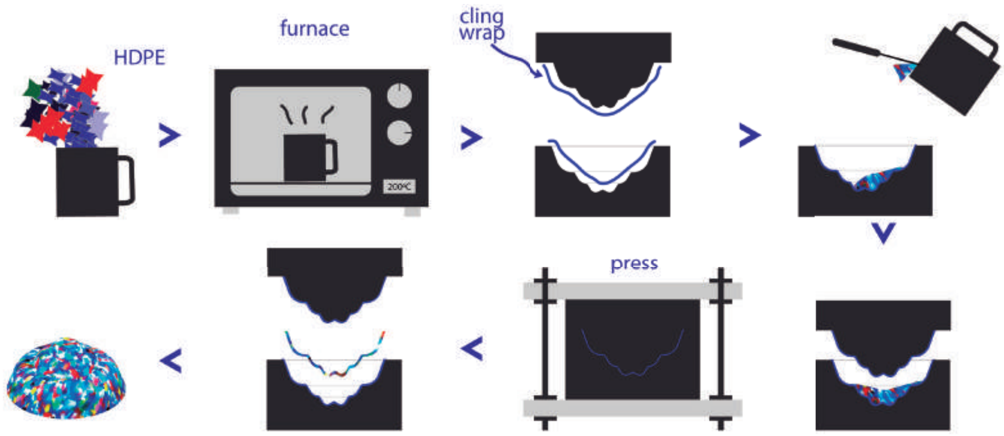


Figure 90 Plaster casting moulding process: 1st experience - mould coated with cling wrap

Overall, during this first phase, no significant results were obtained as the prototypes featured a rough surface, with thickness variations (*Figure 91*). The viscosity of recycled HDPE made it difficult to pour into the mould, resulting in prototypes that were not fully covered by the material (as in the case of the prototype 1 and 4 from *Table 18*).

Appendix II presents the photos of all experiments, as well as the details of the textures.

Table 17 Plaster casting moulding: 1st experience - mould coated with the cling wrap

Tools	Recycled HDPE, ceramic furnacee, plaster mould, aluminium container, cling wrap and press	
Materials	**100% Recycled HDPE**	
Descriptions	**Ceramic furnace**	190 – 220ºC (minimum and maximum)
		20 - 30 min (minimum and maximum)
	Press	45 min
	1st	With the furnace preheated to 250ºC for 20 minutes.
	2nd	Then the aluminium container with the HDPE was placed in the ceramic furnace.
	3rd	When melted, HDPE was poured into the mould previously coated with cling wrap.
	4th	Then the other half of the mould was aligned at the top, and everything was inserted into the press.
	5th	After the mould has cooled, the prototype was removed, and the excess material is cut.
Conclusions	The prototypes reproduced the desired shape. Smooth surface. Thicker top than the walls.	
Improvements	The viscosity of molten (recycled) HDPE complicated the casting process as it becomes complicated to pour the material into the mould quickly. HDPE loss (mostly during the casting process). The cling wrap in contact with the melted HDPE influenced the surface of the prototypes since the cling wrap adhered to the material. The plaster mould preserves heat, which makes the prototype cooling process difficult.	

Figure 91Plaster casting moulding prototype: 1st experience - mould coated with cling wrap

Table 18 Descriptive table of experiments of the mould in the furnace with aluminium foil

No.	Temperature (oC)	Time (min)	Material (g)	Final weight (g)	Surface	Thickness	Observations
1	190	25	100	85	Smooth interior and accented texture exterior	Thicker top than walls	-HDPE did not covered the whole prototype
2	190	30	150	125	Accented texture		-HDPE covered the whole prototype - Traces of burned HDPE
3	190	30	100	95			
4	200	30	80	60	Smooth interior and accented exterior texture		-HDPE did not covered the whole prototype
5	220	20	150	130	Accented texture		-HDPE covered the whole prototype
6	200	30	200	165			
7	220	20	250	210			
8	200	25	100	95		Uniform	
9	200	25	70	50	Smooth		

3.5.1.3.2 Plaster moulding: 2nd experience - mould in the furnace

The whole process is outlined in *Figure 92*. *Table 19* presents the overall results obtained during this first phase of the experiments, while *Table 20* shows the detailed data of each experiment.

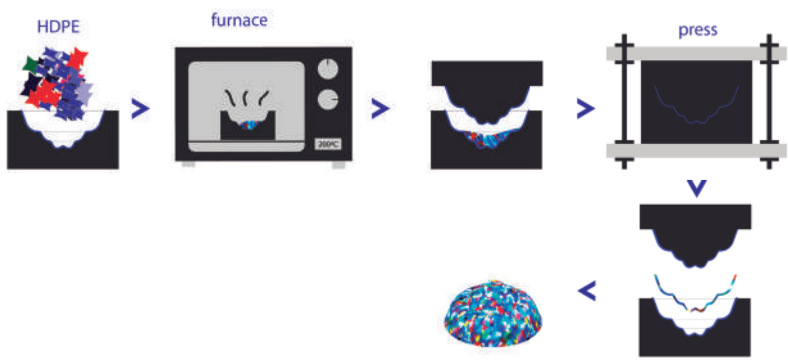


Figure 92 Plaster moulding process: 2nd experience - mould in the furnace

Table 19 Plaster moulding: 2nd experience - mould in the furnace

Tools	Recycled HDPE, ceramic furnace, plaster mould and press	
Materials	100% Recycled HDPE	
Descriptions	**Ceramic furnace**	190 – 250ºC
		30 - 45 min
	Press	70 min
	1st	With the furnace preheated to 250ºC for 20 minutes.
	2nd	It was decided to place the HDPE into the mould to dispense the casting process.
	3rd	The HDPE was then placed in the mould previously coated with aluminium foil and then placed in the ceramic furnace.
	4th	When melted, the mould was removed from the furnace. The other half of the mould was aligned at the top, and everything was inserted into the press.
	5th	After the mould has cooled, the prototype was removed, and the excess material is cut.
Conclusions	The prototypes reproduced the desired shape. However, the prototypes feature a rough surface and some of them present traces of plaster (*Figure 93*). Prototypes with thicker top than the walls. This process deteriorated the plaster mould and ruined the prototypes.	
Improvements	A prolonged process, as the plaster takes a long time to heat up. The plaster mould preserves heat, which makes the prototype cooling process difficult.	

Figure 93 Plaster moulding prototype: 2nd experience - mould in the furnace

Table 20 shows the results obtained. Even as the temperature increased, HDPE was hardly able to melt. The material in contact with the mould remained intact, while the surface melted. Furthermore, this process visibly damaged the moulds.

However, at the end of this phase, an aluminium foil or cling wrap was placed between the mould and the HDPE an aluminium foil or cling wrap.

Appendix III presents the photos of all experiments, as well as the details of the texture.

Table 20 Descriptive table of experiments of the mould in the furnace

No.	Temperature (oC)	Time (min)	Final weight (g)	Surface	Thickness	Observations
1	190	40	85	Accented texture Traces of plaster	Variable, thicker top than walls	- Traces of burned HDPE -HDPE covered the whole prototype

2	190	45	82	Accented texture		-HDPE covered the whole prototype
3	200	40	40	Smooth	Uniform thickness	- HDPE did not covered the whole prototype -Traces of burned HDPE
4	250	30	100	Texture accentuated Traces of plaster	Variable, thicker top than walls	- Did not melt fully -HDPE covered the whole prototype

3.5.1.3.2.1 Plaster moulding: 2.1 experience - mould in the furnace with aluminium foil

The whole process is in *Figure 94*.

Table 21 presents the overall results obtained during this first phase of the experiments, while *Table 22* shows the detailed data of each experiment.

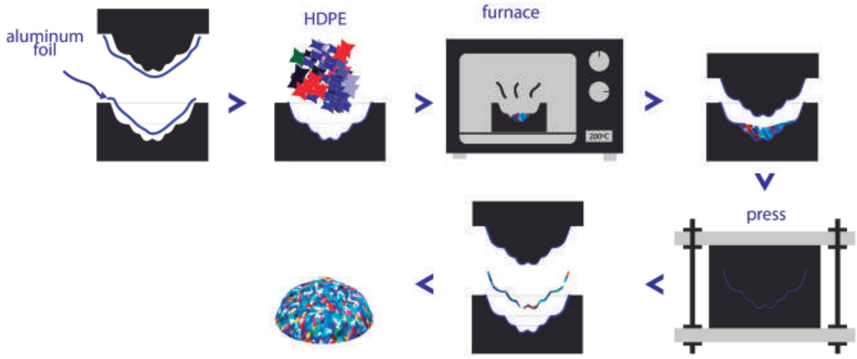


Figure 94 Plaster moulding process: 2.1 experience - mould in the furnace with aluminium foil

Table 21 Plaster moulding: 2.1 experience - mould in the furnace with aluminium foil

Tools	Recycled HDPE, ceramic furnace, plaster mould, aluminium foil and press	
Materials	100% Recycled HDPE	
Descriptions	**Ceramic furnace**	200 – 250ºC 30 - 45 min
	Press	70 min
	1st	With the furnace preheated to 250ºC for 20 minutes.
	2nd	The aluminium foil was placed between the HDPE and the mould.
	3rd	When melted, the mould was removed from the furnace. The other half of the mould was aligned at the top, and everything was inserted into the press.
	4th	After the mould has cooled, the prototype was removed, and the excess material is cut.
Conclusions	The prototypes reproduced the desired shape. However, the prototypes present traces of aluminium foil (*Figure 95*). Thicker top than the walls.	
Improvements	A prolonged process, as the plaster takes a long time to heat up. The plaster mould preserves heat, which makes the prototype cooling process difficult.	

Obseving *Table 22*, it is possible to see that all experiences present traces of aluminium foil. Compared with the previous method, the aluminium foil facilitated the melting process, featuring prototypes with a smoother and brighter surface.

Appendix IV presents the photos of all experiments, as well as the textures details.

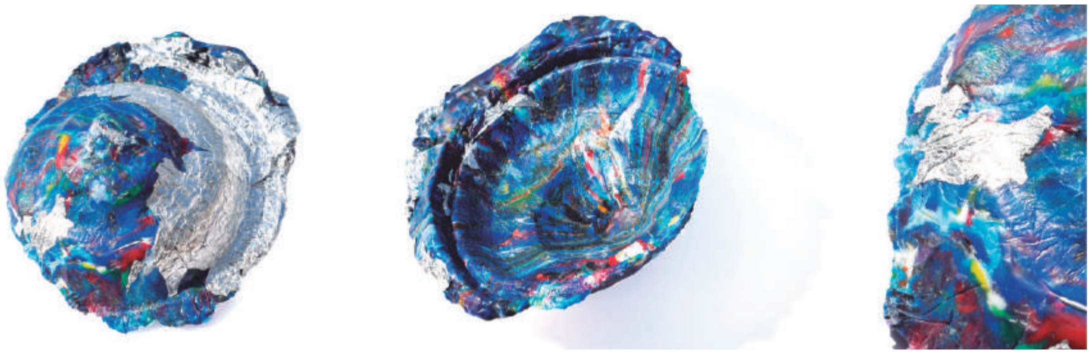


Figure 95 Plaster moulding prototype: 2.1 experience - mould in the furnace with aluminium foil

Table 22 Descriptive table of experiments of the mould in the furnace with aluminium foil

No.	Temperature (oC)	Time (min)	Final weight (g)	Surface	Thickness	Observations
1	220	40	45	Accented texture	Thicker top than walls	-Traces of aluminium foil -HDPE did not covered the whole prototype
2	200	45	60	Accented texture	Uniform	-HDPE did not covered the whole prototype
3	250	30	70	Smooth	Uniform	- HDPE did not covered the whole prototype -Traces of burned HDPE and aluminium foil

3.5.1.3.3 Plaster moulding: 2.2 experience - mould in the furnace with the cling wrap

The whole process is outlined in *Figure 96*.

