Integrating Absolute Sustainability in Product Design: A Case Study within the Manufacturing Industry

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Declaration

I declare that this document is an original work of my own authorship and that it fulfils all the requirements of the Code of Conduct and Good Practices of the Universidade de Lisboa.

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RESUMO

No atual contexto global, onde o planeta enfrenta uma degradação ambiental crescente e ultrapassa vários limites planetários, é essencial repensar como os produtos de consumo são concebidos.

Este projeto explora a aplicação de princípios de sustentabilidade absoluta na reformulação de uma esfregona de limpeza convencional, visando reduzir drasticamente o impacto ambiental sem comprometer a funcionalidade e as necessidades do usuário. O processo começou com uma análise detalhada dos modelos existentes da Fapil e dos principais fatores ambientais associados aos materiais, fabrico, utilização e fim de vida.

Através de uma geração estruturada de conceitos, seleção e prototipagem iterativa, chegou-se a um design final que incorpora materiais sustentáveis e apresenta um formato modular. Esta modularidade facilita a separação e lavagem das fibras em máquinas convencionais, prolongando a vida útil do produto e facilitando a reciclagem e manutenção. Foram utilizados polipropileno reciclado nos componentes estruturais e resíduos de fábrica de fraldas reutilizados nas fibras, aproveitando recursos e reduzindo resíduos. Além disso, o projeto introduziu uma embalagem plantável e sem plástico, com função protetora e simbólica. Uma Avaliação do Ciclo de Vida (ACV) confirmou uma redução significativa do impacto ambiental em comparação com alternativas tradicionais, embora alguns limites planetários ainda sejam ultrapassados.

O projeto evidencia os desafios e oportunidades de integrar a sustentabilidade absoluta no design real de produtos. Apesar de algumas limitações, o resultado representa um progresso relevante e estabelece uma metodologia replicável que pode orientar futuras inovações sustentáveis em produtos.

Palavras-chave: sustentabilidade absoluta, design de produto, avaliação do ciclo de vida, limites planetários, espaço operacional seguro

ABSTRACT

In the current global context, where the planet faces increasingly severe environmental degradation and surpasses several planetary boundaries, it is essential to rethink how consumer products are designed.

This project explores the application of absolute sustainability principles in the redesign of a conventional cleaning mop, with the aim of drastically reducing environmental impact without compromising functionality or user needs. The process began with an in-depth analysis of existing Fapil models and the main environmental factors associated with materials, manufacturing, use, and end of life.

Through a structured generation of concepts, selection, and iterative prototyping, a final design was achieved that incorporates sustainable materials and features a modular format. This modularity facilitates the separation and washing of the fibres in conventional washing machines, prolonging the product's lifespan and enabling recycling and maintenance. Recycled polypropylene was used in the structural components, and waste from diaper factories was reused in the fibres, making use of resources and reducing waste. Furthermore, the project introduced a plantable, plastic-free packaging concept that serves both protective and symbolic functions. A Life Cycle Assessment (LCA) confirmed a significant reduction in environmental impact compared to traditional alternatives, although some planetary boundaries are still exceeded.

The project highlights the challenges and opportunities of integrating absolute sustainability into real-world product design. Despite some limitations, the result represents significant progress and establishes a replicable methodology that can guide future sustainable innovations.

Keywords: absolute sustainability, product design, life cycle assessment, planetary boundaries, safe operating space

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NOMENCLATURE

aSoSOS	Assigned Share of Safe Operating Space
ASR	Absolute Sustainability Ratio
DfE	Design for Environment
DfS	Design for Sustainability
HOQ	House of Quality
LCA	Life Cycle Assessment
PB	Planetary Boundaries
PDS	Product Design Specification
rPP	Recycled PolyPropylene
SDGs	Sustainable Development Goals
SOS	Safe Operating Space
SP	Sharing Principle

1. INTRODUCTION

The consumption of natural resources has increased rapidly on a global scale in recent decades. This increase, largely driven by demographic growth, economic development, and changes in lifestyle, has become one of the main factors triggering profound transformations in the Earth system, causing severe and persistent environmental degradation. This scenario threatens the ability of ecosystems to continue providing essential services for human life and other species, and it raises serious concerns about the sustainability of the current development model [1].

In response to this growing problem, the Planetary Boundaries framework has been proposed as a tool to monitor the biophysical limits of the Earth system. This approach, introduced by Rockström [2] and later expanded by Steffen [3], defines a set of nine critical biophysical processes, such as climate regulation, biodiversity, and biogeochemical cycles, that delineate a safe operating space for humanity. Planetary boundaries establish measurable thresholds for each of these processes with the aim of ensuring that human activity does not compromise their long-term stability ([2], [3], [4]).

The concept of Planetary Boundaries has become influential in international sustainability discourse, particularly in the context of the United Nations 2030 Agenda for Sustainable Development [5]. Although the framework is not explicitly mentioned, the nine environmental processes it identifies are reflected in various Sustainable Development Goals (SDGs). Some are addressed as specific goals, such as climate change, biodiversity, land use, and water, while others, including ocean acidification, air quality, biogeochemical flows, and chemical pollution, are incorporated into broader targets.

This way of conceptualizing sustainability, not as an abstract ideal but as a quantifiable balance within defined limits, leads to the idea of absolute sustainability [5]. Unlike gradual or relative approaches, absolute sustainability is based on the premise that all human activities must remain within the planet’s ecological tolerance [6]. This margin represents Earth's finite capacity to support human activity, and within it, ensure not only the well-being of the current population but also that of future generations. Designing products with zero or minimal environmental impact is not only desirable, it is essential if we are to meet crucial goals, for instance carbon neutrality by 2050. This minimal impact must be understood in relation to the planetary boundaries introduced above, which define the limits of absolute sustainability. In any case, the notion of absolute sustainability is a long-term objective, with a horizon of 20 to 30 years [1].

In this context, the role of industry is fundamental. Factories are currently among some of the main contributors to environmental degradation worldwide [8]. These facilities negatively affect the environment through the emission of air pollutants, the release of toxic waste, and the contamination of water bodies. Moreover, they are responsible for a significant share of greenhouse gas emissions. Industrial activities are estimated to generate 24% of global CO_2 emissions annually, according to the United States Environmental Protection Agency [9]. Regarding water use, factories consume approximately 22% of global freshwater supplies, much of which is discharged back into the environment as untreated wastewater, with harmful effects on aquatic ecosystems. Added to this is the massive generation of industrial solid waste, which accounts for a substantial share of the more than 2 billion tons of waste produced globally each year, much of which ends up in landfills or the oceans [8].

Despite these negative environmental impacts, the industrial sector plays a crucial role in modern society and the manufacturing industry remains a central pillar of the global economy. In 2025, the total output of the manufacturing market is projected to reach 50.84 billion US dollars [10], highlighting the massive scale and contribution of the sector to economic activity. The industry is also expected to encompass around 5 million companies and provide employment to approximately 157 million people across the globe [10]. These figures reflect not only the industry's economic weight but also its essential role in sustaining livelihoods and meeting consumer demand. Recognising this importance means focusing not on questioning the value of manufacturing, but on transforming it in line with the principles of absolute sustainability, in order to ensure its long-term viability within planetary boundaries.

Building on this analysis, this study explores a potential redesign approach that aims to approach absolute sustainability and remain within the Earth's ecological limits. It explores design strategies capable of reducing a product's environmental impact to levels within planetary boundaries across its entire life cycle, from material selection to end-of-life, fully integrating the principles of absolute sustainability. The objective is not to imagine an ideal scenario that is unreachable, but rather to draw a clear, concrete, and ambitiously realistic path toward a future in which designing within planetary boundaries becomes the norm instead of the exception.

1.1 Origin of the project and motivation

For some time now, there has been a growing promotion of sustainability and practices aimed at minimizing environmental impact, such as recycling, reducing water and energy waste, and reuse. This type of commitment has increasingly been recognized as a key factor in contributing to environmental preservation. It has gained strength as engineering presents an opportunity to develop innovative and environmentally responsible solutions. From a professional standpoint, sustainability should be a core principle integrated into all product and technology design processes.

This perspective was personally consolidated during the final degree project, which focused on developing a simulation tool to explore the use of a passive radiative cooling material capable of transferring excess heat into outer space through infrared thermal radiation. It employed the large temperature difference between Earth and space to cool surfaces even below ambient temperature without using energy. This project demonstrated that technology can be a driver of sustainability, opening the door to continue developing solutions that help mitigate the environmental impacts of human activity.

With this prior experience, the need to expand the focus toward sustainable product design became clear. This is a field that is considered fundamental for the future of industry from an engineering perspective. It was during this process that the concept of absolute sustainability was discovered. This approach involves creating products and processes that not only minimize environmental impacts but also preserve natural resources and ecosystems in ways that ensure long-term sustainability and regeneration for future generations. This concept is closely related to the planetary boundaries framework, which defines the limits within which the Earth system can safely operate. Crossing these boundaries could initiate irreversible consequences for the planet and for humanity, including uncontrolled climate change, biodiversity loss, and ecosystem collapse. Absolute sustainability means designing products that not only reduce impact but also actively help maintain these boundaries, operating within a safe operating space that preserves the regenerative capacity of natural resources.

Upon discovering this concept, it became clear that there are currently very few practical studies or applied industrial methodologies that integrate product design with absolute sustainability. Although sustainability is increasingly recognized as a global necessity, most industries have yet to adopt this approach in a systematic and meaningful way. We are facing a climate emergency that is no longer a future threat, but an immediate reality. Climate change is accelerating, and despite global efforts to reduce emissions, the established targets are not being met. Society continues to cross planetary boundaries at a dangerous pace, and without urgent and determined action, we risk losing the Earth as we know it.

The motivation behind this project is clear: to contribute to the creation of truly sustainable products, starting with a common item such as a mop. The goal is to demonstrate that it is possible to design absolutely sustainable products from scratch, not only by improving existing ones but by creating new and innovative solutions that comply with planetary boundaries and the safe operating space. This will help significantly reduce environmental impacts. This work represents an opportunity to lay new foundations for absolutely sustainable product design in a relatively unexplored field and to contribute to the development of more environmentally responsible industrial methodologies.

1.2 Goals

The main objective of this project is to integrate the principles of absolute sustainability into the product design process and validate how they can be applied in practice, not only as an innovative product but also as a proof of concept that can serve as a guide for future industrial designs that are absolutely sustainable. To achieve this, the specific objectives of the project are as follows:

- Evaluate the environmental impact and absolute sustainability of the existing product: The initial objective is to conduct a thorough analysis of the current product to identify areas where its environmental impact can be reduced. This analysis will include the use of Life Cycle Assessment (LCA) methodologies to measure the environmental impact of the product from its manufacturing to the end of its useful life. Additionally, this evaluation will assess whether the product meets the principles of absolute sustainability, providing a foundation for the subsequent goals.

- Develop and validate a product design methodology that incorporates absolute sustainability: Based on the analysis of the existing product, the main objective is to develop a new product that integrates as many of the defined specifications as possible, with absolute sustainability as the central and guiding specification. The Product Design and Development (PDD) process will ensure that these requirements are carefully studied for the final product and that the principles of absolute sustainability are integrated into its design and performance.

- Develop tools to facilitate future absolutely sustainable designs: The project aims to create practical tools and recommendations for applying this methodology to future designs in other industries. This could motivate industries to shift towards more responsible industrial practices that respect planetary boundaries and promote long-term sustainability, ultimately improving global sustainability in industrial production.

With these objectives, this project does not claim to deliver a final product that is absolutely sustainable, but rather to provide a structured approach for integrating absolute sustainability into product design. This will contribute to the broader goal of transforming the industrial sector towards environmentally responsible production models.

2. LITERATURE REVIEW

In this second chapter of the research work, the theoretical foundations underpinning the research field of this master's thesis are explored. The aim is to provide a broad context and review the core themes of this study in order to help the reader understand the issues that will be analysed in depth throughout the thesis. The key topics presented include the stages of the product design and development process, the evolution from relative to absolute sustainability and how absolute sustainability is applied in product design.

2.1 Product design and development process

A *product* is everything a company creates and sells to its customers. A *process* is a sequence of steps that transforms a set of inputs into a set of outputs. Therefore, the *product design and development process* refers to the set of activities carried out from identifying a market opportunity to selling the product. This process includes defining the actual design and establishing all the necessary details for its production and distribution. Successful product development is achieved when the product is cost-effective but also meets the customer needs, the standards for quality, development time, functionality and development capability. However, other aspects such as safety and environmental impact are becoming increasingly important. Thus, balancing performance with additional considerations is crucial for achieving successful product development [11], [12].

For any company that manufactures and sells physical products, product design is of great importance and impacts almost all aspects of the business: from the most obvious and direct ones, such as marketing, research and development (R&D), and new product development, to logistics, sales, public relations, and customer service, among others. The design of the product itself is the most important and distinctive individual representation of the brand. This is why product design is increasingly regarded as a fundamental strategic tool for companies, not only to attract consumers but also to foster greater loyalty towards the product [13].

There are all kinds of products. Below, *Table 1* presents the different types of products along with a brief explanation. It is important to note that this is a fluid and overlapping classification, far from being unique or complete, which is why some products could appear in one or more sections [13].