Table 23 presents the overall results obtained during this first phase of the experiments, while *Table 24* shows the detailed data of each experiment.

Although it presented a smoother surface (Figure 97), it was not yet the desired one. In comparison with the previous method, the cling wrap experiences, also managed to preserve a shiny surface, yet the film eventually melted and interfered with the geometry of the prototype.

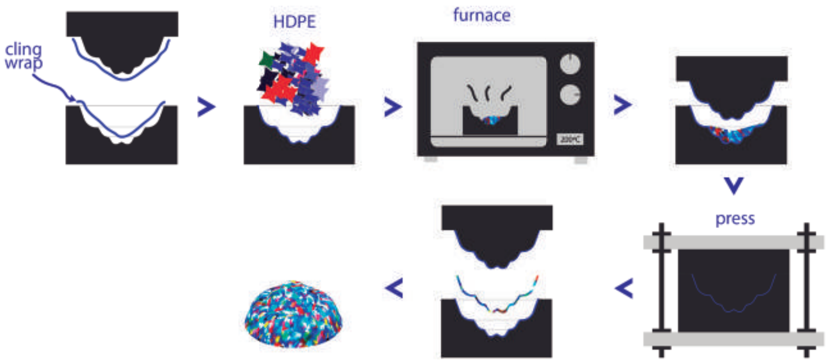


Figure 96 Plaster moulding process: 2.2 experience - mould in the furnace with the cling wrap

Table 23 Plaster moulding: 2.2 experience - mould in the furnace with cling wrap

Tools	Recycled HDPE, ceramic furnace, plaster mould, cling wrap and press	
Materials	100% Recycled HDPE	
Descriptions	**Ceramic furnace**	200 – 220ºC
		40 - 45 min
	Press	70 min
	1st	With the furnace preheated to 250ºC for 20 minutes.
	2nd	The cling wrap was placed between the HDPE and the mould.
	3rd	When melted, the mould was removed from the furnace. The other half of the mould was aligned at the top, and everything was inserted into the press.
	4th	After the mould has cooled, the prototype was removed (*Figure 97*), and the excess material is cut.
Conclusions	The cling wrap did not withstand the high temperatures of the furnace, which caused it to melt. Thicker top than the walls.	
Improvements	A prolonged process, as the plaster takes a long time to heat up. The plaster mould preserves heat, which makes the prototype cooling process difficult.	

Figure 97 Plaster moulding prototype: 2.2 experience - mould in the furnace with the cling wrap

As the material was placed directly in the mould, no loss of material was verified, which makes the final prototype weight equal to the material's initial weight. The high temperatures and time spent did not prove beneficial because the results were far from expected (Table 24). That said, there was no justification for pursuing this method.

Appendix V presents the photos of all experiments, as well as the textures details.

Table 24 Descriptive table of experiments of the mould in the furnace with cling wrap

No.	Temperature (oC)	Time (min)	Final weight (g)	Surface	Thickness	Observations
1	200	40	100	Accented texture	Thicker top than walls	-HDPE did not covered the whole prototype
2	220	45	95			-HDPE did not covered the whole prototype -Traces of burned HDPE

3.5.1.3.4 Plaster casting moulding: 3rd experience – mould brushed with vaseline

The whole process is outlined in *Figure 98*.

Table 25 presents the overall results obtained during this first phase of the experiments, while *Table 26* shows the detailed data of each experiment.

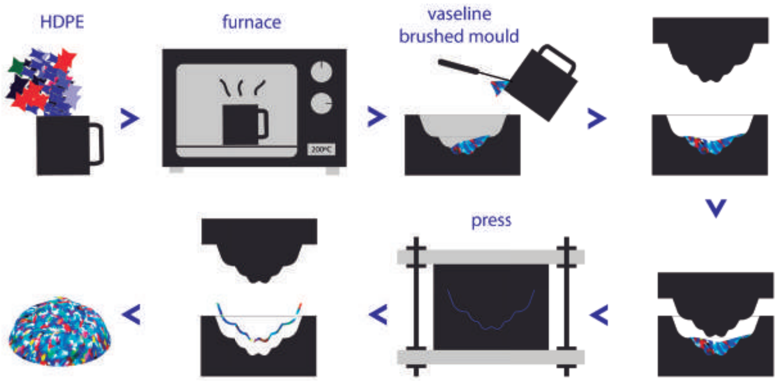


Figure 98 Plaster casting moulding process: 3rd experience – mould brushed with vaseline

It was noted that the spacing between the moulds did not allow the passage of viscous molten HDPE, which justifies the fact that most of the experiments feature an unstable thickness. Due to it, the moulds were constructed to increase the spacing between the male and female mould facilitating the output and flow of HDPE. After that, the prototypes showed a uniform thickness (*Figure 99*).

After several experiments it is possible to conclude that: the casting process must be executed quickly; the press has to be used to achieve the desired thickness; as well as it is necessary to use something (cling wrap, aluminium foil or vaseline) to protect the surface of the mould (to prolong its use time).

Appendix VI presents the photos of all experiments, as well as the textures details.

Table 25 Plaster casting moulding: 3rd experience – mould brushed with vaseline

Tools	Recycled HDPE, ceramic furnace, plaster mould, aluminium container, vaseline and press	
Materials	100% Recycled HDPE	
Descriptions	**Ceramic furnace**	150 – 220ºC
		20 - 50 min
	Press	30 min
	1st	With the furnace preheated to 250ºC for 20 minutes.
	2nd	The cling wrap was placed between the HDPE and the mould.
	3rd	The aluminium container with the HDPE was placed in the furnace.
	4th	When melted, the HDPE was poured into the plaster mould (previously brushed with vaseline).
	5th	Then, the other half of the mould was aligned at the top, and everything was inserted into the press.
	6th	After the mould has cooled, the prototype was removed (*Figure 99*), and the excess material is cut.
Conclusions	The most favourable results were obtained even though some of the prototypes presented similar problems to the other experiments. The prototypes reproduced the desired shape.	

Improvements	Very slow process, as the plaster takes a long time to heat up. The plaster mould preserves heat, which makes the prototype cooling process difficult.

Figure 99 Plaster casting moulding prototype: 3rd experience – mould brushed with vaseline

The most favourable results were obtained throughout this phase, and in addition to faithfully reproducing the geometry, the prototypes were easy to remove from the mould (due to the vaseline), as well as having a smooth and shiny surface, acceptable weight and a desired uniform thickness.

Table 26 Descriptive table of experiments of the mould brushed with vaseline

No.	Temperature (oC)	Time (min)	Material (g)	Final weight (g)	Surface	Thickness	Observations
1	150	50	100	70	Accented texture	Variable, thicker top than walls	-HDPE covered the whole prototype
2	220	30	90	80			-HDPE did not covered the whole prototype
3	180	45	100	100		Uniform	-HDPE covered the whole prototype - Did not fully melt
4	170	35	100	100			-HDPE did not covered the whole prototype
5	190	30	80	65		Variable, thicker top than walls	-HDPE covered the whole prototype
6	200	20	100	75		Irregular Deformed prototype	-HDPE did not covered the whole prototype
7	200	20	50	35		Uniform	
8	200	20	100	50	Smooth		- HDPE covered the whole prototype
9	200	20	70	55		Irregular Deformed prototype	

3.5.2 Thermoforming

The thermoforming process requires a preformed thermoplastic sheet of material that's heated to a softened state. After that, the thermoplastic sheet is deformed within a mould via a plug or air pressure, cooled and ejected, as shown in *Figure 100*.

Figure 100 Thermoforming process

One of the essential aspects of this process is the softening temperature of the thermoplastic sheet. The material must be readily mouldable but still maintain its structural integrity because overheating affects the profile's thickness and may potentially lead to sagging.

Therefore, to use this process, it was necessary to build two wooden boxes (*Figure 101*), to create a vacuum. Both boxes are sealed except for the top and side. The various holes in the top allow the material suction, while the side hole allows the vacuum cleaner tube to enter.

For this process, it was still necessary to produce HDPE sheets. The whole process is presented in *Table 27*.

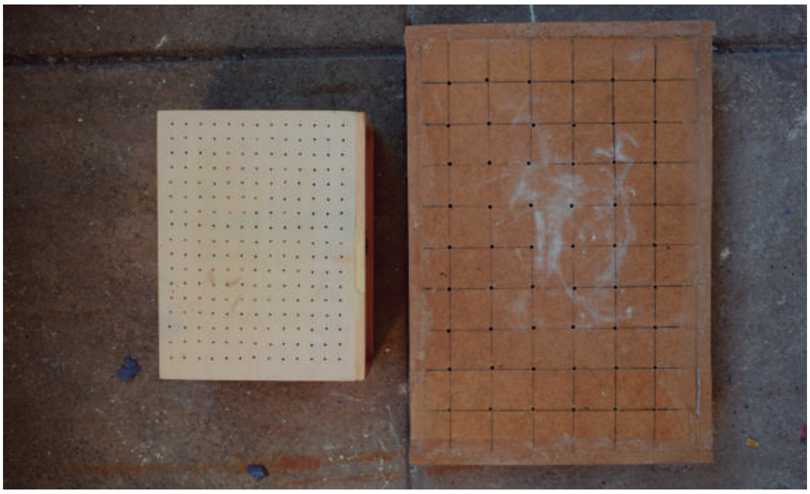


Figure 101 Pine (left) and MDF (right) boxes built for the thermoforming process

Table 27 HDPE sheets production

<table>
<tr><th>Tools</th><td colspan="2">Recycled HDPE, stainless-steel plates, ceramic furnace and bench vise</td></tr>
<tr><th>Materials</th><td colspan="2">100% Recycled HDPE</td></tr>
<tr><th rowspan="10">Descriptions</th><th rowspan="2">Ceramic furnace</th><td>180 – 200ºC</td></tr>
<tr><td>15 - 20 min</td></tr>
<tr><th>Bench vise</th><td>60 min</td></tr>
<tr><th>Machining</th><td>40 min</td></tr>
<tr><th>1st</th><td>With the furnace preheated to 250ºC for 20 minutes.</td></tr>
<tr><th>2nd</th><td>The shredded HDPE was placed on top of the plate, then inserted into the furnace.</td></tr>
<tr><th>3rd</th><td>When melted, the plate was extracted from the oven, where another identical plate was placed over the molten HDPE.</td></tr>
<tr><th>4th</th><td>Then everything was put in the bench vise.</td></tr>
<tr><th>5th</th><td>Finally, the resulting HDPE sheets were cut to fit the frames.</td></tr>
<tr><th>Conclusions</th><td colspan="2">From this process, plates of various thicknesses were obtained.</td></tr>
</table>

3.5.2.1 Thermoforming: 1st experience

Before using the wooden boxes, the plaster mould was placed in the oven with the HDPE sheet on top. The whole process is outlined in *Figure 102*.

Table 28 presents the overall results obtained during this first phase of the experiments, while *Table 29* presents the detailed data of each experiment.

Appendix VIII presents the photos of all experiments, as well as the textures details.

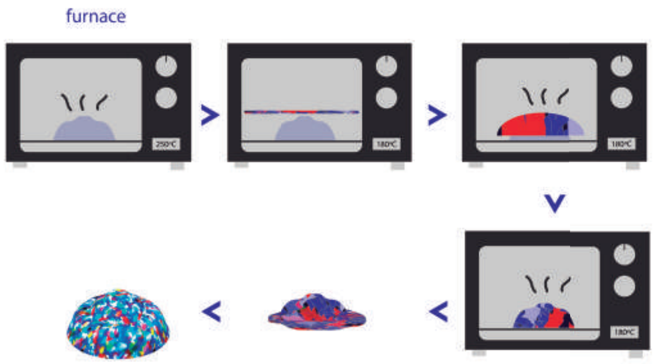


Figure 102 Thermoforming process: 1st experience

Table 28 Thermoforming: 1st experience

Tools	Recycled HDPE, plaster mould and oven	
Materials	100% Recycled HDPE	
Descriptions	**Oven**	120 – 150ºC
		10 - 25 min
Descriptions	**Machining**	10 min
	1st	With the oven preheated to 250ºC for 20 minutes.
	2nd	The male mould was placed in the oven with the HDPE sheet on top.
	3rd	When the HDPE melted, the assembly was removed from the oven.
	4th	The prototype was removed from the mould.
	5th	Lastly, the excess material was cut.
Conclusions	The experiments were conducted at low temperatures, as can be seen in *Table 29*. The HDPE sheets did not take long to deform (*Figure 103*). Thin thickness. Among all experiments, temperature caused holes in the material.	
Improvements	Despite the low temperatures, HDPE melted quickly and uncontrollably as prototypes were unable to reproduce the toy's external geometry faithfully.	

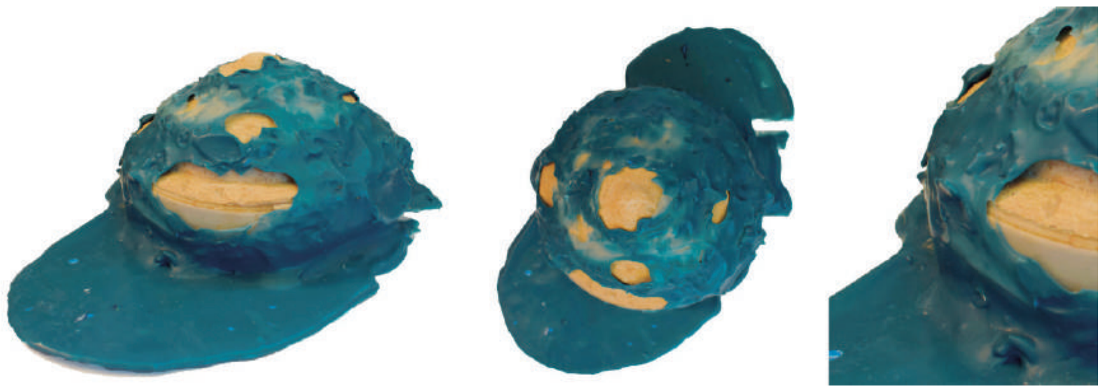


Figure 103 Thermoforming prototype: 1st experience

Table 29 Descriptive table of experiments of the thermoforming first experiments

No.	Temperature (oC)	Time (min)	Material (g)	Surface	Thickness	Observations
1	150	10	45			-HDPE covered the whole prototype -Did not reproduce the external shape -The prototype has holes
2	130	20	55	Accented texture	Uniform 2mm	-HDPE covered the whole prototype -Did not reproduce the external shape
3	120	25	50			-HDPE covered the whole prototype -Did not reproduce the external shape -The prototype has holes

3.5.2.2 Thermoforming: 2nd experience

The whole process is outlined in *Figure 104*.

Table 30 presents the overall results obtained during this first phase of experiments, while *Table 31* presents the detailed data of each experiment.

Appendix VIII presents the photos of all experiments, as well as the textures details.

Contrary to previous experiments, this process has shown improvements, as in the vast majority of prototypes it reproduced well the inner form. The same cannot be said for the outside. Through this process, it was possible to produce very lightweight prototypes. They had smooth and shiny surfaces (in other cases with a sharp texture); uniform thickness (some still had holes); solid structures and others not so much.

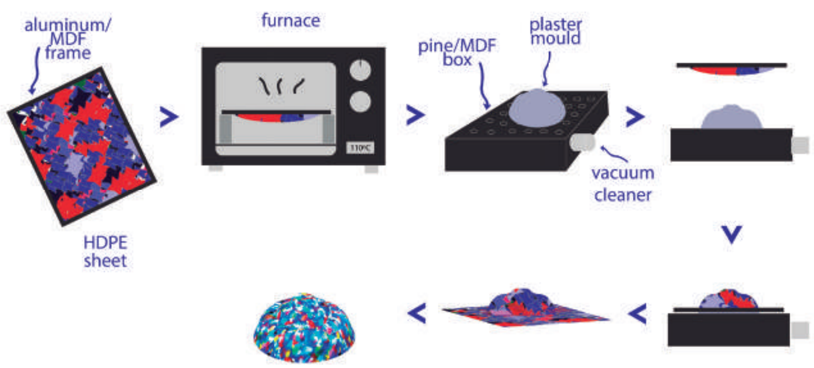


Figure 104 Thermoforming process: 2 nd experience

Table 30 Thermoforming: 2nd experience

Tools	Recycled HDPE, plaster mould, oven and aluminium / MDF frame	
Materials	100% Recycled HDPE	
Descriptions	**Oven**	100 – 170ºC
		5 - 14 min
	Colling	5 min
	Machining	10 min
	1st	With the oven preheated to 200ºC for 10 minutes.

	2nd	The HDPE sheet was fixed to the aluminium / MDF frame.
	3rd	With the lowest oven temperature, everything was put in the oven.
	4th	The HDPE sheet, together with the frame, was only removed from the oven when the HDPE sheet showed some deformation as in *Figure 105*.
	5th	At the same time, the male mould was placed on the MDF / pine box (on the perforated face), as showed in *Figure 106*. Then the vacuum cleaner was placed in the side hole.
	6th	The sheet, along with the frame was removed from the oven and placed on top of the mould (*Figure 107*). (During this process the vacuum cleaner must be switched on.)
	7th	With the HDPE sheet cooled, the vacuum cleaner is turned off, and the prototype is removed from the mould.
	8th	Lastly, the excess material was cut (*Figure 108*).
Conclusions	The experiments were conducted at low temperatures, as can be seen in *Table 31*, to control the deformation of the HDPE sheets. The oven time was quite short, as the sheets did not take long to deform (as they had a thin thickness). In some experiments, the HDPE sheets did not melt evenly. When the aluminium frame was used, the HDPE sheet tended to melt near the frame (as in the case of experiments 1 to 7 from *Table 31*). By using the MDF frame, the melting process showed an improvement as the material began to melt right in the middle where it should be melting (as in the case of experiments 8 to 17 from *Table 31*).	
Improvements	Despite the low temperatures, HDPE melted quickly and uncontrollably as prototypes were unable to reproduce the toy's external geometry faithfully.	

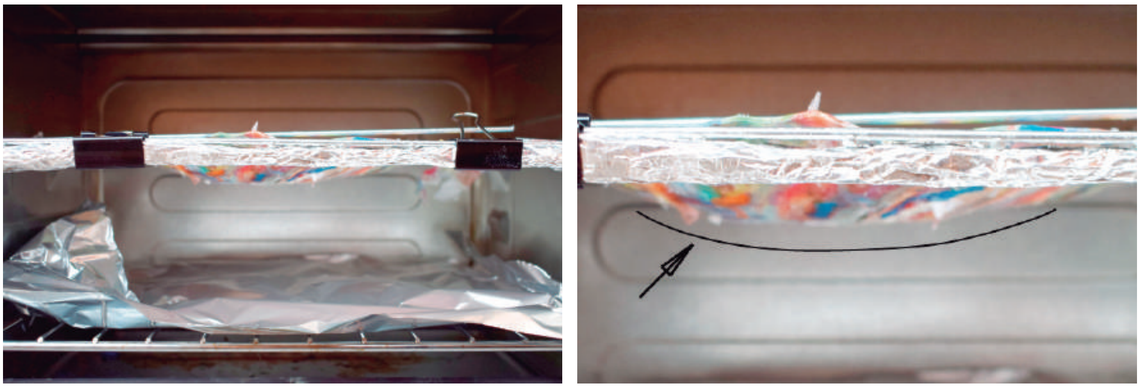


Figure 105 HDPE sheet deformation in the furnace

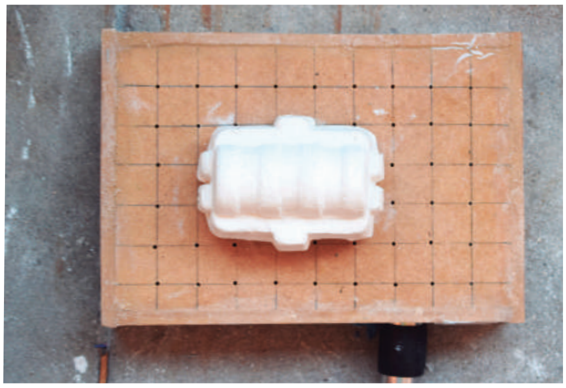


Figure 106 Plaster mould on top of the MDF box

Figure 107 HDPE sheet on top of the plaster mould

Figure 108 Thermoforming prototype: 2nd experience

This process made it possible to determine the thickness of the experiments (since the thickness of the prototype depended on the thickness of the material and its thermal conductivity). The thick sheet determined how difficult thermoforming would be (as in the case of experiments 13 and 17 from *Table 31*). Because the thicker the material, the harder it becomes to melt it evenly. In the case of the thinner sheets, they deform faster; however, they are susceptible to the opening of holes (as in the case of experiments 1, 2, 6 to 9, 11 and 12 from *Table 31*).