Table 1. Example of a general product classification based on market type, properties, and final functions (adapted from [13])

TYPES OF PRODUCTS	DESCRIPTION	EXAMPLES
Consumer durables	Such products must perform well, look appealing, and be cost-effective. Their design often involves multidisciplinary teams of designers, engineers, and manufacturing specialists	These include items like appliances, vehicles, computers, and furniture.
One-off artistic works	For these types of products, appearance is the most important aspect, above the product's own functionality.	These are products designed as art pieces or limited editions, but so are an iPod or a Coca-Cola bottle.
Consumables	For these products, the most important task of the product designer is the packaging, branding, and marketing, rather than the consumable product itself.	Examples of these include butter, bottled water, or motor oil.
Stock items	These are raw materials used in the manufacture of other products. Product designers may be involved in embossing, surface texture, and finishes for other products.	Raw materials like metal rolled sections, rod and bar stock, plastics, woven sheet, and laminates.
Industry products	Such products are bought by manufacturing companies for assembly into their own products. Functionality and performance are essential, while appearance is secondary.	Items such as ball and roller bearings, electric motors and controllers, circuit boards, and gas turbine engines.
Industrial equipment products	These are self-contained machines designed to perform complex functions within industry. The focus is on performance and functionality rather than appearance.	Examples include industrial work-stations, machine tools, earth-moving machinery, and passenger aircraft.
Special purpose products	These products are designed for specific functions and often made to order. They tend to focus on specialized needs, which is why designers must be flexible and adapt to different tasks.	Items like military equipment, space exploration devices, or custom-built machinery.
Industrial plant	These refer to large-scale facilities or installations involved in manufacturing or industrial operations	Examples include power plants, refineries, or chemical processing plants.

An alternative product classification categorises various product types and their characteristics, as outlined in *Table 2* [12].

Table 2. Example of a product classification focused on development processes and Technology (adapted from [12])

TYPES OF PRODUCTS	DESCRIPTION	EXAMPLES
Technology-Push Products	Start with a given technology and match it to a market opportunity. They contain basic materials or process technologies. However, they are unlikely to succeed unless the proposed technology offers a clear competitive advantage, and competitors lack suitable alternatives or face significant challenges in using them.	Artificial veins, insulation for electric cables, outerwear fabrics, dental floss, bagpipe bag liners
Platform Products	Products based on an existing technological subsystem, previously developed for other applications, which can be adapted to new markets.	Intel chipset, Apple iPhone operating system, Gillette razor blade design
Process-Intensive Products	The production process imposes very strict constraints on product properties, requiring simultaneous development of the process design and product development. These products are produced in very high volumes and in bulk.	Semiconductors, food, chemicals, paper
Customized Products	Slight variations of existing standards, modified to meet specific customer requests by altering the design, dimensions, and/or materials. Typically, they follow a highly defined, detailed, and often automated development process.	Switches, motors, batteries, containers
High- Risk Products	Products with high technical or market risks. Generic processes are modified to address risks early on. Parallel exploration of multiple solutions ensures at least one succeeds.	Nuclear fusion technologies, advanced medical devices, autonomous drones
Quick-Build Products	Products with rapid build-and-test cycles, enabling multiple iterations for a flexible and fast market response.	Software, electronic products
Complex Systems	Large-scale products with many interconnected subsystems and components. Development is conducted in parallel with specialized teams focusing on system integration.	Automobiles, airplanes

Both classifications define categories based on key product functions or characteristics, such as durability, industrial use, or customization. However, the first classification adopts a more general perspective, focusing on market types or the final properties and functions of the product, while the second focuses on a process and technology-oriented approach.

These two classifications exemplify different methods for organizing and understanding product types in specific contexts. Nonetheless, many other classifications may exist due to the extensive variety of products, each adapted to fulfil particular requirements, such as market strategies, industrial processes, or design methodologies.

2.1.1 Stages of Product Development

Product development, like any other process, is highly effective if it is well described and specified. One of the advantages is that it allows for excellent coordination and collaboration among all participants, as well as effective planning of the project's stages, key points, and timelines. It also ensures product quality by meticulously selecting the process's inspection points. Furthermore, having all the necessary information organized and recorded is key to identifying opportunities for potential improvement ([12], [14]).

The generic product development process essentially consists of six phases. It begins with the planning phase, followed by concept research, system-level design, and then detailed design, testing and refinement, and finally, production. *Figure 1* shows a diagram of these six phases.

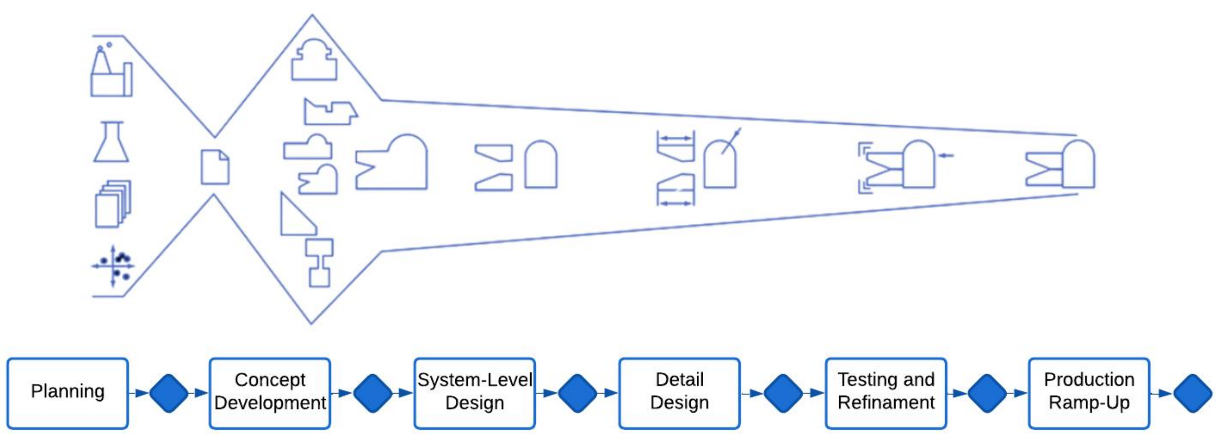


Figure 1. Generic product design and development process (adapted from [12])

The planning phase is also known as the "phase zero" since it is when the project is approved. Once opportunities, relevant technological developments, and market objectives have been identified, the product is specified, leading the way for the next phase ([12], [15]).

The concept development phase serves as a fundamental framework for the development process, acting as the foundation from which the project will take shape. In this phase, the needs of the previously defined target market are thoroughly identified and translated into actionable design goals. It also sets the direction and scope of the project, providing a structured pathway for the subsequent design and development stages. Key activities in this phase include identifying customer needs to ensure that the product will address actual demands and expectations, defining detailed product specifications that will serve as design and performance benchmarks, and generating a range of possible concepts that explore different design solutions. Following this, the most promising concepts are carefully evaluated and rigorously tested to validate their feasibility and alignment with project goals. These methods guide a team from a mission statement through a selected product concept ([12], [16]).

During the system-level design phase, the product is detailed into subsystems, and initial plans for the production system are created. In this phase, the geometric design of the product is developed, a functional specification for each subsystem is defined, and a preliminary process flow diagram for final assembly is prepared [12].

In the detailed design phase, all necessary specifications for geometry, materials, and tolerances of all product components are included, as well as all standard parts that will be sourced from suppliers. At this stage, product drawings, specifications for purchased parts, and manufacturing and assembly process plans are created ([12], [13]).

Next is the testing and refinement phase, where various versions and prototypes are developed. These prototypes are tested to determine if the product meets the needs and fulfils the established requirements, as well as its primary function. Subsequent prototypes are thoroughly evaluated, including testing by actual customers. Final questions are addressed, leading to the final product ([12], [17]).

The final phase is production, where the product is created using the predefined production system. Employees are trained, and any outstanding issues are resolved. The first products are provided to selected customers and carefully evaluated. Gradually, production is scaled up, and the product is launched. Afterward, a postlaunch project review is conducted, identifying ways to improve the development process for future projects [12].

Nevertheless, as already mentioned, these are the general phases, and the more specific processes are defined based on the unique context of the product and the company. For example, when it comes to technology-push products, which is one type of product classification, there can also be further subcategories based on different characteristics [12]. These characteristics may require changes to be made in the product development process.

It is also essential to emphasize the importance of review and checkpoints. After each stage, a thorough assessment must be conducted to verify and approve that the phase has been successfully completed and to ensure the project remains on track. The following *Figure 2* therefore, illustrates the complete process flow diagram, including the respective checkpoints, that is typically implemented in a generic product development process.

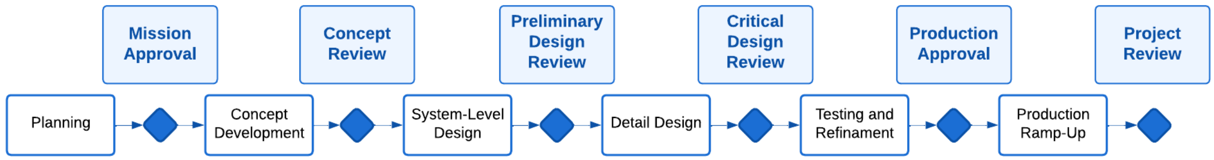


Figure 2. Generic product development process (adapted from [12])

Nevertheless, as previously mentioned, the product design process is adapted to the specific needs of each case. For instance, if the stages of design, prototyping, and testing are carried out more than once, this repetition will be clearly reflected in the process flow diagram. *Figure 3* illustrates this scenario, showing how certain phases may occur multiple times. It also presents another common situation in which different phases are developed in parallel. These examples demonstrate the flexibility of the design process and how it can be reflected in the flow diagram according to the requirements of each project.

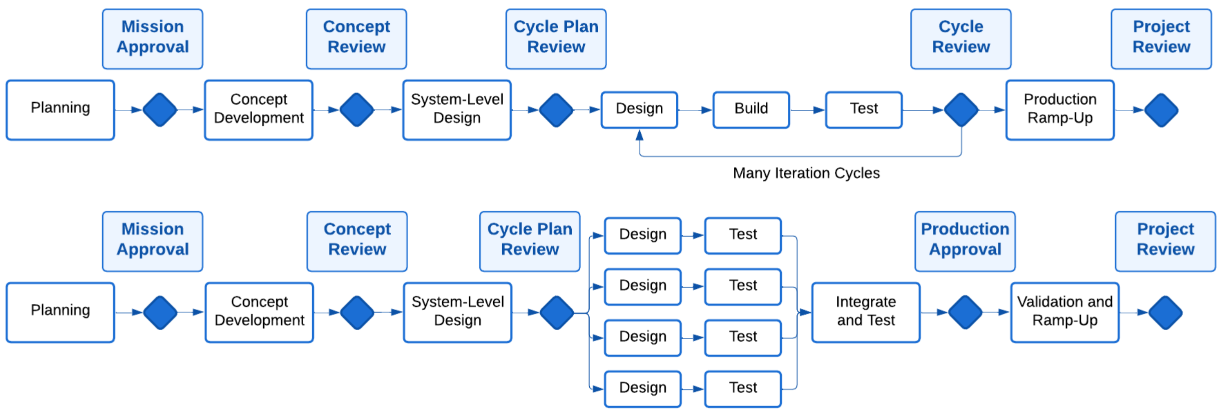


Figure 3. Examples of the flexibility of the design process (adapted from [12])

2.1.2 General Principles of Detail Design

One of the most important stages in product development is the design stage. As such, design plays a role in many parts of the overall process. First, there is the brief, which identifies the customer's needs. Based on this, the Product Design Specifications (PDS) are completed. The concept design phase itself follows, during which ideas are generated, sketches and drawings are produced, and the concept is evaluated. After that is the design development phase, where technical drawings are created and prototypes are built. Finally, there is the detail design phase, which focuses on exploring materials, manufacturing techniques, testing, and refinement ([12], [13]).

The concept development phase involves a series of interconnected activities that transform initial ideas and market needs into viable product concepts. These activities provide a structured framework to ensure that the final design addresses functional and technical requirements. This section explores the key activities that define concept development: Identifying Customer Needs, Product Specifications, Concept Generation, Concept Selection, and Concept Testing [12]. Each of these steps plays a crucial role in guiding the design process towards solutions that are innovative, feasible, and environmentally responsible.

The first step in concept development is Identifying Customer Needs. This step is very important because it determines the requirements of the product. Therefore, the main objectives of this phase are to ensure that the product focuses on the customer's needs, to identify both latent or hidden needs as well as explicit ones, and to provide a database to justify the product specifications [12]. It is also important to organise the needs in a hierarchy and establish a relative importance among them. Once all of these needs have been identified, it is necessary to reflect on the results and the process itself [12].

Normally, customer needs are expressed in subjective terms. For this reason, development teams usually establish them in precise and measurable details, translating them into specifications [12]. The term *product specifications* is used when making a precise description of the necessary characteristics of the product [12]. A document called Product Design Specifications (PDS) is created, which outlines the current design objective in detail, describing the problem but not the solution [13]. It breaks the problem down into smaller categories, where all measurable properties must be specified as precisely as possible, including their allowed tolerances [13]. For this reason, the product designer must regularly consult the PDS to ensure that all design proposals are appropriate. Likewise, the customer or end-user group must agree on every detail in the document. Moreover, the PDS is a dynamic document, meaning it can be reviewed and updated if necessary, as long as all parties involved agree on the changes [13].

The next stage is Concept Generation that includes sketches, prototypes, and detailed descriptions in order to create a product that fully meets the customer's needs and can be successfully commercialized. From an economic point of view, it is estimated that around 85% of the total product cost is determined during the concept design phase alone [13].

Moreover, design can be carried out through convergent or divergent thinking [13]. In the first case, the design is developed sequentially, while in the second, all possible solutions are explored laterally to generate multiple pathways, ultimately arriving at the solution best suited to the requirements and needs.

Successful designers use various generation techniques that involve extensive research to understand the product's needs and meet the requirements of the PDS. These methodologies help clarify the design objectives, structure the design process, and find the inspiration needed to generate fresh ideas ([18], [16]). Therefore, methodologies are a key element of this phase, although none of them guarantees a solution to the problem [13].

One of the most widely used techniques among design teams is brainstorming, which is highly effective for quickly generating a large volume of ideas [18]. Brainstorming allows for creative and innovative thinking, encouraging the generation of surprising and unconventional proposals. The core principle of this technique is that all ideas are considered valid, no matter how unusual they may seem ([18], [19]). The focus is on quantity rather than quality to help overcome mental blocks and fosters an open-minded, collaborative atmosphere within the team.

Designers also use mind maps ([18], [20]). These are diagrams used to link ideas starting from keywords or other reference points. They work like concept maps, where a main idea is written in the centre, and related ideas are added around it in a radial structure. This helps organize thoughts clearly by identifying connections between concepts, which supports both problem-solving and decision-making processes ([18], [20]). Mind maps are also useful for presenting complex information in a simpler and more visual way [20]. Their easy-to-understand format helps improve communication, making it easier for teams to share ideas and clarify concepts.

In addition, there are other techniques used to generate ideas, such as the breaking the rules method. This approach allows designers to temporarily challenge conventional norms by breaking established rules, which encourages more radical and creative thinking [13]. Another known technique is lateral thinking, which focuses on shifting perspectives and moving away from traditional step-by-step logic [13]. Another would be the technique of reverse thinking that involves flipping your assumptions and thinking about a problem differently, with the possibility of reveal hidden assumptions [18]. These methods help open up new ways of thinking and support the exploration of unconventional solutions to design problems, along with many other techniques that are also commonly used.

During the concept generation phase, quick sketches also play a very important role. These are highly effective for presenting ideas and making communication easier within the team. Designers often need to translate a concept from a three-dimensional idea into a two-dimensional sketch, and then back into a three-dimensional representation of that idea [13]. In the design development stage, CAD (Computer-Aided Design) plays a key role in helping designers resolve complex issues and refine their ideas with greater precision [13].

At this stage, the process of Concept Evaluation begins. This is the point where the design process moves from being mainly creative and divergent to becoming more structured, analytical, and convergent [13]. Instead of generating new ideas, the aim is now to assess and refine those that have already been proposed. The different proposals are reviewed, combined, and improved, gradually leading to the development of a single, well-defined solution that best meets the overall goals of the project [13]. To support this decision-making process, a set of clear evaluation criteria is defined based on the project's initial requirements. This stage is crucial for narrowing down alternatives and ensuring that the final solution is not only innovative, but also avoids subjectivity and aligns with the project's practical needs.

Finally, comes the Detail Design phase where the selected concepts are transformed into a fully detailed design with the necessary dimensions and specifications for manufacturing the product ([12], [13]). In other words, the concept is turned into a set of manufacturing drawings and documentation. The detail design process consists of five basic steps. Product subdivision is the first step, where the design is broken down into smaller parts. The second step involves designing and selecting the components needed for the product [13]. After that, in the integration of parts step, these components are brought together into the final product layout. Product prototype testing follows, ensuring the design works as intended through testing. Finally, the completion of release drawings provides all the necessary information for the manufacturing process, including dimensions, materials, and processes [13].

In conclusion, designing a product involves many complex steps, from the initial idea to final production. While technical aspects are essential, designers must also consider the impact of their work. Social, cultural, and ethical considerations all play a key role in promoting responsible design [12]. For this reason, sustainability is becoming increasingly important, and it must be considered to create products that are not only functional and attractive, but also environmentally and socially responsible.

2.2 Sustainability

Sustainability is a widely recognised concept today and is commonly defined as an approach that can meet the needs of present generations without compromising the ability of future generations to meet their own needs, while ensuring a balance between economic growth, social cohesion, and environmental protection ([21], [22], [23]). Although this may seem like a matter of caution, it is more a question of equity, involving a moral obligation towards future generations, rather than immediate self-interest. In fact, sustainable development involves not only equity between generations, but also equity within the same generation.

Although it seems like a widely recognised concept today, it has not been explored or adopted extensively until the last decades. The concept of sustainability, in a form similar to how we understand it today, was first introduced by the World Council of Churches in 1974, where it was stated that social stability could not be achieved without the fair distribution of all that is scarce [24], among other claims. In addition, Western ecologists proposed this idea of a "sustainable society" as a response to growing global environmental concerns, at a time when many people around the world were living in poverty and in very difficult circumstances [24].

The term sustainable development emerged from the International Union for the Conservation of Nature and Natural Resources in 1980 and gained real significance in 1987, when the United Nations World Commission on Environment and Development, published the report Our Common Future [25]. The key recommendation of this document, widely known as the Brundtland Report, was the need for a new approach to sustainable development that could balance the demands of environmental protection and economic growth. This led to the already mentioned definition of sustainable development as the ability to meet present needs without compromising the ability of future generations to meet their own needs [6]. The starting point of the concept of sustainable development was the goal of integrating ecological thinking into economic policy. More deeply, it was conceived as an effort to bring ecological ideas into the centre of politics, which in the modern world is mainly focused on economics. The slogan sustainable development was quickly adopted by governments and international agencies, and at the United Nations Conference on Environment and Development (UNCED), held in Rio de Janeiro in 1992, world political leaders expressed their support for this goal [25].

More recently, ecological economists have defined sustainability in terms of not exhausting capital [24]. They argue that we are currently depleting the Earth's "natural capital," and in the words of green economist Herman Daly, treating the world as if it were a business in liquidation [24]. However, there is disagreement about how far technological progress can allow human-made capital to replace natural capital, and about how strictly the idea of preserving natural capital should be followed [24].

On the other hand, due to limited knowledge about nature and about the future potential of science and technology to solve problems, economists tend to calculate average risks, often ignoring or downplaying worst-case scenarios and recommending risky strategies for the future of the environment [24]. In contrast, ecologists emphasize worst-case outcomes and call for greater efforts to prevent them [24]. As a result, equity problems can also be found within the same generation.

In 2015, the United Nations adopted the 2030 Agenda for Sustainable Development, which outlines three key dimensions of sustainability: social, environmental, and economic, reflected in the concepts of people, planet, and profit. The agenda includes 17 Sustainable Development Goals (SDGs) to be achieved by 2030 [6], [27].

Figure 4. The 17 Sustainable Development Goals (SDGs) [23]

This initiative led to agreements such as the Paris Agreement, which aims to limit the impacts of climate change by keeping the increase in global temperature close to 1.5°C above pre-industrial levels. Later, in 2020, the same countries that signed the Paris Agreement were required to present more ambitious targets, as the previous ones would not be sufficient to reach the goal of a maximum 1.5°C increase by 2030 [26]. Thus, the period between 2020 and 2030 is referred to as the Decade of Action [26].

In conclusion, sustainability has evolved from a response to environmental and social concerns into a key concept for addressing global challenges. While it aims to integrate environmental, economic, and social dimensions, its definition remains ambiguous and open to various interpretations, making consistent and effective implementation a continuing challenge.

2.2.1 From relative to absolute sustainability

Although sustainability has become a key frame of reference for addressing global challenges, its definition remains, to some extent, ambiguous and open to multiple interpretations. This highlights the need to rethink and redefine the concept so that it can more clearly guide policies and actions aimed at ensuring a real balance between economic development, social justice, and environmental preservation, both for present and future generations.

The problem lies in the fact that the Earth's natural resources are finite and that there is a limited capacity of the environment to absorb pollution. This is why, from a broader perspective on climate stability, Rockström [2] and later Steffen [3] identified nine planetary environmental processes that are considered essential for planetary self-regulation and the stability of environmental conditions. For each process, they proposed a "safe operating space" determined for specific control variables defining the planetary boundaries (PBs). These boundaries cannot be exceeded so as not to compromise the stability of our natural systems. Violating one or more PBs may lead the Planet to abrupt and irreversible changes [28]. Some PBs have already been exceeded, and it is crucial to reduce impacts to levels below these boundaries. This is based on the assumption that, in the long term, lowering human pressure on these processes will help bring them back within the safe limits [28].

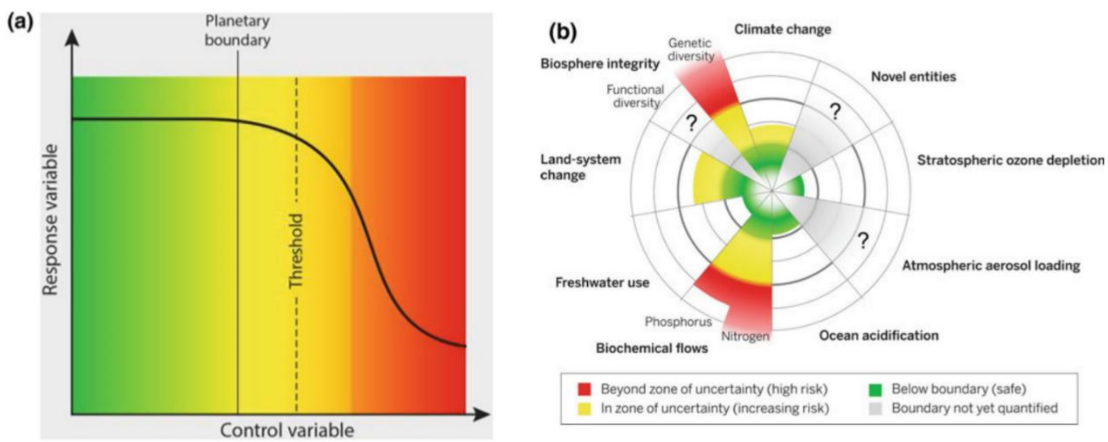


Figure 5. (a) Illustrates the concept of thresholds and boundaries in relation to an ecosystem's response to increasing human pressure. (b) Shows the proposed nine boundaries (two of them subdivided for specific pressures) and that mankind has currently exceeded four of them, two beyond the zone of uncertainty. Font: [6]

Nevertheless, determining which part of the environmental or resource space an individual country or company can claim requires an allocation based on the science-based boundaries, like the PBs framework, and sharing principles.

The Safe Operating Space (SOS) is defined as the difference between the Planetary Boundaries (PB) and the pre-industrial level [28]. The pre-industrial level represents the natural state of environmental conditions before significant human impact. This concept quantifies how far the planet has deviated due to human activities and provides a reference point to restore safe environmental limits [28].

To make the SOS concept practical and apply it to smaller scales such as countries, companies, or products, this limited safe space must be allocated. This allocation is guided by ethical principles and distributive justice that determine how to share the limited environmental resources fairly [28].

Various methodologies have been developed to determine and allocate the Safe Operating Space (SOS) for specific contexts. These approaches vary depending on the allocation principles chosen, analytical tools, and the scale of application. Despite their diversity, they share common challenges and limitations that must be addressed to ensure robust and consistent sustainability assessments.

The most common allocation principles used to assign the SOS are:

- Egalitarian (per capita): The egalitarian principle proposes distributing resources equally among all individuals or units, regardless of their historical emissions or current needs. This principle is based on the idea of equality, assuming that each person has the same right to the planet's limited resources. When compared with other approaches, this stands out for its simplicity and ease of application, but also for not considering inequalities between countries or economic sectors when using the resources [28].

- Utilitarian: The allocation aims to maximise total aggregate benefit, prioritising agents or entities that can use resources more efficiently or generate a greater collective good [28]. Thus, those agents that can use resources more efficiently to generate the greatest total benefit are prioritised. An example of this approach is the allocation of SOS to large economies like the European Union, the United States, and China [29]. In this case, economies with greater capacity to maximise the common good are prioritised, encouraging economic efficiency but disadvantaging poorer countries or those with less capacity to generate economic benefits.

- Needs-based: The needs-based principle assigns more resources to those with greater needs to ensure a minimum level of welfare or development [28]. This seeks to correct existing inequalities and guarantee that no one falls below a minimum sustainability threshold. A clear example of this principle is found in a study that developed the 'Fulfilment of Human Needs' (FHN) principle as a sharing principle that operationalises sufficientarianism (making sure everyone gets enough) [30]. This principle is tested in two case studies (a food item and a textile) against four of the PBs: climate change, land-system change, water use, and nitrogen cycling.