Although this method has great potential, it was not possible to obtain the desired geometry. The thin sheet of HDPE was susceptible to pitting holes, and the thicker sheet was difficult to control. Besides that, some factors may have potentiated failures during this experimentation phase, from the oven or vacuum power to HDPE sheet quality, among other factors.

Table 31 Descriptive table of experiments of the thermoforming experiments

No.	Temperature (oC)	Time (min)	Material (g)	MDF/ Pine box	Surface	Observations
1	170	5	45	MDF	Texture accentuated with holes	-Did not reproduce the external/ internal shape -poorly melted material -Solid (not deformed when applying force)
2	160	10	40			
3	150	10	10		Smooth and shiny texture	- Partially reproduced the external / internal shape -Fragile (deformed when applying force)
4	140	10	15			
5	130	10	125			-Did not reproduce the external/ internal shape -poorly melted material -Solid (not deformed when applying force)
6	120	10	52			-Did not reproduce the external/ internal shape -poorly melted material -Fragile (deformed when applying force) -The prototype has holes
7	110	15	165		Accented texture	-Did not reproduce the external/ internal shape -poorly melted material -Solid (not deformed when applying force) -The prototype has holes

<table>
<tr><td>8</td><td>100</td><td>8</td><td>42</td><td rowspan="10">Pine</td><td>Smooth texture</td><td>- Partially reproduced the external / internal shape
-Fragile (deformed when applying force)</td></tr>
<tr><td>9</td><td>140</td><td>8</td><td>120</td><td rowspan="2">Accented texture</td><td>-Did not reproduce the external shape
-Did reproduce the internal shape
-Solid (not deformed when applying force)</td></tr>
<tr><td>10</td><td>150</td><td>10</td><td>105</td><td>-Did not reproduced the external / internal shape
-Poorly melted material
-Solid (not deformed when applying force)
-The prototype has holes</td></tr>
<tr><td>11</td><td>150</td><td>10</td><td>58</td><td rowspan="7">Smooth and shiny texture</td><td>-Poorly melted material
- Fragile (deformed when applying force)
-Did not reproduce the external/ internal shape
-The prototype has holes</td></tr>
<tr><td>12</td><td>150</td><td>12</td><td>30</td><td>-Did reproduce the external / internal shape
-Solid (not deformed when applying force)</td></tr>
<tr><td>13</td><td>150</td><td>10</td><td>100</td><td>-Poorly melted material
-Did reproduce the external / internal shape
-Solid (not deformed when applying force)</td></tr>
<tr><td>14</td><td>150</td><td>14</td><td>140</td><td rowspan="4">-Did not reproduce the external shape
-Did reproduce the internal shape
-Solid (not deformed when applying force)</td></tr>
<tr><td>15</td><td>150</td><td>12</td><td>110</td></tr>
<tr><td>16</td><td>150</td><td>12</td><td>142</td></tr>
<tr><td>17</td><td>150</td><td>12</td><td>137</td></tr>
</table>

3.5.3 Advantages and disadvantages of production processes

During the prototyping phases, various manufacturing techniques were used, which helped to strengthen knowledge about thermoplastics, moulds and different manufacturing processes. However, after the various experiments, it was possible to determine the advantages and disadvantages of each tried processes (shown in the *Table 32*).

The aluminium mould is a good investment; besides faithfully reproducing the shape of the mould, it can be used several times without showing any wear. Also, the wood and plaster can be used as moulds for the polymer casting process; however, the moulds are more susceptible to damage. Regarding the thermoforming process, despite not having the best results, it was possible to see that this technology has the potential for future uses.

Table 32 Advantages and disadvantages of production processes

Mould / Process used	Advantages	Disadvantages
Aluminium mould	- Reusable mould - Resistant to erosion and thermal fatigue - Rigid - Can be shaped into smooth, complex shapes - Practical moulds - Able to produce complex and detailed geometries - Faithful reproduction of the the desired product - Good surface finish - Good dimensional accuracy - High production rates	- Expensive mould - Valid for mass production only - Requires special tooling - Requires skills for precise and high-quality metalworking - High tooling cost - The high tolling cost make this process economical for small production runs - There is always minimal excess material (although it can be reused)
Pine wood mould	- Inexpensive material (when compared with aluminium) - Abundant wood - Light - High strength - Pine wood is easy to work even though specific machines are needed - More complex and detailed geometries can be produced - Smooth and shiny surface - Faithful reproduction of the desired product	- Must be smoother and sealed (with aluminium foil) to become effective (in order to preserve the integrity of the mould as well as the surface of the product) - Traces of aluminium foil - Repeated production damages mould - The mould cannot be placed in the furnace - Production of mould production requires specialized machines -There is always excess material, (although it can be reused) - HDPE viscosity slows down the process
Plaster mould	- Easy to produce, no specialized machines required - Cheap and abundant material - Able to produce complex and detailed geometries - Smooth and shiny surface - Faithful reproduction of the desired product - Hardens to robust, rigid and massive shapes that can be shaped after curing	- Must be smoother and sealed (with aluminium foil, cling wrap or vaseline) to become effective (in order to preserve the integrity of the mould as well as the surface of the product) - Traces of aluminium foil or cling wrap - Repeated production damages mould - Heavy - Fragile - Slow mould production (24 / 72h drying time) - There is always excess material, (although it can be reused) - HDPE viscosity slows down the process
Thermoforming	- Product thickness depends on sheet thickness - Able to produce complex and detailed geometries (internally) - This process can be recreated and adapted by more rudimentary materials and technologies - Able to produce multiple products at once - Smooth and shiny surface - Faithful reproduction of the desired product	- This process requires a wooden case, a frame, a vacuum cleaner and HDPE sheets. - Uncontrollable melting of HDPE sheets - Difficulty reproducing the outer surface of the product - Difficulty reproducing the external shape of the toy - There is always excess material, (although it can be reused)

3.5.4 Final manufacturing process

After several attempts, the production process chosen for the prototypes was the vaseline brushed plaster mould. A table was created to validate the requirements fulfilled to verify if this process met the criteria needed. This validation is in the following *Table 33*.

Table 33 Validation of requirements imposed as well as how they were validated

Requirements		Validation	How it was validated
Use only recycled HDPE		V	During the production of the prototypes, only recycled HDPE was used.
Easy to operate manufacturing process, cheap and viable		V	Plaster is a cheap material, and can reproduce the toy's shape, and is easy to operate.
Explore different colours mixtures of HDPE		V/X	Throughout the experiments, it was not possible to explore much the colour variation. Since, before shredding, the caps were not separated. Once shredded, it became complicated to separate by colour.
Toys requirements	**Mechanical strength**	V	The geometry and thickness of each toy can withstand the stresses related to its use without breaking or distorting.
	Avoid edges, ropes, cables and anchorages	V	Each toy features smooth faces with rounded edges and simple shapes. In addition, to eliminate potential hazards and accidents, ropes, cables and anchors were eliminated.
	Prevent ingestion	V	Beach kids toys dimensions prevent ingestion.
	Burn in contact with flame	X	HDPE burns slowly, and the drops continue to burn after falling.
	Health risk	V	Since the toy industry makes toys from recycled HDPE, this indicates that this material does not pose any health risks.
	Containing chemicals	V	Contains no chemicals banned/limited by the EU.
	Hygiene and cleanliness requirements to avoid any risk of infection or disease	V	The smooth surface and geometry of the toys make it easy to wash, preventing any risk of infection or disease.
Anthropometry and ergonomic measurements of the children hands		V	It was tricky to adapt the measurements to an age range as children develop at different ages. However, the Beach kids measurements emerged from the reconciliation of the anthropometric table measurements along with the market research toy measurements.
Appropriate age		V	
Representative of the city of Matosinhos		V	Each toy represents a monument. The simplified geometry of the Anémona, Terminal of Cruzeiros and Matosinhos Municipal Market originated the Beach kids toys. This way, Beach kids not only promotes recycling, but it also supports the city.

Improve the production process by exploring new production process:	v	Plaster moulds and the thermoforming process were used. Through the plaster moulds, it was possible to manufacture the best prototypes. However, the thermoforming process has great potential.
Exploring efficient methods for the cutting of excess material	v	The excess material from the final prototypes was cut with a box opener. However, this process may delay the production line.
Avoid wasting material	v/x	The weight of HDPE throughout the exploration phase varied. The viscosity of HDPE has complicated the production process, so it is difficult to determine the exact grams. However, excess material can still be used.

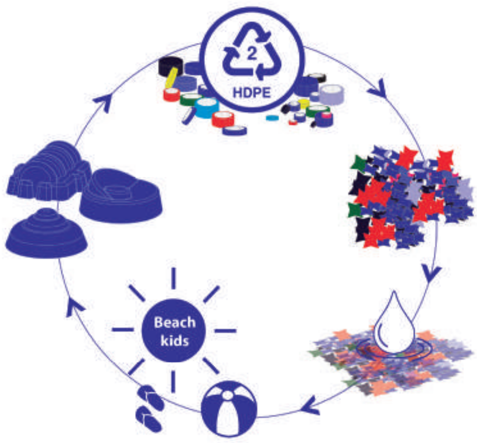


Figure 109 Beach kids production stages

The whole process is shown schematically in *Figure 109* and the production process of Beach kids is shown schematically in *Figure 110*.

The process begins with the plastic collection; then the separation (HDPE); after that, the material is shredded; washed out, and is allowed to dry.

After that, several ideas are developed through a creative process supported by a concept, originating products, similar to Beach kids' toys.

First, the furnace is preheated to 250ºC for 20 minutes. Then the HDPE (shredded) is placed in an aluminium container and placed in the furnace (at 200ºC approximately 20 minutes). Simultaneously, the mould is brushed with vaseline. The HDPE is then poured into the mould. The other half of the mould is placed immediately on top and then compressed on the press. After approximately 30 minutes, the prototype is removed from the mould. Lastly, the excess material is cut with a box opener.

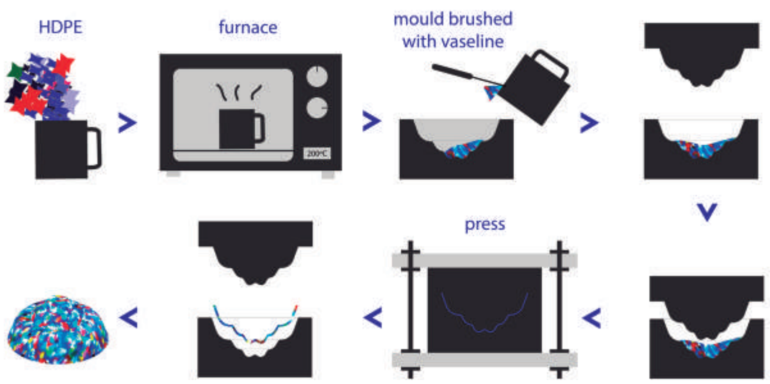


Figure 110 Manufacturing process of the Beach kids

3.6 Final results - Beach kids

Finally, the Beach kids, a three-way beach toys collection made from **100% recycled HDPE** (*Figure 111, 112, 113 and 114*). The name Beach kids combines the beach concept with the target audience of this project, the children.