- Grandfathering (based on historical emissions): Allocation is based on previous resource use, giving more quota to those who were major emitters or consumers in the past [28]. This approach is based on the idea of recognising historical responsibilities. International climate agreements such as the Kyoto Protocol [31] or the Paris Agreement [32], reflect this principle indirectly as they allocate more emission quotas to developed countries that are responsible for the majority of greenhouse gas emissions. This principle was used to give companies some time to adapt to new regulations.

These different ways of allocating the SOS influence the results of sustainability assessments. This phenomenon is known as ethical dependence. It means that absolute sustainability is not a single objective measure. Instead, it depends on the ethical and normative perspective chosen to allocate the environmental space. Therefore, two assessments applying different allocation principles can reach different conclusions about the sustainability of the same product or service.

After identifying the core concept of absolute sustainability, it becomes clear that achieving it requires not only reducing environmental impact but also ensuring that this reduction keeps the impact within scientifically established safe limits. This is why optimizing technologies that, by their nature, cannot meet these requirements is counterproductive [33]. An example of this is internal combustion engines. Despite improvements in fuel efficiency, these technologies still rely on fossil fuels and therefore can never be considered absolutely sustainable. As such, resources have been allocated to refining a technology that cannot provide a long-term environmentally friendly solution, when instead they should be invested in technologies such as electric or hydrogen vehicles, which have the potential to meet the criteria of absolute sustainability.

Therefore, it is important to understand that optimizing a product to slightly reduce its environmental impact may seem like a step in the right direction, but this approach does not guarantee that the product is sustainable in absolute terms. A relative reduction in impact may improve internal performance indicators for a company, but it does not ensure compliance with planetary boundaries. In fact, efficiency improvements may lead to unintended consequences, such as the so-called rebound effect: greater efficiency reduces the cost of using a resource, which may ultimately encourage increased consumption and cancel out the initial environmental benefits.

2.3 Design for Sustainability

Since the Industrial Revolution, factories marked the beginning of large-scale environmental change. Burning fuels to power machinery was the first alarming practice that introduced unprecedented levels of air pollution and greenhouse gas emissions into the atmosphere. In addition, the development of factories led to massive migration to urban areas, forming large industrial cities known for their unhealthy air quality [8].

Today, factories are one of the main contributors to air pollution, which contributes to climate change, smog, and acid rain, serious environmental and health risks. Industrial processes account for 24% of global annual CO_2 emissions, according to the Environmental Protection Agency [34]. They also release volatile compounds, dust, fine particles, and hazardous air pollutants (HAPs). Furthermore, factories use around 22% of the world’s freshwater supplies, most of which is released as untreated wastewater into aquatic ecosystems [35]. In addition, industrial waste makes up a significant part of the 2 billion tons of global waste produced every year, much of which ends up in landfills or the ocean [35]. Moreover, the industrial sector represents about 37% of global energy consumption.

Because of all this, industries must focus on shifting their culture to prioritize environmentally friendly practices, where zero tolerance for polluting activities becomes the key decision-making factor. Factories must adopt renewable energy and circular economy models, or they risk losing customers, as studies show that 88% of consumers prefer companies with sustainable practices [8]. Therefore, it is not just a moral obligation, but also a survival strategy. Adopting sustainable manufacturing is the only way forward, and the data proves it.

Corporate Social Responsibility (CSR) is a concept that has been established across different fields like business, universities, and governments. The idea of CSR originated in academia in 1953 with the book Social Responsibilities of the Businessman by Howard Bowen, which was the first to question what responsibilities businesspeople should or should not assume towards society. This concept points out that large companies have a concrete impact on a significant number of people, making it necessary to link policies and decision-making in firms to society's goals and values. Later, in the 1960s, Davis proposed that the responsibility of companies is proportional to the amount of power they have over society. Therefore, companies with greater economic influence or closer ties to certain power groups have greater social responsibility [36]. Later, in 1971, Victor Papanek published Design for the Real World, where he demanded that industries and designers face their global, social, and environmental responsibilities [13]. In 1999, Herman Miller created a design for environment (DfE) team responsible for developing more environmentally sensitive designs [12].

Although the debate about companies' responsibilities to society has existed for more than half a century, it had not reached today's global dimensions. The production and use of the huge number of consumer products available today is a major cause of pollution, deforestation, and global warming, all of which threaten our environment [13]. The term *green design* has been replaced by *sustainable design*, intensifying the need for a more serious focus on today's environmental problems [13].

One of the key aspects in achieving truly sustainable design is to incorporate environmental objectives from the very beginning, the product planning phase [12]. At this initial stage, the needs that the product must meet are defined, as well as the technical, economic, and environmental constraints that must be considered throughout the entire development process. If environmental goals are not addressed at this point, it becomes very difficult to implement meaningful changes later, when most design decisions have already been made [12].

Design for Environment (DfE) objectives serve as guidelines or checklists to ensure that the final product minimizes its ecological impact throughout its entire life cycle [12]. These objectives can be applied across different stages, from material selection to product recovery after its useful life has ended. The *Table 3* below shows specific examples of DfE goals organized by life cycle stage: materials, production, distribution, use, and recovery. These criteria not only help reduce environmental impacts but can also lead to economic and operational benefits, such as lower material costs, increased energy efficiency, and improved waste management [12].

Table 3. Example DfE goals, arranged according to the product life cycle stages (adapted from [12])

LIFE CYCLE STAGE	EXAMPLE DESIGN FOR ENVIRONMENT GOALS
Materials	- Reduce the use of raw materials - Choose plentiful, renewable raw materials - Eliminate toxic materials - Increase the energy efficiency of material extraction processes - Reduce discards and waste - Increase the use of recovered and recycled materials
Production	- Reduce the use of process materials - Specify process materials that can be fully recovered and recycled - Eliminate toxic process materials - Select processes with high energy efficiency - Reduce production scrap and waste
Distribution	- Plan the most energy-efficient shipping - Reduce emissions from transport - Eliminate toxic and dangerous packaging materials - Eliminate or reuse packaging
Use	- Extend useful product life - Promote use of products under the intended conditions - Enable clean and efficient servicing operations - Eliminate emissions and reduce energy consumption during use
Recovery	- Facilitate product disassembly to separate materials - Enable the recovery and remanufacturing of components - Facilitate material recycling - Reduce waste volume for incineration and landfill deposit

Another related concept is Design for Sustainability (DfS), whose main goal is to create and redesign products that use minimal resources and have reduced impacts on the environment, society, and human health, while also ensuring economic viability [37]. There are multiple design principles that support DfS. For example, dematerialisation aims to reduce raw materials, energy, material input during use, and waste. Modular design is another approach that enables components to be used across multiple products [38]. These examples are highlighted because they illustrate how design decisions can contribute directly to reducing resource use and environmental impacts. Another widely discussed principle is lightweight design (LWD), which aims to increase resource efficiency in products by reducing weight. However, this can sometimes conflict with other key DfS goals such as ease of disassembly and repairability, though there are already studies addressing this issue [37].In conclusion, there are many different techniques and methods to apply sustainability in product design, but they all aim to improve technologies that may never be fully sustainable in an absolute sense, as mentioned earlier. Therefore, every product still has an environmental impact.

2.3.1 Absolute Sustainability in Product Design

Until now, the current approach to sustainability in product design has focused on minimising impacts in comparison with past performance rather than aiming for absolute sustainability goals. Most studies tend to prioritise incremental improvements within existing systems, often without questioning whether these efforts are truly sufficient [39]. This reveals a growing gap between what is labelled as "sustainable" in theory and what is actually achieved in practice [40]. Many projects labelled as sustainable may not bring about significant environmental benefits when assessed against absolute sustainability criteria. This discrepancy can lead to a false sense of progress, where the sustainability label is used without a critical evaluation of the real ecological impact or a commitment to systemic change. It is therefore essential to redefine sustainability objectives in product design, shifting them towards planetary boundaries and deep transformations rather than settling for incremental improvements within the current system.

Although the literature on absolute sustainability in product design is still limited, there are several studies that have begun to explore this concept and apply it to real-world cases. For example, one study examines the environmental impact of conventional and modular buildings in Australia and Denmark, aiming to assess whether they meet the established planetary boundaries [41]. This work focuses on evaluating the current situation and identifying the life cycle stages with the highest impact, such as the energy used during the building's operation. While it suggests that reducing operational energy could be a potential improvement, it does not propose a concrete solution or calculate the precise impact of such changes.

Another study has looked at how the apparent sustainability of a product varies depending on the principle used to share the safe operating space. This is illustrated by a study on the production of short rotation coppice poplar wood panels in Austria and Slovakia [42]. Rather than selecting a single best method, the study highlights that the choice of sharing principle has important implications and requires deeper ethical and technical debate. In this case, although the results show how they change depending on the principle applied, the study does not discuss which method is better, nor does it propose specific improvements or assess whether these would bring the product within planetary boundaries.

Another study analyses material dissipation in the construction sector, introducing the concept of dissipation carrying capacity to quantify whether the irreversible loss of materials (such as iron or aluminium) in the life cycle of a school building falls within absolute planetary limits [43]. The results show that in most cases, current dissipation rates exceed these limits, highlighting the need to review how materials are designed and managed to achieve absolute sustainability. The study points out the need to review design and material management practices, but does not propose specific changes or assess whether these would be viable or effective.

In contrast, another study focusing on electric vehicle batteries goes further by proposing a stepwise approach to determine absolute environmental sustainability targets [44]. In addition to analysing the current impact of the battery, it suggests concrete improvement strategies, such as changing suppliers of raw materials or adjusting production locations, and it quantitatively calculates the impacts of these changes in specific scenarios. The results show that these strategies can significantly reduce carbon emissions, but the product still does not reach absolute sustainability according to planetary boundaries. The study concludes that achieving absolute sustainability would require much deeper reductions and a more radical rethink of processes and components involved.

Finally, an approach based on planetary boundaries has been applied to assess the environmental impact of doing laundry at the European scale, using a case study of detergent with bio-based surfactants [45]. Emissions and environmental impacts of the activity were calculated and compared with the assigned safe operating space quotas. The study showed that even with improvement scenarios like more efficient washing machines or renewable energy sources, the activity still exceeds its quota and is not absolutely sustainable. It also underlines that the choice of sharing principle has a much greater impact on the conclusions than other sources of uncertainty, and concludes that much deeper transformations would be needed to ensure absolute sustainability.

Taken together, these studies show that although absolute sustainability is gaining attention, most of them focus only on measuring the current environmental impacts of products and identifying possible areas for qualitative improvement. Only in a few very specific cases has there been an attempt to quantify the impact of actual changes to see whether they truly improve sustainability in relation to planetary boundaries. Even in these cases, the results indicate that improvements are often insufficient or would require much deeper and more radical transformations. Despite the urgency of the current environmental situation, translating planetary boundaries into practical criteria for sustainable decision-making remains a complex challenge. Indeed, the need for practical tools and more robust methodologies has already been highlighted [46], with calls for a paradigm shift towards a more rigorous and boundary-based approach to environmental management. The message is clear: to move towards true absolute sustainability, it is not enough to measure current impacts. We also need to establish concrete criteria and practical tools that enable the design of products that operate within the safe operating space defined by planetary boundaries.

To respond to this challenge, this master's thesis sets out a methodology to explore how planetary boundaries can be applied concretely in product design. Through a detailed environmental impact analysis of a real-world example (a cleaning mop), the study identifies the life cycle stages that contribute most to environmental impacts. Based on this analysis, a complete redesign is proposed that prioritises recycled materials, modularity and the reduction of non-essential components. The aim is to minimise impacts and move closer to absolute sustainability. This project does not only aim to quantify the impact of a specific change, but also to show how absolute sustainability goals can start to be integrated in real industrial product design, establishing a foundation for future and more ambitious developments.

3. METHODOLOGY

Given the current lack of studies addressing absolute sustainability in product design, this project aims to explore a viable solution by developing an absolute sustainable product in collaboration with the well-known company Fapil. This chapter presents the overall methodology for this dissertation.

3.1 Overall Methodology

This study follows a structured and comprehensive methodology that combines theoretical analysis with practical product development, aligned with the goal of approaching absolute sustainability. To begin with, an in-depth literature review was conducted to define key sustainability concepts and identify relevant allocation principles grounded in distributive theories (including egalitarianism, utilitarianism, and others). In parallel, the mop was chosen as the case study in collaboration with Fapil, with plant visits and interviews providing detailed technical and user requirements.

Following this, a robust Life Cycle Assessment (LCA) was conducted using the Environmental Footprint (EF) method and SimaPro software, considering sixteen impact categories to quantify environmental impacts. These impacts were then compared with planetary boundaries using the EF method and applying three different allocation principles (economic cost, emissions, and energy consumption) that reflect various fairness perspectives. This enabled the calculation of the Assigned Share of Safe Operating Space (aSoSOS) for each mop model, which was subsequently used to determine the Absolute Sustainability Ratio (ASR) and assess whether each mop alternative remained within its fair share of the planet's safe operating space.

In parallel, the product development phase began with concept generation sessions, using methods like brainwriting and the SCAMPER technique to ensure a broad exploration of ideas. These ideas were then refined and evaluated using the House of Quality and selection matrices, balancing functionality, manufacturability, sustainability, and cost.

Once the most promising concept was identified, prototypes were developed using SolidWorks CAD models and 3D printing (Bambu Lab). This stage also included rigorous testing, validation, and iterative improvements, incorporating feedback from Fapil and academic supervisors to ensure both technical feasibility and market relevance.

Throughout this process, environmental impact considerations were integrated into every stage, ensuring that design decisions were consistently guided by sustainability principles and aligned with user needs and market requirements. The overall methodology followed in this work is summarised in the *Figure 6* below.

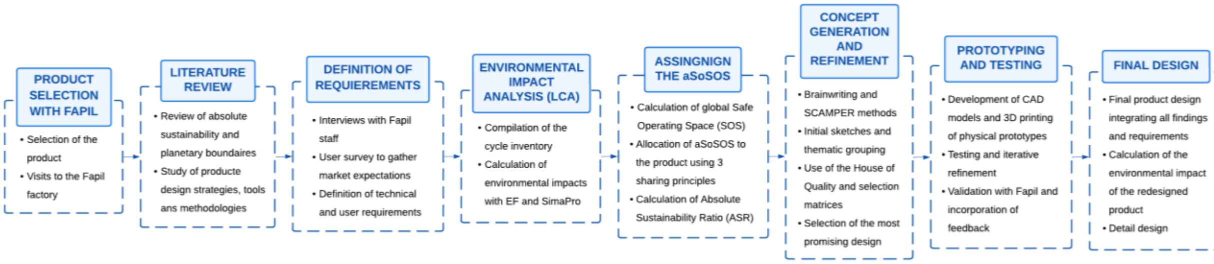


Figure 6. Methodology applied in the project

3.2 Environmental Analysis

To determine if a product is sustainable from an absolute perspective, a series of steps must be followed ([47], [48], [49]), starting with the quantification of environmental impacts throughout its entire life cycle and moving to the allocation of the share that belongs to it within the planet's safe operating space. This process combines the quantitative assessment of these impacts with the use of allocation principles that define how much of the global planetary limits can be assigned to a specific product. With this approach, sustainability is considered not only in relative terms but is directly linked to the capacity of the Earth system to maintain environmental balance.

3.2.1 Life Cycle Assessment

Life Cycle Assessment (LCA) is a well-established and standardised method, defined in the ISO 14040 [50], that assesses the environmental aspects associated with a product throughout its life cycle, from raw material extraction, through manufacturing and sales, to waste disposal [51]. This method is commonly used by companies and organizations to communicate their sustainability performance, as well as to compare products for internal purposes. The LCA study consists of four phases [52], [6]:

- <u>Goal and scope definition:</u> This phase defines which parts of the life cycle are to be studied. A product typically has five phases: raw material extraction, manufacturing, transport, use and sale, and waste disposal. All of these phases may be considered, or only some of them. Additionally, the specific objective of conducting the LCA is determined, along with the system boundaries, the target audience, the functional unit, and other relevant parameters.

- <u>Inventory analysis:</u> This is the data collection phase. It involves describing the material and energy flows within the product system, taking into account its interaction with the environment, the raw materials consumed, and the emissions produced. Inputs and outputs are quantified throughout the life cycle of the product.

- Impact assessment: In this phase, the results of the inventory analysis are translated into potential environmental impacts while estimating the resources used.

- Interpretation: Life cycle interpretation involves a critical review of the results, both at the end of the study and throughout all its phases.

Figure 7 shows the four stages according to the ISO 14040 guidelines.

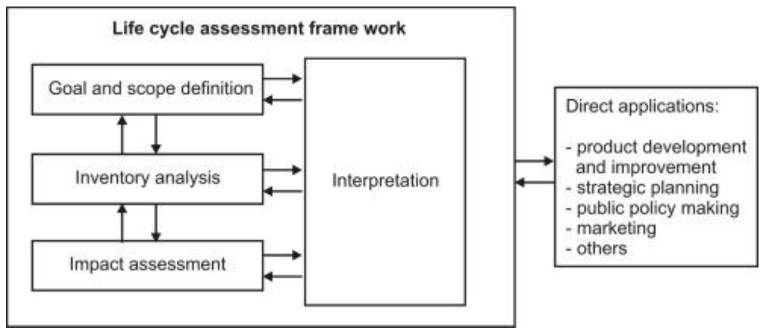


Figure 7. The four stages of LCA under the ISO 14040 guidelines from [51]

3.2.2 Assigning the share of the safe operating space

To assess whether a product is truly sustainable from an absolute perspective, it is essential to connect the environmental impacts of that product with the Earth's biophysical limits, known as planetary boundaries. To do this, the environmental impacts (calculated using the EF method) were directly compared with the thresholds that the Earth system can tolerate, using reference values for the planetary boundaries. It is important to clarify that while this study uses planetary boundaries as reference values to evaluate absolute sustainability, it does not apply the official control variables defined by the Planetary Boundaries framework. Instead, the approach compares the Environmental Footprint (EF) impact categories with carrying capacities, providing a more practical approach. This approach enabled a robust and scientifically rigorous assessment to determine whether the impacts stayed within the safe operating space for each environmental category [54].

This conceptual process is illustrated in *Figure 8*, which shows how the global safe operating space is first allocated to individual products or activities and can then be upscaled to assess larger units such as companies, sectors or nations. The diagram begins with the global planetary boundaries, which define the maximum safe environmental pressures. Through the process of allocation, a portion of this global safe operating space is assigned to each product, known as the Assigned Share of the Safe Operating Space (aSoSOS). This share represents the part of the global safe space that a specific product can "occupy" without exceeding the Earth system's capacity.

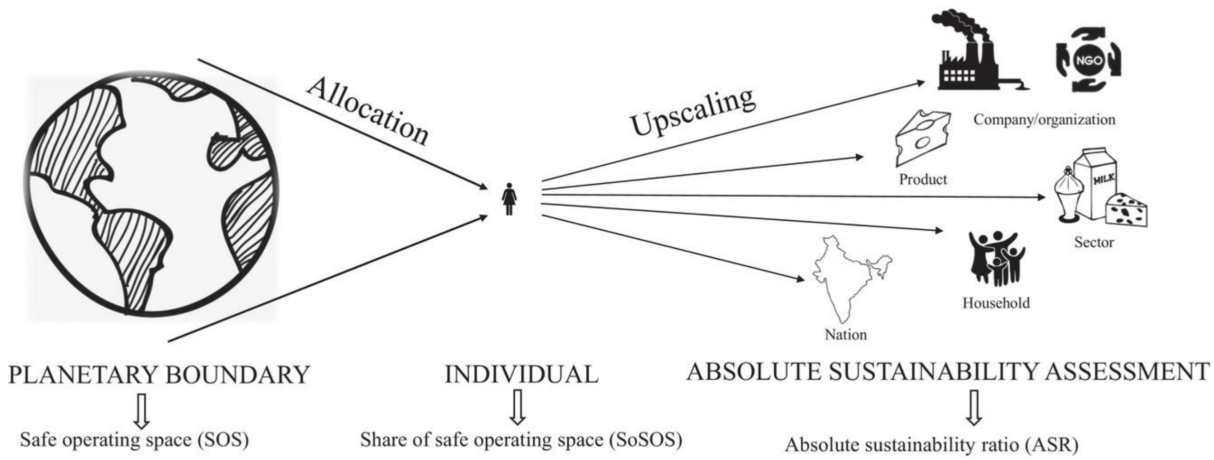


Figure 8. Downscaling from global to individual level, followed by upscaling to e.g. product level from [28]

The diagram also shows how this product-level assessment can be upscaled to include households, companies, sectors and even entire nations. This makes it possible to evaluate absolute sustainability at any decision-making level, always based on the same physical limits of the planet.

Thus, the final calculation of the Assigned Share of the Safe Operating Space (aSoSOS) is expressed by combining the global SOS value for each impact category with the weight assigned to the product according to the chosen allocation principle. This is shown in *Equation 1*:

$$aSoSOS_{p,i}^{t} = SOS_{i}^{t} \times SP_{i} \tag{1}$$

where :

$aSoSOS_{p,i}^{t}$:	assigned share of safe operating space for product p in a given time t for an impact category i
SOS_{i}^{t} :	Safe operating space in a given time t for an impact category i
SP_{i} :	Estimated weight of sharing principle for an impact category i

Once the allowed impact has been determined through the aSoSOS, the next step is to calculate the Absolute Sustainability Ratio (ASR). The ASR is calculated by comparing the actual environmental impact of the product, as determined by the LCA, to its assigned share of the safe operating space. This is expressed in *Equation 2*:

$$ASR = \frac{Actual\ Impact}{Allowed\ Impact} = \frac{LCA}{aSoSOS_{p,i}^{t}} \tag{2}$$

If the ASR is lower than one, it indicates that the product stays within its assigned share of the safe operating space and is considered sustainable from an absolute perspective for a given category. If the ASR is equal to or greater than one, it means the product’s impact exceeds its allocated share of the Earth’s safe operating space. The ratio also serves as an indicator of how close the product is to achieving absolute sustainability. It should be noted that the product can only be considered sustainable from an absolute perspective if the ASR is lower than one for all impact categories.

3.3 Product Development

The product development phase encompasses a comprehensive series of activities aimed at transforming initial concepts into tangible and validated solutions. This stage integrates research, design, prototyping, and validation processes to ensure that the final product meets both technical specifications and sustainability objectives. Throughout this phase, continuous collaboration between academic teams and industry partners plays a vital role in aligning project goals with practical feasibility and market requirements.

3.3.1 Concept Development Methodology

The process of concept development is a crucial stage in product design, particularly when aiming to integrate both innovation and sustainability within functional requirements. In this work, the generation and selection of concepts were carefully structured to ensure a thorough exploration of ideas while maintaining a clear focus on project goals.

The concept generation phase began with a collaborative session involving a diverse group of participants, including students and academic supervisors from the Instituto Superior Tecnico. This multidisciplinary team brought together different perspectives, combining technical knowledge, creative thinking, and sustainability awareness.

Figure 9. Concept Generation meeting at IST

To stimulate creativity and maximise the breadth of ideas, two main structured activities were employed during the ideation sessions: brainwriting and the SCAMPER technique. Brainwriting encouraged silent, individual idea generation by having participants write or sketch their concepts without immediate group influence. The SCAMPER method was applied to challenge and evolve these initial ideas further. By systematically questioning each concept through seven categories (Substitute, Combine, Adapt, Modify, Put to another use, Eliminate, and

Rearrange), participants were encouraged to rethink assumptions and explore alternative solutions. This structured creativity tools proved effective in deepening the exploration of potential design innovations.

The ideas generated through these activities were subsequently organised into thematic groups to better manage and analyse the wide range of concepts. This grouping facilitated a clearer understanding of the various design directions and highlighted common themes such as material sustainability, modular design, and functional improvements.

Following the initial ideation activities, the House of Quality methodology was applied to organise and prioritise the various ideas generated. This structured approach allowed for a systematic mapping of customer requirements against potential design solutions, highlighting key areas of focus and guiding further concept development.

Subsequently, a second brainstorming session was conducted. Unlike the initial divergent ideation phase, this session focused on refining and elaborating concrete concepts based on the insights derived from the House of Quality analysis. The objective was to translate broad ideas into specific, actionable design solutions that addressed both functional and sustainability goals.

Once a comprehensive set of concepts was assembled, the focus shifted to the selection phase. A criteria-based evaluation methodology was implemented to objectively assess each concept's feasibility and alignment with the project's technical and sustainability objectives. The evaluation criteria were chosen carefully to balance manufacturability, usability, environmental impact, durability, aesthetics, and cost considerations.

Each criterion was assigned a weight reflecting its relative importance to the overall project goals. Concepts were then scored against these criteria, with particular emphasis placed on the connector mechanism design, independent of final material selections, which were to be addressed in later development phases.

A selection matrix was employed to aggregate scores and provide a transparent and systematic means to identify the most promising concepts for further development and prototyping. This methodological approach ensured that decision-making was data-driven and aligned with both practical and strategic priorities.

Through this iterative and structured process of concept generation and selection, a robust foundation was laid for the subsequent phases of design refinement and validation.

3.3.2 Prototyping Plan

Prototyping is a fundamental and iterative part of the design and development process. It involves creating physical or virtual models of a product to explore various aspects such as functionality, form, and integration. Prototypes serve as essential tools to test and refine design concepts throughout the project lifecycle.

This process plays multiple roles. It allows for verifying the effectiveness of the design and its compliance with project requirements, which is crucial for continuous learning and successful development. Additionally, prototyping facilitates clear communication among stakeholders, enhancing their understanding of the design intent. It also supports the integration of different components, ensuring cohesive functionality.

A balanced approach between digital and physical prototyping is key. Digital prototypes, created through CAD modelling, offer flexibility for detailed design iterations, while physical prototypes provide tangible feedback on practical implementation. This balance ensures that designs are both innovative and feasible, a critical factor for projects involving complex mechanical or structural components.