The primary purpose of these toys is to demonstrate the potential of recycled HDPE. Beach kids, not only for diverting HDPE waste, but was also designed to make society aware of the environmental effects of ours actions, endorse recycling and help promote the city of Matosinhos.

Each toy represents an emblematic monument of the city of Matosinhos. Through formal simplicity, it is possible to describe the Anémona in *Figure 115* and *116* the Terminal of Cruzeiros in *Figure 117* and *118*, and the Matosinhos Municipal Market in *Figure 119* and *120*.

What catches the eye the most are the colours, where the various shades of blue, along with white, red and green tones cause a chaotic and inconsistent pattern which define the uniqueness of each toy. The singularity of the Beach kids can lead to conversations about recycling and value of plastics, which can influence the public to pay more attention to the waste they produce and especially where they leave it.

Last but not least, some general and detailed photos of the Beach kids set are presented.

Figure 111 Beach kids

Figure 112 Beach kids - Usability test

Figure 113 Beach kids

Figure 114 Beach kids sand shape

3.6.1 Anémona

Figure 115 Anémona

Figure 116 Anémona usability testing

3.6.2 Terminal of Cruzeiros

Figure 117 Terminal

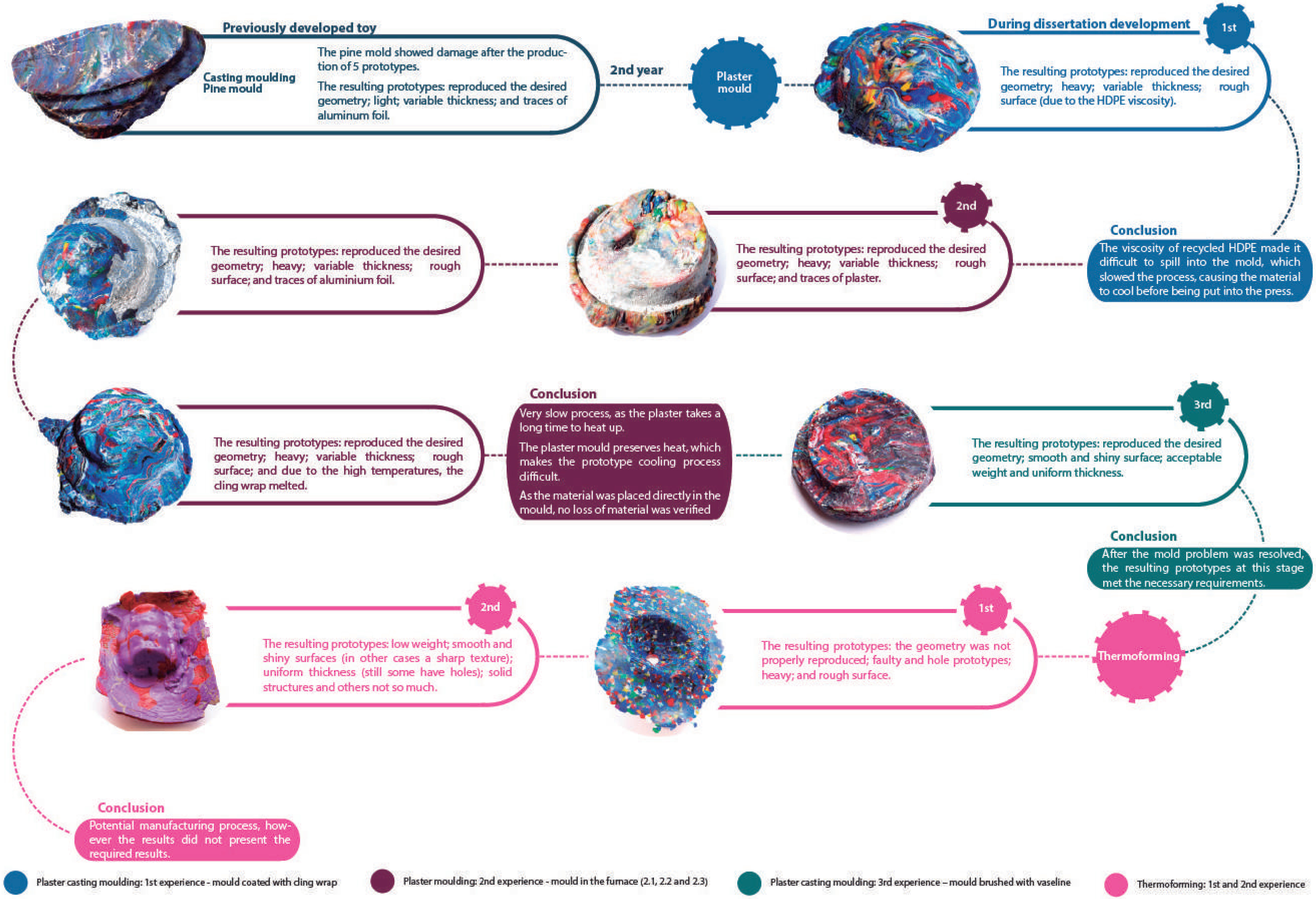
Figure 118Terminal usability testing

3.6.3 Matosinhos Municipal Market

Figure 119 Mercado

Figure 120 Mercado usability testing

3.7 Summary of the case studies



IV Conclusions

4.1 General conclusions

Currently, today's harmful effects caused by humans are notorious and more than publicized. The population is more aware and concerned about the ecosystem, which reflected in some industries. Plastics have reached the oceans and wildlife confuses them with food. The EU is moving towards a circular economy aimed at achieving zero waste. That led design to create strategies to promote material recycling, reuse and recovery. Increasingly more solutions and alternatives to plastic waste are emerging, and more industries are looking to use more recycled plastic. Today's problem is a business opportunity for many companies. The green trend implemented in our society and used by companies to launch eco-friendly products to the market. Some reputable companies seek to adopt strategies and change their principles to address environmental issues (some of them are shown in *2.4 Form waste to the material – Market research* chapter). The toy industry still consumes mostly virgin material, as few companies bet on the potential of recycled material. Nevertheless, projects like Beach kids or companies like Green Toys or ecoBirdy are gaining notoriety due to the exclusive use of recycled plastics, namely HDPE. This material has great potential to be used efficiently in numerous products, including products intended for children.

During the MDIP, several projects got developed in the scope of sustainability, projects featured here, such as designer Axel Silva's seat stool Gibada (Silva 2018) and designer Flávia Freixas' set of buttons, beach slippers and necklaces (Freixa 2016). Still, within the MDIP scope, the WWWY project was developed, where the Beach kit protector set, and the Beach kids toys got designed. Throughout the MDIP, it was possible to study and explore HDPE residues. Also, various production methods got explored. The aluminium, pine and plaster moulds were studied, and the thermoforming process was also adapted. The exploitation of these multiple techniques was due to the need to make the production process as inexpensive as possible and easy to operate, i.e. to dismiss skilled labour. Thus, the use of plaster moulds, which, although not generally used for polymer modelling, is a cheap and effective technique to produce the Beach kids. Also, the prototyping process helped to consolidate knowledge about the material. Through intensive HDPE exploration, it was possible to create the Beach Kids toy collection for children to play on the beach.

The three toys resemble the three most emblematic monuments, namely the Anémona sculpture, the Terminal of Cruzeiros and the Matosinhos Municipal Market. This way, the visitors of Matosinhos can remember the city through these artefacts. These toys have the particularity of being made from 100% recycled HDPE from bottle caps. Each toy is unique and has a colourful and irregular pattern that evokes the curiosity of the material's origin. Some colour mixtures were explored; however, what caught the eye were the blue prototypes since the colour is associated with the ocean. Every toy is designed under the EU defined Toy Safety requirements. The Beach kids have a simplified geometry with rounded edges that withstands the stress related to its use. Allied with its smooth surface and meeting the hygiene and cleanliness requirements to avoid any risk of infection or disease. The toy measurements emerged through the reconciliation of anthropometric table measurements, along with market research, and were strategically thought to prevent its ingestion.

The toys collection creates a link between the material (waste from the city of Matosinhos), the city and the environmental concerns. Besides fighting the plastic waste and diverting it from landfill or sea currents, it helps reduce environmentally harmful emissions such as CO2and considerably reduces energy costs. The role of design is essential because it dictates and influences the future of products as well as persuades consumers and their style of product acquisition. Besides, people's constant concern about polymer waste will be used as a starting point and a design opportunity to make people understand that recycled products are not second-class products and can compete with high-quality products. This opportunity needs to be explored through product development to demonstrate the real value of this wasted material and also to explore new solutions and weigh every decision made.

Further investigation of the potential of polymers and their reuse is required. Gradually, circular strategies are being implemented considering the magnitude of the entire product life cycle and determining strategies that facilitate material recycling.

4.2 Future work

Although the objectives were achieved, some aspects can be further refined. That said, here are some detailed recommendations to improve in the future:

i. Partner with companies to increase and better manage waste;

ii. Use a metal mould, and it would be possible to multiply production and improve the final quality of the project;

iii. Further, explore the thermoforming process;

iii.i. Build a larger wooden box, and try to produce more than one prototype at a time;

iii.ii. Minimize material or reuse production waste;

iii.iii. Determine the exact and most appropriate temperature for the HDPE sheets to melt without puncturing;

iii.iv. Determine the thickness of the HDPE sheet required to obtain a solid and robust prototype.

iv. Improve the strength and durability of plaster moulds;

iv.i. Control the thickness of the toy;

iv.ii. Determine the exact HDPE weight to use;

iv.iii. Minimize material or re-use production waste;

iv.iv. Make the casting process more efficient and faster.

v. Place the HDPE recycle mark, so users can efficiently classify, categorize and recycle the toy;

vi. Expand the family of Beach kids toy, based on other Matosinhos monuments;

vii. Obtain the CE certificate to market the toy in the EU;

viii. Check if the Beach kids toys comply with ISO 8124 requirements and standards.