In this work, a similar prototyping system was adopted. The designs were developed using SolidWorks CAD software, enabling precise 3D modelling and iterative refinement of components. These virtual models were then materialised using a Bambu Lab 3D printer, which allowed for rapid production of physical prototypes to evaluate form, fit, and function. The integration of CAD models with 3D printing was carried out through the dedicated application of the Bambu Lab printer, Bambu Studio, which facilitated seamless transfer and preparation of the digital designs for physical fabrication. *Figure 10* shows a photo of one of the prototypes being created using the Bambu Lab 3D printer and all the printed prototypes.

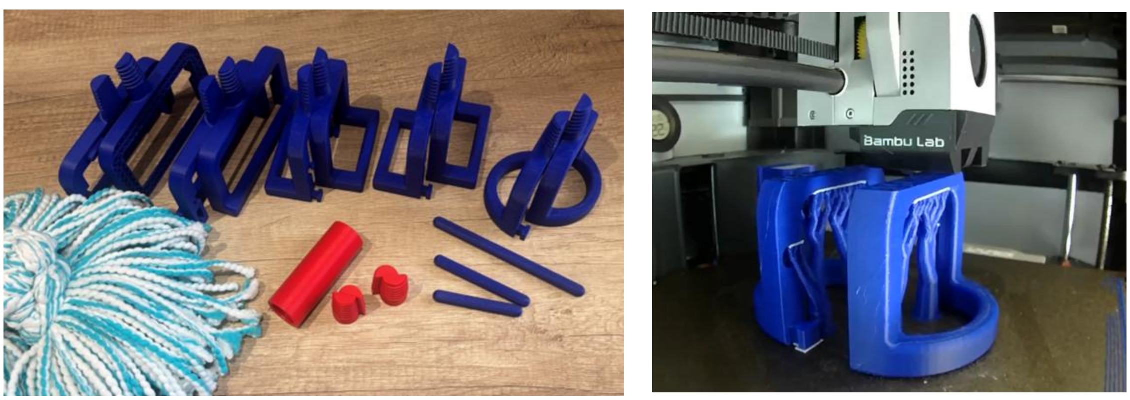


Figure 10. Prototyping process using the Bambu Lab 3D printer

The combined use of SolidWorks for detailed design and the Bambu Lab 3D printer for physical prototyping provided an efficient and effective workflow. This approach supported continuous improvement of the designs and ensured alignment with the project's objectives throughout the development process.

Throughout the prototyping phase, continuous evaluation of the design specifications has been essential to improve the product and ensure its validation. Each prototype iteration was carefully reviewed against functional and dimensional requirements to refine and enhance the design.

In addition to internal testing, validation has been conducted in collaboration with Fapil, whose extensive experience and expertise with the product have been invaluable. Their input provided practical insights and professional feedback that greatly contributed to aligning the prototypes with real-world use and industry standards.

Environmental impact considerations were integrated throughout the design and prototyping process by following established assessment methodologies. This approach ensured that sustainability principles informed design decisions from the early stages without the need to conduct a full environmental impact study at every iteration. The application of such methodologies allowed for targeted improvements aimed at minimising the product's environmental footprint while maintaining its functionality.

The iterative process of prototyping, testing, and environmental assessment enabled ongoing improvements, ensuring that the product not only meets technical specifications but also satisfies quality and sustainability expectations. This collaborative and multi-faceted approach with Fapil has ensured that the final design is both feasible and optimised for its intended application.

4. PRODUCT DEVELOPMENT

Based on the findings from the existing product analysis, this chapter begins with the generation of the initial concepts and concludes with the final product concept, detailing each critical phase of the methodology. The concept generation phase leads to the creation of preliminary designs, which, once evaluated against established selection criteria, result in the development of a first model. This model is then refined and adapted to satisfy all previously identified needs and requirements. Through subsequent prototype development and specification of technical details, a comprehensive and fully detailed design is achieved.

4.1 Case Study

The project began with a research phase and a thorough study of the existing product. This stage was key to understanding the broader context, identifying improvement opportunities, and laying the foundation for the subsequent development process.

The first step was to hold a meeting with the company Fapil and the academic supervisors. During this meeting, the general objectives of the project were jointly defined, and the product to be analysed and redesigned was selected.

As a result of this discussion, it was decided to focus the project on the company’s core product and the one with which Fapil was founded and began its operations: the mop. This product was considered an ideal candidate for applying the principles of absolute sustainability to a common and an everyday object with a high impact due to its widespread production and use. Therefore, a consensus was reached to explore the possibility of designing a fully sustainable mop.

With the object of study clearly defined, several visits were made to Fapil's facilities to gain first-hand insight into the internal operations of the company, its production lines and, in particular, the complete mop manufacturing process. These visits allowed for a detailed observation of each production stage, the materials used, the product's components, and its supply chain.

At the same time, to further deepen the understanding of the product, a series of interviews were conducted with Fapil staff (Annexe A 01). These interviews were fundamental in clarifying the current technical specifications of the mop, as well as the industrial constraints and requirements that had to be considered when proposing any redesign.

Moreover, considering that this is a product widely used by the general population, it was deemed appropriate to complement the technical analysis with a user-centered perspective. For this reason, a survey was designed and distributed, answered by 34 participants (Annexe A 02), with the aim of identifying real user needs and gaining a better understanding of their preferences, usage habits, and expectations regarding the product. This information provided a highly valuable qualitative perspective that helped align the technical requirements with market demands.

Once all this information had been collected and analysed, both from the company and the users, it was possible to clearly and justifiably define the product requirements. These are presented in *Table 4* and include aspects such as functionality, ease of use, and environmental impact.

Table 4. Needs and requirements for the product

NEEDS	REQUERIMENTS
Cleaning efficiency	Absorbent fibres made of materials resistant to chemical products
Priced affordably	It must be reasonably priced to ensure accessibility for a wide range of consumers while remaining competitive with similar products on the market
Dryness	The mop must effectively remove excess water from the floor, ensuring it dries quickly
Bucket compatibility	It must be compatible with the wringing system (manual, centrifugal or pedal-operated)
Durability and resistance	Able to withstand the pressure exerted during use
Ergonomics, comfort and ease of use	Lightweight design to reduce fatigue during use, proper size for comfortable use, non-slip grip, and allows the application of force comfortably
Handle-to-head connection	Solid attachment of the fibres to handle
Absolute sustainability	Minimise impact across the entire life cycle to stay within planetary boundaries

Among the entire list of requirements, it is important to highlight that the three most relevant and essential for the company at this time are cleaning efficiency, priced affordably, and dryness, as outlined in the interviews included in Annexe A 01. Both cleaning efficiency and dryness are key properties of the product because they represent its core functionality. The main purpose of a mop is to clean, and these two needs are the most basic to achieve that goal. Moreover, they are also the features that most differentiate the product from the competition, as they represent some of the most significant modifications made to traditional mops. On the other hand, cost is a crucial factor in today’s capitalist market. If the product is too expensive, the company notices that its retail companies (such as supermarkets) do not allocate space for it in the market.

Another essential feature of the mop, and in fact where the original idea for this product emerged, is the handle. A strong connection between the fibres and the handle is vital to prevent users from having to bend down. If the fibres were not securely attached to the handle, the whole invention would be pointless.

Furthermore, adding a handle would also be meaningless if the fibres couldn’t be wrung out without touching them. This is why bucket compatibility is also required. Nevertheless, if the mop were not compatible with existing buckets, a new bucket would need to be designed. However, doing so would not be a very sustainable solution, as all previously manufactured buckets would become obsolete before reaching the end of their useful life.

This need highlights the requirement of the project: absolute sustainability, which seeks to minimize environmental impact across the entire life cycle and stay within planetary boundaries. Later on, we will explore the methodology to achieve this goal, but examples include reusing as many existing parts as possible, manufacturing new components using more sustainable materials, reducing material variety and designing the product to be modular.

Another important property for improving the product is the durability and resistance it offers. This is a key factor in extending the product's useful life, which reduces the need for replacement. Not only is this beneficial economically for the user, but it is even more important from a sustainability perspective.

Finally, but no less important, ease of use must be highlighted. If a product is too complex and users don’t understand how to use it, they simply won’t buy it. Since the goal is to create a product that reaches the largest number of people possible, simplicity is essential. In addition, good ergonomics and comfort will make cleaning easier and more pleasant, improving the user experience and increasing the chances of repeat purchases or recommendations.

With these requirements, the aim is to meet the needs of users while also aligning with Fapil's goals as a company. They reflect a well-balanced approach, and each one has been carefully chosen to guide the entire design and development process. If the final product succeeds in meeting all these criteria, the result will undoubtedly be a practical, competitive, and successful solution that delivers value to users and strengthens Fapil’s position in the market.

4.1.1 Environmental Impact

In this study, the LCA was conducted using the Environmental Footprint (EF) method, which is the official tool of the European Union for harmonising environmental analyses [53]. The EF method covers sixteen environmental impact categories, including climate change, acidification, human toxicity, ecotoxicity, eutrophication and photochemical ozone formation, among others. This range of categories provides a comprehensive and detailed understanding of the product's environmental impacts.

The selection of the EF method is justified by its alignment with the absolute sustainability framework, as its impact categories are directly linked to the planetary boundaries defined by scientific research ([54], [47]). In this way, the data obtained through the EF method can be directly compared to absolute reference values (SOS) to evaluate whether the product remains within the safe operating space of the Earth system.

Applying this methodology to this case, the goal and scope of the assessment were first clearly defined. The main objective is to assess the environmental impact of a mop from the extraction of raw materials to its arrival at the consumer, in order to evaluate the feasibility of creating an absolutely sustainable mop. The impact resulting from the life cycle of one mop has been selected as the functional unit. The system boundaries include the five phases of the mop's life cycle: the extraction and production of materials, transportation to the factory, production of the star and white cover, assembly of the final product, its sale and use during its useful life, and the end-of-life treatment of the product.

Subsequently, with the help of the previously mentioned interviews and visits to the production plant, all the necessary information was gathered to conduct a robust inventory analysis. To do so, a diagram of the product process determined in the first phase was created. This is shown in *Figure 11* and helps to understand the system boundaries selected for the environmental analysis of the case study.

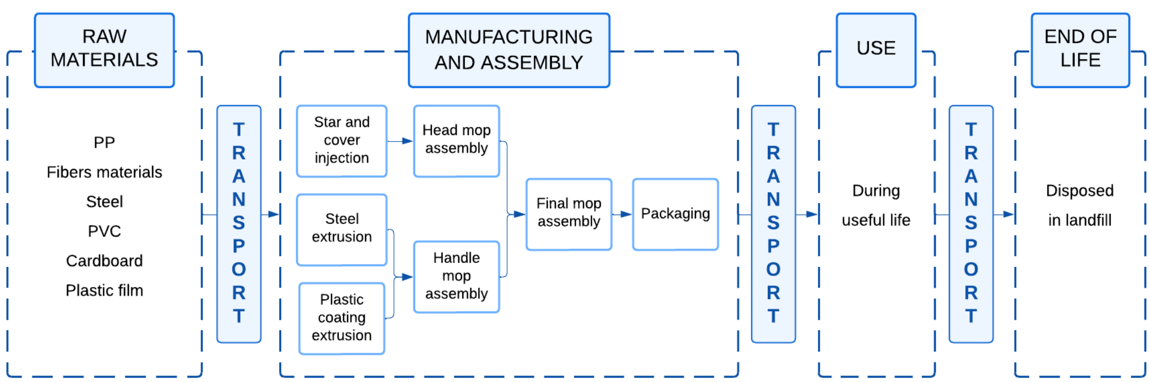


Figure 11. Complete Life Cycle of a Mop

Through this diagram, it was possible to determine the system inputs and outputs more clearly and concisely. It is important to highlight that, among all the different mop models distributed by Fapil, six specific ones with different types of fibres were selected for analysis. *Figure 12* shows the six models chosen for the study, which are, in order: microfiber, terry microfiber strips, cotton, power mop, ecological, and viscose strips. It is also worth noting that, although the handles are not shown in the figure, they are identical across all models and were, of course, included in the study. Additionally, the transport from the store to the point of use was disregarded, as its impact is considered negligible compared to the transport from the factory to the store and no reliable data is available for this purpose.

Figure 12. The six mop models from Fapil that are selected for the study

Based on all the information gathered for each of the six mop models, including their specific materials, components, and the detailed production process, a comprehensive life cycle inventory was compiled. This inventory forms the basis for the environmental analysis detailed in Annexe A 03, *Table A.1* and *Table A.2*. In addition, the LCA was performed using the SimaPro v9.3 software and the Ecoinvent database. Ecoinvent is a comprehensive and widely used life cycle inventory database that provides detailed and reliable environmental data for products and processes worldwide. It is also compliant with ISO 14040 and 14044 standards.

Anyway, since some process data were not available in the Ecoinvent database, the energy consumption of these processes was estimated. Based on this information, the environmental impact for each damage category was then calculated according to the corresponding energy consumption.

Subsequently, to calculate the environmental impact, the impact categories to be used in the study were defined, as shown in *Table 5*. Based on these, it was also determined that the impact assessment method adopted would be Environmental Footprint 3.1 (EF 3.1), which includes normalization and weighting factors published in July 2022.

Table 5. Impact categories used in the study

IMPACT CATEGORY	IMPACT INDICATOR	UNIT
Acidification	Accumulated exceedance (AE) characterizing the change in critical load exceedance of the sensitive area in terrestrial and main freshwater ecosystems, to which acidifying substances deposit	mol H^+ eq
Climate change	Global Warming Potential 100 years. Baseline model of the IPCC 2021	kg CO_2 eq
Ecotoxicity, freshwater	Comparative Toxic Unit for ecosystems (CTUe) expressing an estimate of the potentially affected fraction of species (PAF) integrated over time and volume per unit mass of a chemical emitted	CTUe

Eutrophication, freshwater	Phosphorus equivalents: Expression of the degree to which the emitted nutrients reach the freshwater end compartment (phosphorus considered as limiting factor in freshwater)	kg P eq
Eutrophication, marine	Nitrogen equivalents: Expression of the degree to which the emitted nutrients reach the marine end compartment (nitrogen considered as limiting factor in marine water)	kg N eq
Eutrophication, terrestrial	Accumulated Exceedance (AE) characterizing the change in critical load exceedance of the sensitive area, to which eutrophying substances deposit	mol N eq
Human toxicity, cancer	Comparative Toxic Unit for humans (CTUh) expressing the estimated increase in morbidity in the total human population per unit mass of a chemical emitted	CTUh
Human toxicity, non-cancer	Comparative Toxic Unit for humans (CTUh) expressing the estimated increase in morbidity in the total human population per unit mass of a chemical emitted	CTUh
Ionising radiation – human health	Ionizing Radiation Potentials: quantification of the impact of ionizing radiation on the population, in comparison to Uranium 235	kBq U-235 eq
Land use	Soil quality index. CFs set was re-calculated by JRC starting from LANCA® v2.5 as baseline model	Pt
Ozone depletion	Ozone Depletion Potential (ODP) calculating the destructive effects on the stratospheric ozone layer over a time horizon of 100 years	kg CFC-11 eq
Particulate matter	Disease incidence due to kg of PM2.5 emitted, calculated applying the average slope between the Emission Response Function (ERF) working point and the theoretical minimum-risk level	disease incidence
Photochemical ozone formation	Photochemical ozone creation potential (POCP): potential contribution to photochemical ozone formation. Valid only for Europe (LOTOS-EUROS model)	kg NMVOC eq
Resource use, fossils	Abiotic resource depletion - fossil fuels (ADP-fossil)	MJ
Resource use, minerals and metals	Abiotic resource depletion (ADP ultimate reserve)	kg Sb eq
Water use	m^3 water eq. deprived. Relative Available WAter REmaining (AWARE) per area in a watershed, after the demand of humans and aquatic ecosystems has been met	m^3 deprived

Once all the system variables were established, the LCA for the six selected Fapil mops was calculated, as shown in *Table 6* below.

Table 6. LCA of each mop

DAMAGE CATEGORY	UNIT	MICROFIBER	TERRY MICROFIBER STRIPS	COTTON	POWER MOP	ECOLOGICAL	VISCOSE STRIPS
Acidification	mol H+ eq	0,0103908	0,00980104	0,01349439	0,01285102	0,00667131	0,01035458
Climate change	kg CO2 eq	2,37662135	2,41218427	2,25945494	2,68392975	1,62009045	2,10311351
Ecotoxicity, freshwater	CTUe	20,0575373	19,2688119	19,6073824	30,6363498	15,8832585	19,7482396
Particulate matter	disease inc.	1,8138E-07	1,7173E-07	1,9386E-07	2,0479E-07	1,2962E-07	1,7607E-07
Eutrophication, marine	kg N eq	0,00249134	0,00286449	0,01551335	0,00550431	0,0020905	0,00263322
Eutrophication, freshwater	kg P eq	0,00056836	0,00050992	0,00234465	0,00086699	0,00037216	0,00049956
Eutrophication, terrestrial	mol N eq	0,02346924	0,02203479	0,04103674	0,03130816	0,01462211	0,02015876
Human toxicity, cancer	CTUh	6,0193E-09	5,9096E-09	5,4738E-09	6,2434E-09	5,6428E-09	5,8564E-09
Human toxicity, non-cancer	CTUh	4,5799E-08	4,281E-08	4,395E-09	3,275E-08	3,6147E-08	4,2276E-08
Ionising radiation	kBq U-235 eq	0,15146021	0,13759788	0,12008938	0,14567937	0,10766948	0,13474456
Land use	Pt	16,136395	15,0160461	130,087381	39,3416096	12,4719698	23,337111
Ozone depletion	kg CFC11 eq	2,3541E-06	1,606E-06	4,4673E-08	1,3278E-06	2,3486E-08	2,3118E-07
Photochemical ozone formation	kg NMVOC eq	0,01011491	0,0092449	0,00814516	0,01037949	0,00575581	0,00780581
Resource use, fossils	MJ	38,9080826	35,4081628	27,0264059	37,1114941	22,0177199	28,8355829
Resource use, minerals and metals	kg Sb eq	1,7415E-05	1,6357E-05	1,4886E-05	1,872E-05	1,1597E-05	1,4654E-05
Water use	m3 depriv.	0,33559647	0,34545389	0,29531489	1,37937756	0,20588958	0,43571261

The analysis reveals that the ecological mop has the lowest impact across all damage categories compared to the others. In contrast, the mop models with the highest environmental impact are the cotton mop and the power mop.

In this project, the allocation of the safe operating space (SOS) to the product was carried out using three different sharing principles to provide complementary perspectives: one based on the economic cost of the product, another on the greenhouse gas emissions it generates (CO_2 equivalent emissions), and another based on the energy it consumes ideally, across its life cycle. These allocation variables were chosen because they are among the most widely used in absolute sustainability assessments, as they represent different perspectives based on distributive justice theories ([55], [56]).

For the economic-based approach, the assigned share of the safe operating space (SP) was calculated using Portuguese population data [57] divided by the global population [58], combined with the average mop cost relative to final consumption expenditure per capita in Portugal [59]. This calculation, based on 2022 data, is shown in *Equation 3* below:

$$SP_{price} = \frac{\begin{array}{c}portuguese\\population\end{array}}{\begin{array}{c}world\\population\end{array}} \times \frac{\begin{array}{c}mop\ consumption\\cost\end{array}}{\begin{array}{c}final\ consumption\\expenditure\ per\\capita\ in\ Portugal\end{array}} = \frac{10.417.073}{8.021.407.192} \times \frac{2,40}{166.851.300.000} = 1,87\ x\ 10^{-14} \tag{3}$$

Once all the factors are determined, the aSoSOS can be calculated using *Equation 1*, followed by the calculation of the ASR for each mop using *Equation 2*, which will indicate their corresponding absolute sustainability. These results are presented in *Table 7* below, where all damage categories that exceed the threshold for absolute sustainability are highlighted in red. This confirms that the ecological mop exceeds the fewest limits, while the cotton and power mop models exceed the most.

Table 7. ASR comparison of mop alternatives based on the cost of the product

DAMAGE CATEGORY	UNIT	SOS	SoSOS	ASR					
				MICROFIBER	TERRY STRIPS	COTTON	POWER MOP	ECOLOGICAL	VISCOSE STRIPS
Acidification	mol H+ eq	1E+12	0,01868	0,55625291	0,524681	0,72239776	0,68795639	0,35713638	0,55431375
Climate change	kg CO2 eq	6,81E+12	0,12721078	18,6825473	18,9621063	17,7615058	21,0982892	12,7354812	16,5325106
Ecotoxicity, freshwater	CTUe	1,31E+14	2,44707955	8,19652034	7,87420741	8,01256436	12,5195561	6,49069972	8,07012573
Particulate matter	disease inc.	516000	9,64E-09	18,8177805	17,8165177	20,1126414	21,2463051	13,4480405	18,26662
Eutrophication, marine	kg N eq	2,01E+11	0,00375468	0,6635288	0,76291173	4,13173832	1,46598718	0,556771	0,70131644
Eutrophication, freshwater	kg P eq	5810000000	1,09E-04	5,23685376	4,69839443	21,6035837	7,98842609	3,42907963	4,60292466
Eutrophication, terrestrial	mol N eq	6,13E+12	0,11450838	0,20495657	0,19242948	0,35837325	0,27341374	0,12769464	0,17604617
Human toxicity, cancer	CTUh	962000	1,80E-08	0,33496264	0,32885873	0,30460355	0,34743136	0,31400975	0,32589842
Human toxicity, non-cancer	CTUh	4100000	7,66E-08	0,5979898	0,55896754	0,05738543	0,42761482	0,47197227	0,55198801
Ionising radiation	kBq U-235 eq	5,27E+14	9,84435818	0,01538548	0,01397733	0,0121988	0,01479826	0,01093718	0,01368749
Land use	Pt	5,21E+15	97,322782	0,16580285	0,15429117	1,33665909	0,40423844	0,12815057	0,23979083
Ozone depletion	kg CFC11 eq	539000000	1,01E-05	0,23380875	0,15950244	0,00443692	0,13187977	0,00233259	0,02296046
Photochemical ozone formation	kg NMVOC eq	4,07E+11	0,00760276	1,33042652	1,2159923	1,07134273	1,36522682	0,75706889	1,02670765
Resource use, fossils	MJ	2,24E+14	4,18431923	9,29854546	8,46210839	6,45897324	8,86918327	5,26195988	6,89134393
Resource use, minerals and metals	kg Sb eq	219000000	4,09E-06	4,25703879	3,99848774	3,63877631	4,57598644	2,83469487	3,58202137
Water use	m3 depriv.	1,82E+14	3,39975937	0,09871183	0,10161128	0,08686347	0,405728	0,06056004	0,12815984

To validate the study, an additional assessment was carried out using an SP based on CO_2 equivalent emissions generated by each product throughout its life cycle. In this case, the CO_2 equivalent emissions resulting from the LCA of each mop were used, along with Portugal's total CO_2 equivalent emissions in 2022, which amounted to 59.71 Mt CO_2eq [60], as shown in *Equation 4* below:

$$SP_{emissions} = \frac{portuguese\ population}{world\ population} \times \frac{mop\ CO_2\ eq\ emission}{CO_2\ eq\ emissions\ in\ Portugal} \tag{4}$$

With this new SP, which varies for each mop, an SoSOS is obtained for each one, and consequently, an ASR. The results are shown in *Table 8* below.

Table 8. ASR comparison of mop alternatives based on CO_2 eq emissions

DAMAGE CATEGORY	UNIT	MICROFIBER		TERRY STRIPS		COTTON		POWER MOP		ECOLOGICAL		VISCOSE STRIPS	
		SoSOS	ASR	SoSOS	ASR	SoSOS	ASR	SoSOS	ASR	SoSOS	ASR	SoSOS	ASR
Acidification	mol H+ eq	0,051690183	0,201021	0,052463656	0,186816	0,049141879	0,274601	0,058373968	0,22015	0,03523606	0,189332	0,045741541	0,226371
Climate change	kg CO2 eq	0,352010145	6,751571	0,357277499	6,751571	0,334656196	6,751571	0,397526724	6,751571	0,239957566	6,751571	0,311499891	6,751571
Ecotoxicity, freshwater	CTUe	6,771413946	2,96209	6,872738971	2,803658	6,437586143	3,045766	7,646989852	4,006328	4,615923813	3,440971	5,992141807	3,29569
Particulate matter	disease inc.	2,66721E-08	6,800442	2,70712E-08	6,343677	2,53572E-08	7,645293	3,0121E-08	6,798937	1,81818E-08	7,129326	2,36026E-08	7,459749
Eutrophication, marine	kg N eq	0,010389727	0,239789	0,010545195	0,271639	0,009877518	1,570572	0,011733168	0,469124	0,007082448	0,295166	0,00919405	0,286405
Eutrophication, freshwater	kg P eq	0,00030032	1,892514	0,000304814	1,672891	0,000285514	8,212036	0,000339153	2,556341	0,000204722	1,817888	0,000265758	1,879749
Eutrophication, terrestrial	mol N eq	0,316860821	0,074068	0,321602213	0,068516	0,301239718	0,136226	0,357832426	0,087494	0,215997046	0,067696	0,280395643	0,071894
Human toxicity, cancer	CTUh	4,9726E-08	0,12105	5,047E-08	0,117092	4,72745E-08	0,115787	5,61558E-08	0,11118	3,38971E-08	0,166469	4,40034E-08	0,133091
Human toxicity, non-cancer	CTUh	2,1193E-07	0,216104	2,15101E-07	0,199024	2,01482E-07	0,021814	2,39333E-07	0,136839	1,44468E-07	0,250211	1,8754E-07	0,225422
Ionising radiation	kBq U-235 eq	27,24072633	0,00556	27,64834685	0,004977	25,89777021	0,004637	30,76308131	0,004736	18,56940343	0,005798	24,10579185	0,00559
Land use	Pt	269,3058524	0,059918	273,3356492	0,054936	256,0291894	0,508096	304,128375	0,129359	183,5798707	0,067938	238,3134261	0,097926
Ozone depletion	kg CFC11 eq	2,7861E-05	0,084495	2,82779E-05	0,056792	2,64875E-05	0,001687	3,14636E-05	0,042202	1,89922E-05	0,001237	2,46547E-05	0,009377
Photochemical ozone formation	kg NMVOC eq	0,021037904	0,480795	0,021352708	0,432961	0,020000745	0,407243	0,023758205	0,43688	0,014341076	0,401351	0,018616807	0,419288
Resource use, fossils	MJ	11,57860095	3,360344	11,751859	3,012984	11,00778089	2,455209	13,07576891	2,838188	7,89287736	2,789568	10,24610507	2,814297
Resource use, minerals and metals	kg Sb eq	1,13202E-05	1,538425	1,14895E-05	1,423685	1,07621E-05	1,383185	1,27839E-05	1,464341	7,7167E-06	1,502781	1,00174E-05	1,462831
Water use	m3 depriv.	9,407613268	0,035673	9,548385441	0,036179	8,94382197	0,033019	10,62406224	0,129835	6,412962855	0,032105	8,324960373	0,052338

In addition, a third variation of the SP was calculated based on energy consumption. In this case, the SP was computed by comparing the life cycle energy consumption of each mop (obtained using SimaPro) with the total energy consumption of Portugal in 2022, which was 50,568 GWh [61], as shown in *Equation 5* below:

$$SP_{energy} = \frac{portuguese\ population}{world\ population} \times \frac{mop\ energy\ consumption}{energy\ consumption\ in\ Portugal} \tag{5}$$

Again, since the SP depends on each mop, an SoSOS is obtained for each one, and therefore, an ASR. The results are presented in *Table 9* below.