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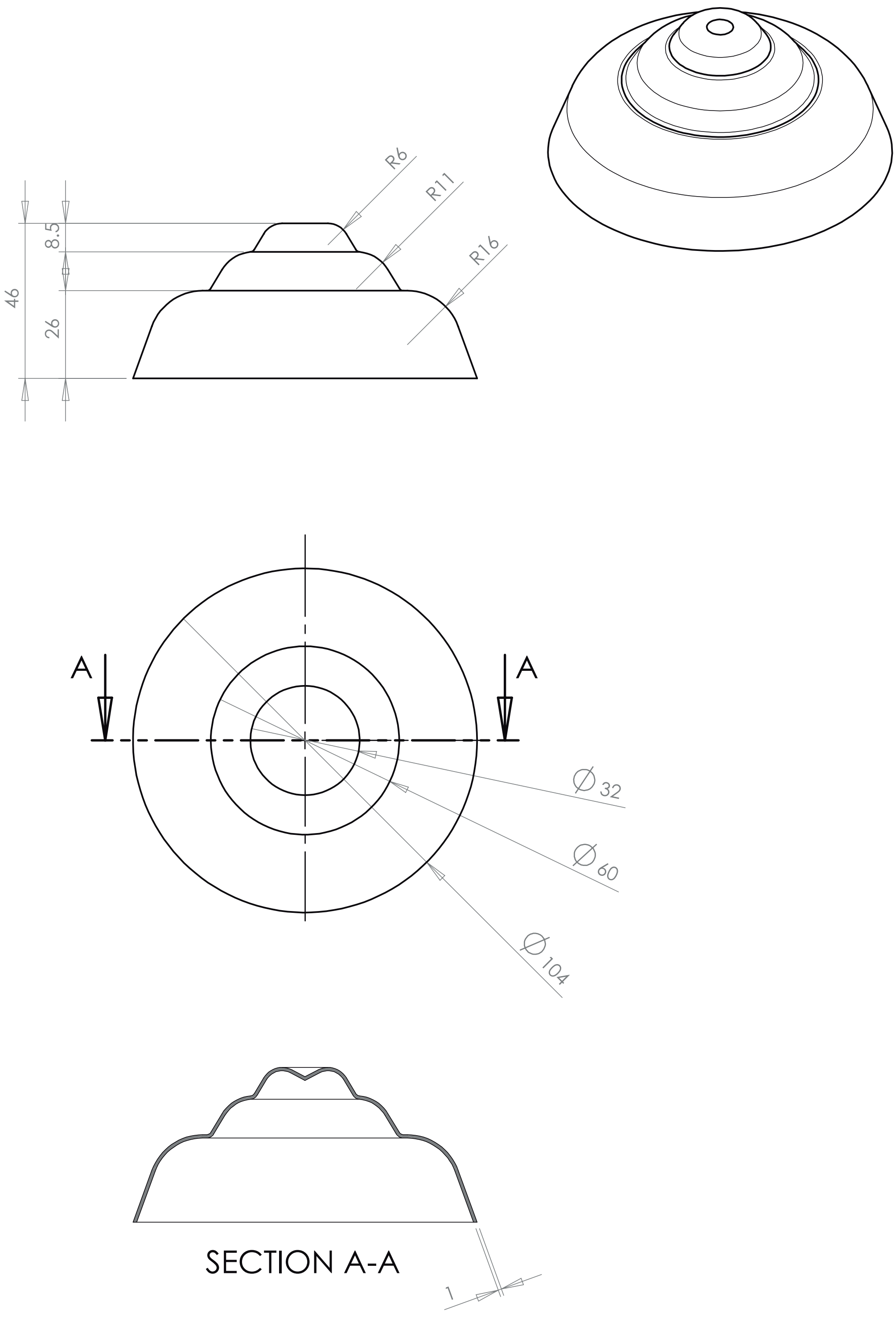
Appendix I



DWG NO. **Anémona** A4

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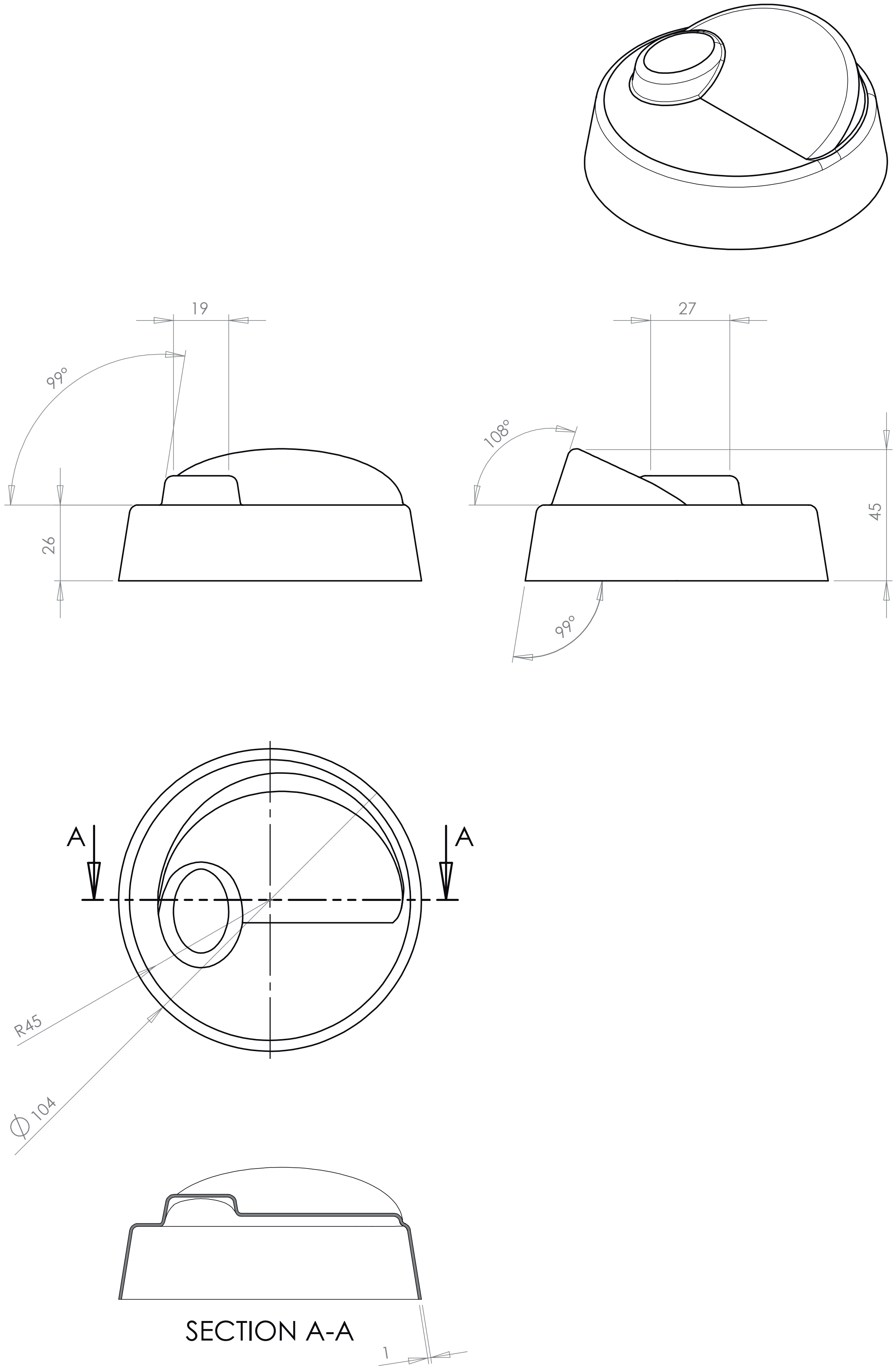


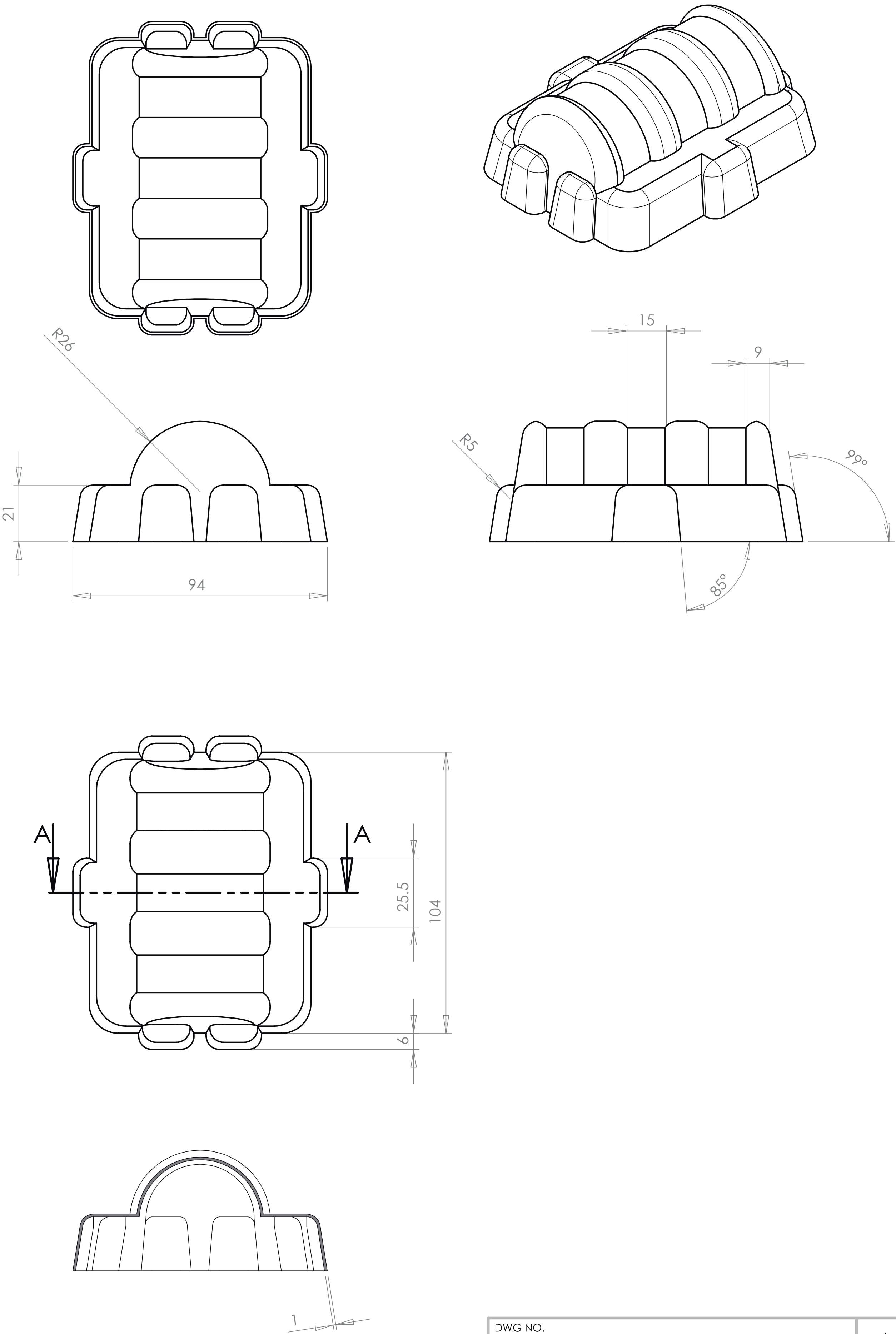
DWG NO.

Terminal

A4

1:1SCALE

SHEET 2 OF 3



SECTION A-A

100

DWG NO.

Market

A4

1:1SCALE

SHEET 3 OF 3

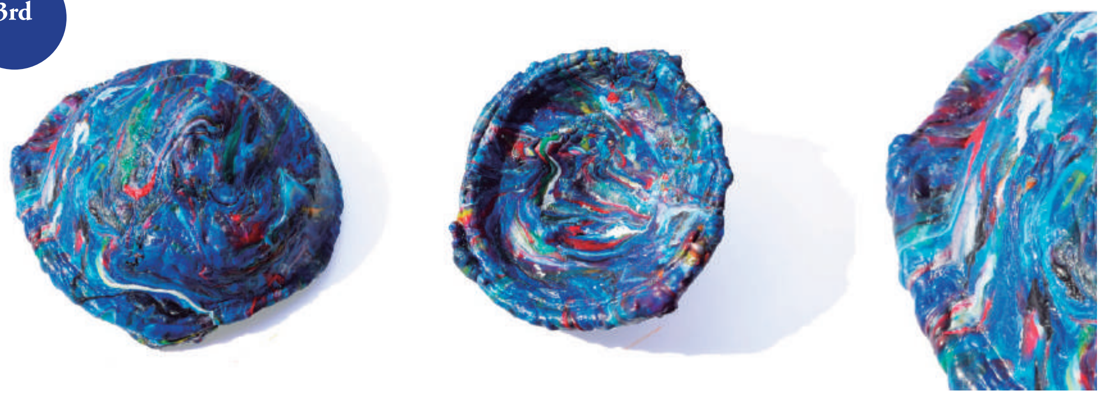
Appendix II

Experiments of the mould coated with the cling wrap.

1st

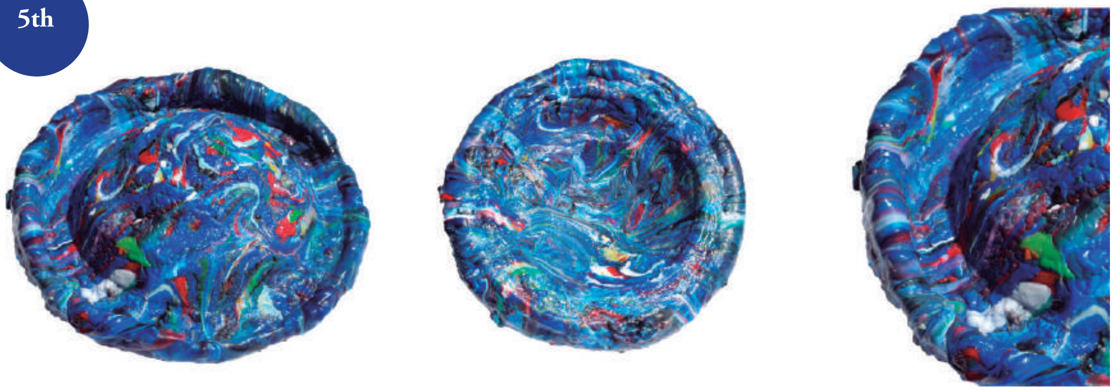
2nd

3rd



4th

5th



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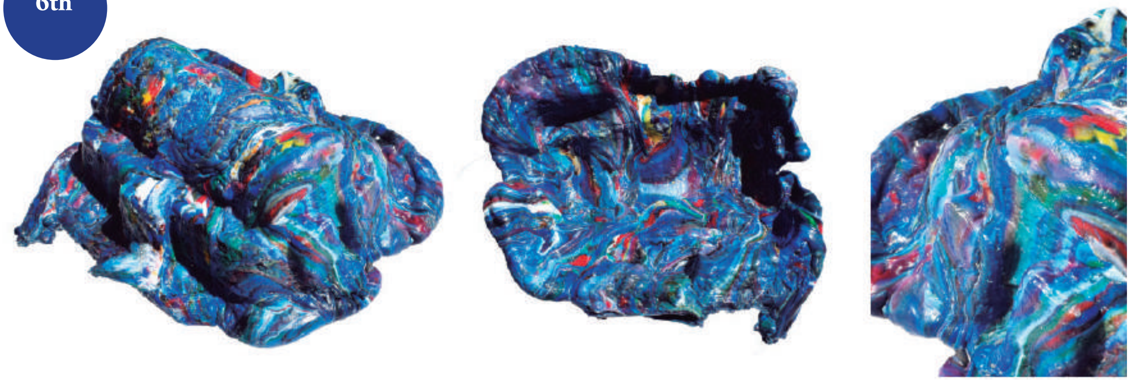
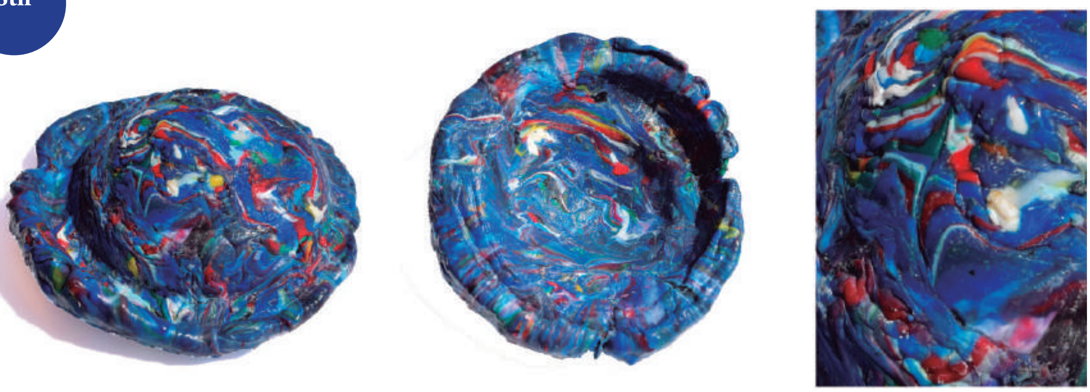


7th

8th



9th

Appendix III

Experiments of the mould in the furnace.

1st

2nd

3rd

4th



Appendix IV

Experiments of the mould in the furnace with aluminium foil.

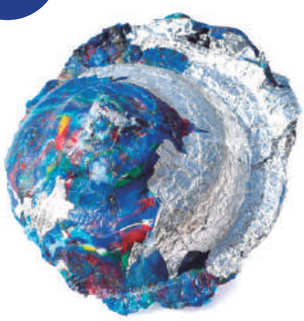
1st

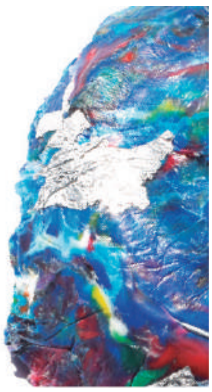


2nd



3rd

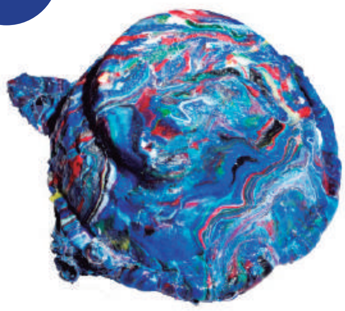




Appendix V

Experiments of the mould in the furnace with cling wrap.

1st



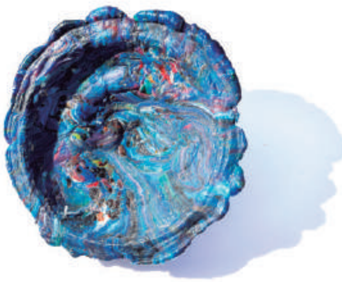
2nd



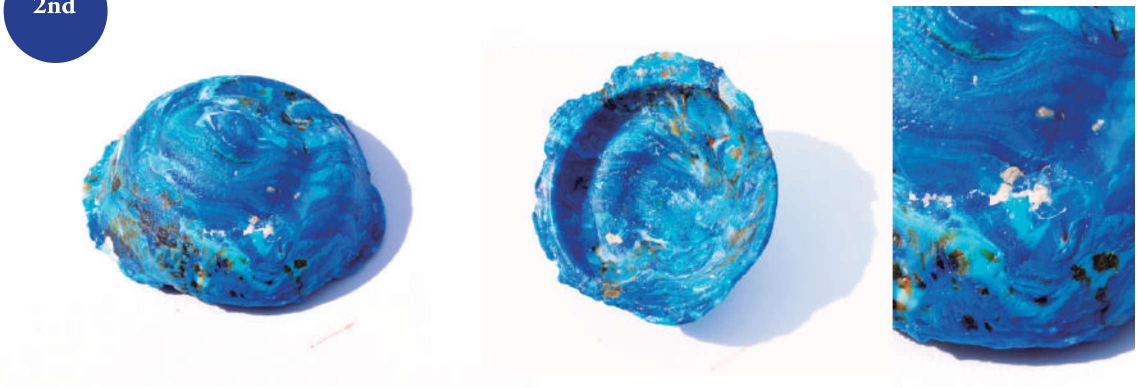
Appendix VI

Experiments of the mould brushed with vaseline.

1st

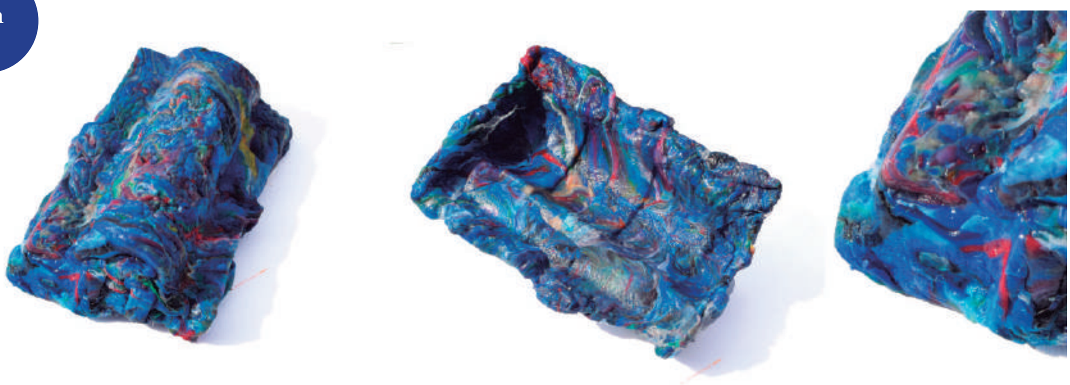




2nd



3rd

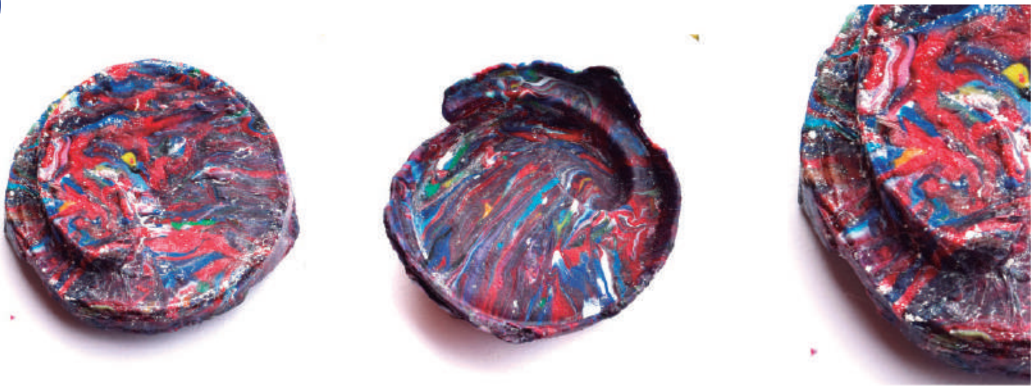
4th



5th

6th

7th



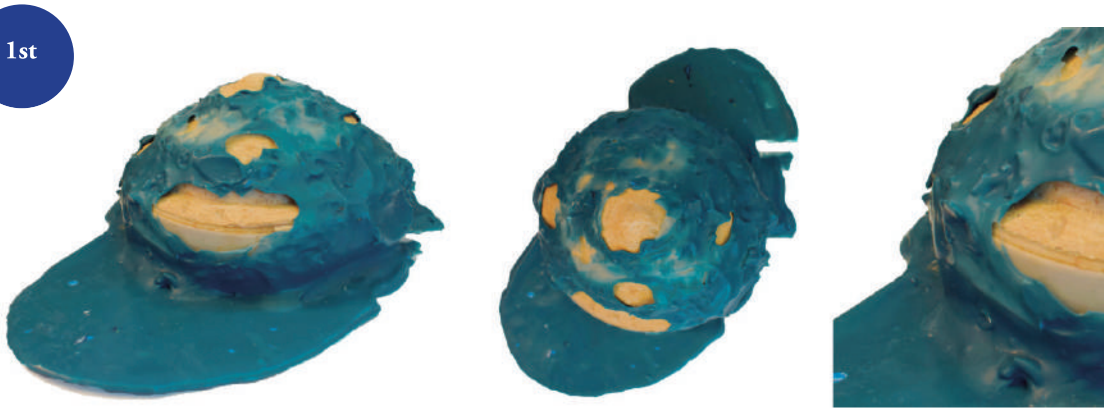
8th

9th

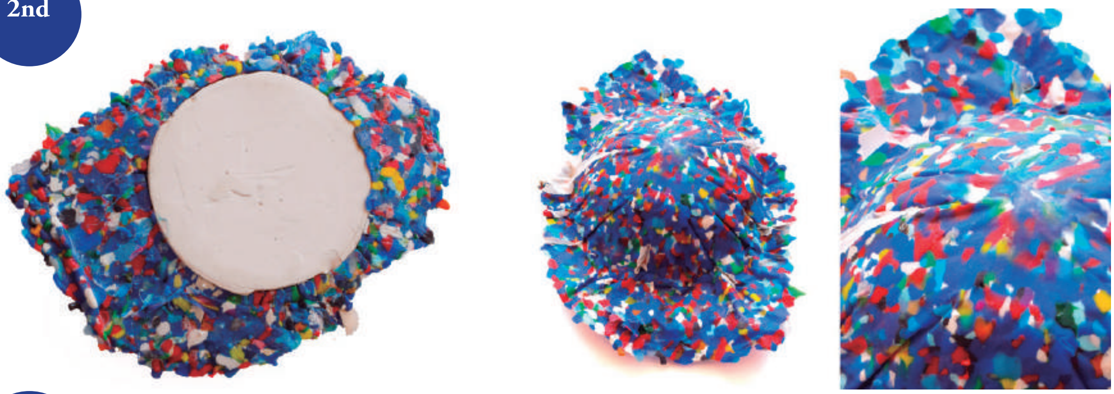
Appendix VII

1st Thermoforming experiments.

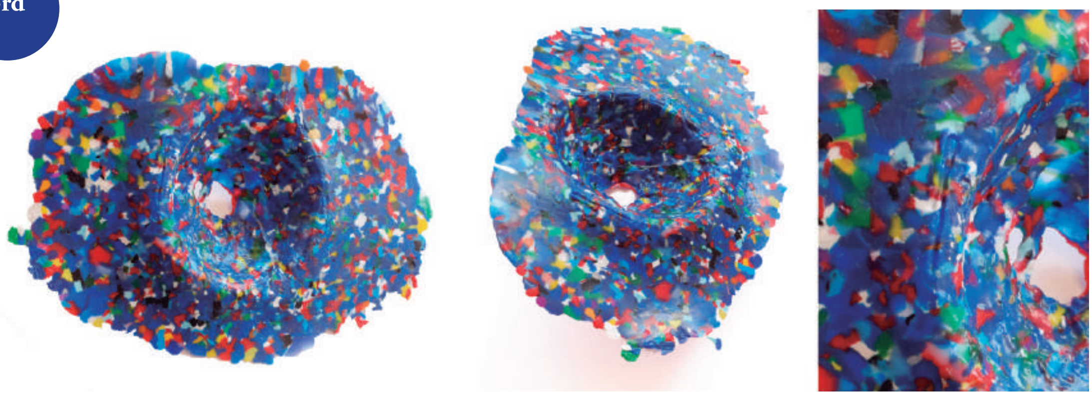
1st



2nd



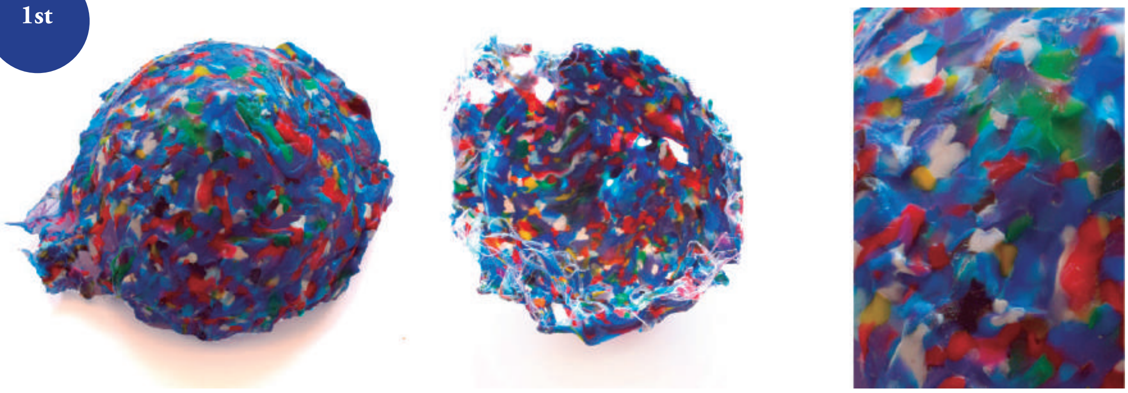
3rd



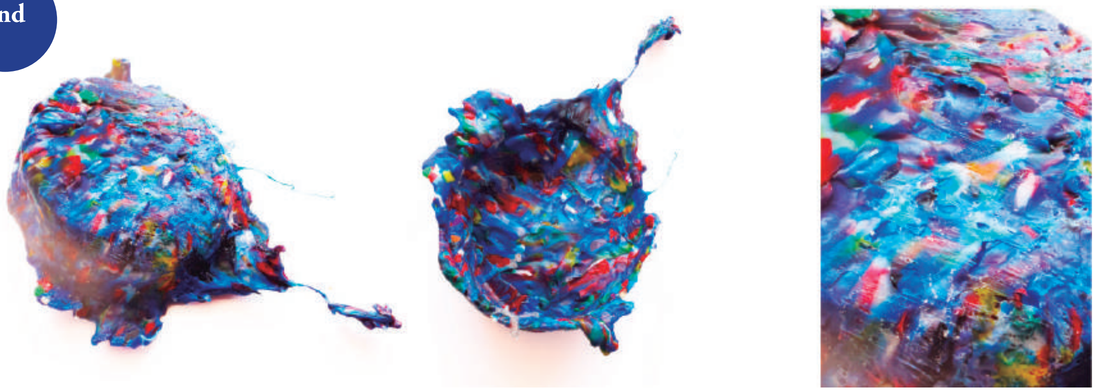
Appendix VIII

2nd Thermoforming experiments.

1st



2nd



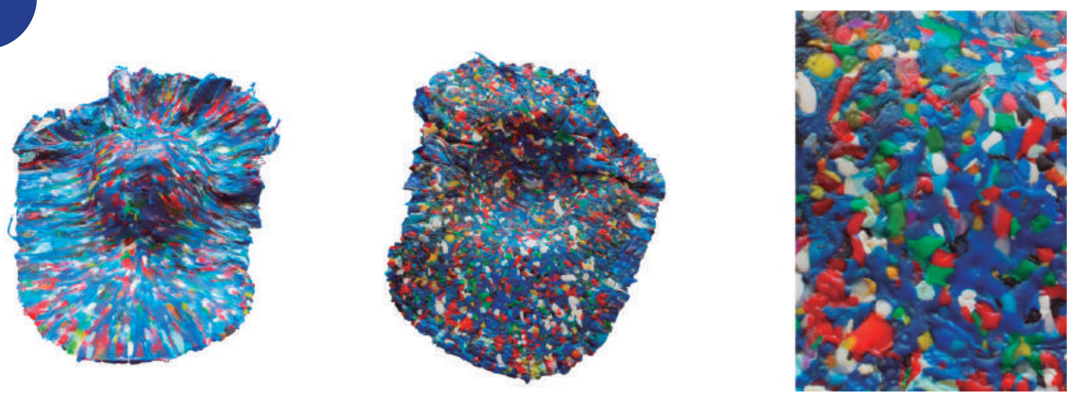
3rd

4th

5th

6th

7th



8th

9th

10th

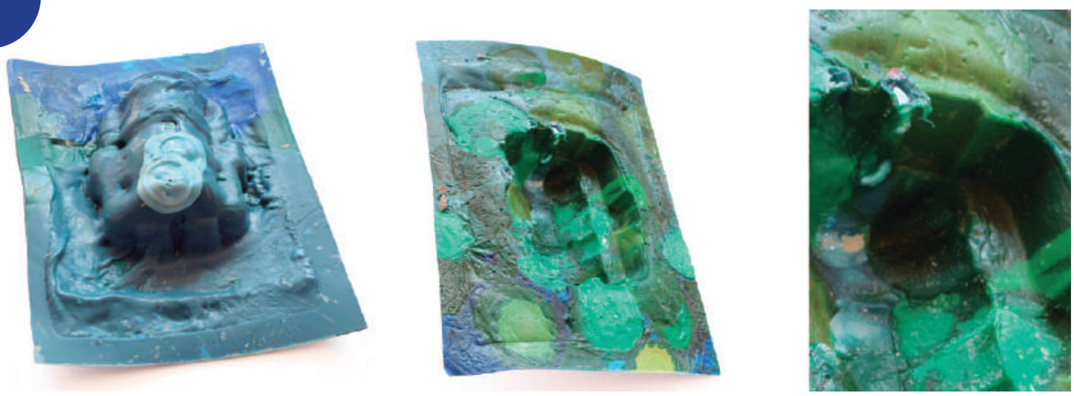
11th

12th

13th

14th

15th



16th

17th