Table 9. ASR comparison of mop alternatives based on energy consumption

DAMAGE CATEGORY	UNIT	MICROFIBER		TERRY STRIPS		COTTON		POWER MOP		ECOLOGICAL		VISCOSE STRIPS	
		SoSOS	ASR	SoSOS	ASR	SoSOS	ASR	SoSOS	ASR	SoSOS	ASR	SoSOS	ASR
Acidification	mol H+ eq	0,012793121	0,812218	0,012806127	0,76534	0,00941253	1,433662	0,012553556	1,023696	0,008487062	0,786056	0,011235869	0,921565
Climate change	kg CO2 eq	0,087121152	27,2795	0,087209725	27,65958	0,064099329	35,24928	0,085489716	31,39477	0,057796893	28,03075	0,076516265	27,48584
Ecotoxicity, freshwater	CTUe	1,675898811	11,96823	1,677602636	11,48592	1,233041432	15,90164	1,644515834	18,6294	1,111805129	14,28601	1,471898777	13,41685
Particulate matter	disease inc.	6,60125E-09	27,47696	6,60796E-09	25,98854	4,85687E-09	39,91531	6,47763E-09	31,61502	4,37932E-09	29,59909	5,79771E-09	30,36885
Eutrophication, marine	kg N eq	0,002571417	0,968858	0,002574032	1,112841	0,001891919	8,199799	0,002523265	2,181425	0,001705899	1,225451	0,00225841	1,165961
Eutrophication, freshwater	kg P eq	7,4328E-05	7,646642	7,44036E-05	6,853438	5,46868E-05	42,87422	7,29362E-05	11,88697	4,93098E-05	7,547393	6,52804E-05	7,652512
Eutrophication, terrestrial	mol N eq	0,07842183	0,299269	0,078501558	0,280692	0,057698809	0,711223	0,076953298	0,406846	0,05202569	0,281055	0,068875874	0,292682
Human toxicity, cancer	CTUh	1,2307E-08	0,489099	1,23195E-08	0,479699	9,05485E-09	0,604513	1,20765E-08	0,516986	8,16455E-09	0,691134	1,08089E-08	0,541817
Human toxicity, non-cancer	CTUh	5,24518E-08	0,87316	5,25051E-08	0,815353	3,85914E-08	0,113886	5,14696E-08	0,636301	3,4797E-08	1,038809	4,60671E-08	0,917698
Ionising radiation	kBq U-235 eq	6,741974604	0,022465	6,748828926	0,020388	4,960403316	0,02421	6,615724004	0,02202	4,472681701	0,024073	5,921302712	0,022756
Land use	Pt	66,6521588	0,242099	66,71992164	0,225061	49,03928136	2,652718	65,40402668	0,601517	44,21759329	0,282059	58,53887501	0,39866
Ozone depletion	kg CFC11 eq	6,89549E-06	0,341398	6,9025E-06	0,232662	5,07335E-06	0,008805	6,76637E-06	0,19624	4,57453E-06	0,005134	6,05613E-06	0,038173
Photochemical ozone formation	kg NMVOC eq	0,0052068	1,942635	0,005212094	1,773739	0,0038309	2,126174	0,005109297	2,031491	0,003454234	1,666306	0,004572998	1,706935
Resource use, fossils	MJ	2,865659035	13,57736	2,868572447	12,34348	2,108406723	12,8184	2,811996541	13,19756	1,901101899	11,58156	2,516834549	11,45708
Resource use, minerals and metals	kg Sb eq	2,80169E-06	6,215956	2,80454E-06	5,8325	2,06134E-06	7,221473	2,74923E-06	6,809179	1,85867E-06	6,239154	2,46066E-06	5,955227
Water use	m3 depriv.	2,328347966	0,144135	2,330715113	0,148218	1,713080462	0,172388	2,284747189	0,603733	1,544645293	0,133292	2,044928071	0,21307

These different allocation approaches each provide a unique perspective on how to share the planet's limited resources. However, the economic-based approach is considered the most robust for this study because it uses more comprehensive and consistent data. In contrast, the emission-based and energy consumption-based approaches are more sensitive to errors and incomplete data due to the complexity of these processes and their dependence on technology, location and other contextual factors.

It is also important to note that the different sharing principles used in this study reflect the distributive theories discussed in the literature review, including egalitarianism, utilitarianism, grandfathering and others. By incorporating approaches based on population share (Egalitarianism), emissions (Grandfathering) and economic expenditure (Utilitarianism), this study explicitly integrates these theoretical foundations into the allocation of the safe operating space. This ensures that the final assessment is not only technically sound but also aligned with established ethical frameworks for fairness and responsibility in the use of the planet's limited resources.

This integrated assessment, based on the Environmental Footprint (EF) method and using three different allocation principles, provides a comprehensive evaluation of whether the mop alternatives can be considered absolutely sustainable. It ensures that the analysis is not limited to relative improvements but is directly linked to the global limits of the Earth system.

4.2 Concept Generation

Once the product, its requirements, and objectives were defined, the concept generation phase began. This is the process that helps generate a wide variety of potential solutions and ideas that meet the identified needs.

The initial phase involves a divergent exploration of possibilities, where creativity and practical insights come together to propose multiple solutions. To support idea generation, various techniques and methodologies were considered, as highlighted in the literature review. To generate a wide range of ideas, a brainstorming session was conducted to encourage innovation while remaining closely aligned with the project's objectives.

The purpose of the first brainstorming session was to identify key directions. Since absolute sustainability had not previously been applied to product development, this approach helped open up potential avenues of exploration to begin generating viable solutions.

A typical brainstorming session can sometimes feel too open-ended, which can make it more difficult to come up with ideas. To make the process more effective and structured, two specific activities were proposed to facilitate smoother idea generation.

One of the techniques used was brainwriting. Unlike brainstorming, where participants say their ideas out loud, this method involves silently writing them down. This encourages everyone to think freely without being influenced by others.

In this technique, each participant received a sheet of paper and had five minutes to write or draw three ideas related to any aspect of the mop: its components, fibers, materials, or even its aesthetics. After five minutes, each person passed their sheet to the person next to them. They then had another five minutes to add new ideas or expand on the existing ones by introducing new concepts. The process continued until everyone had seen and contributed to every sheet [62]. A copy of the resulting papers can be found in Annexe A 04.

The second activity was based on the SCAMPER method, a structured creativity technique designed to help modify and improve existing concepts. Once the most unconventional ideas have been explored, this activity is particularly useful for reviewing the ideas generated so far and exploring new areas that may not have been previously considered. SCAMPER uses guiding questions that stimulate idea generation by challenging current assumptions and encouraging new perspectives. This method is particularly useful for enhancing and evolving product concepts during the early development phase [63]. The list of guiding questions used in this activity, which are intended to support continuous idea generation across all SCAMPER categories, can be found in Annexe A 05. The SCAMPER acronym represents the categories of questions related to:

- <u>Substitute:</u> The overall question to consider is: *What can be substituted or changed within the product, process, or system?* This prompt encourages identifying elements (materials, components, users, functions) that could be replaced with alternatives to improve functionality, sustainability, or user experience.

- Combine: The overall question to consider is: *How can different parts, functions, or ideas be combined to enhance performance or value?* This technique promotes synergy by merging elements that are typically separate, potentially creating multifunctional or hybrid solutions.

- Adapt: The overall question to consider is: *What can be adapted or adjusted from another context or application?* This question focuses on leveraging existing ideas, products, or processes from other industries or domains and tailoring them to fit the current problem or design context.

- Modify: The overall question to consider is: *What aspects can be modified, exaggerated, or minimized?* Consider changing attributes such as shape, scale, colour, material, or texture. This can reveal which features are most critical and lead to more refined, optimized designs.

- Put to another use: The overall question to consider is: *Can the product or its components be used in a different context or for a different purpose?* This dimension encourages rethinking utility, identifying new users or markets, and potentially repurposing designs to extend their life cycle or value.

- Eliminate: The overall question to consider is: *What can be removed, simplified, or reduced without compromising core functionality?* By stripping away unnecessary elements, this prompt supports design efficiency, sustainability, and cost reduction.

- Rearrange: The overall question to consider is: *How can elements be reordered, restructured, or reversed?* This encourages breaking habitual sequences, considering new workflows, or inverting existing systems to uncover overlooked opportunities or constraints.

From these two activities, a large number of ideas were generated and later grouped into four main categories. The first major group focused on recycling. In order to achieve an absolute sustainable product, it was evident that virgin plastic and fibers needed to be replaced with recycled materials. Additionally, the fact that the handle was made of metal coated in plastic, along with plastic adapters, made the product extremely difficult to recycle afterward. The inability to separate materials effectively meant it would likely be sent to landfill. Therefore, the complete handle and the piece that connects and holds the mop fibers together should be made from the same recycled material.

Based on this concept, various material possibilities were explored, including a market analysis of mops that are currently marketed as eco-friendly [64] or ecological [65]. It is also worth noting that Fapil already offers an ecological mop, in which the fibers are made using waste material from a nappy factory. In addition, the company has an entire product line called the *Ocean Line*, featuring various items made with at least 20% recycled maritime plastic.

Following extensive research, it was concluded that the most suitable materials for the mop are those listed in *Table 10* for the other components required to support the fibers and the handle and *Table 11* for the fibers.

Table 10. Potential materials for the handle and connection piece components

MATERIAL	MECHANICHAL STRENGTH	WEIGHT	WATER RESISTANCE
Recycled Nylon (PA6)	High	Light	Very High
Sustainable Wood	Medium-high	High	Low
Bamboo	High	Medium	High
Recycled Polypropylene (rPP)	High	Light	Very High (+chemicals resistant)

Table 11. Potential fiber materials

MATERIAL	ABSORPTION	MECHANICHAL STRENGTH	BIODEGRADABILITY
Recycled Cellulose Fibers	Very High	Medium	High
Bamboo Fibers	High	High	High
Seaweed Fibers	Moderate	Low-Medium	High
Recycled Cotton Fibers	High	Medium-High	High
Recycled Nylon (PA6)	Low	High	Moderate
Nappy Fibers	Very High	Medium-High	Moderate-High

One of the most popular ideas that emerged during the brainstorming session was the concept of a modular design. Although the current mop is already composed of two separate parts, this design is not truly efficient in terms of absolute sustainability. The current separation does not allow for proper disassembly of materials once the product reaches the end of its life cycle. This presents a significant barrier to recycling and waste reduction. Therefore, the team concluded that the new solution needed to allow the fibers to be easily separated from the rest of the mop without adding additional or mixed materials.

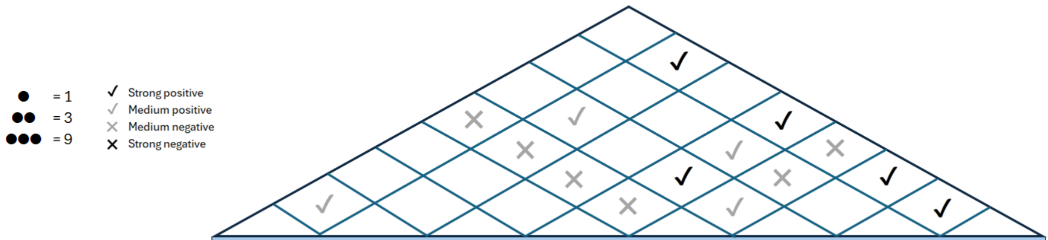
The idea was to create a grouping system for the fibers that would enable users to remove them effortlessly. This would not only facilitate proper disposal and recycling of the rest of the mop, but it would also make it possible to wash the fibers in a washing machine after each use. This regular cleaning could even extend the lifespan of the mop, making it more sustainable overall. However, the mechanism to separate the fibers had to meet several key requirements, including being simple, safe and user-friendly. Essentially, it needed to be aligned with all the criteria set out in the PDS. It is important to note that, during this initial brainstorming session, no concrete solutions or technical implementations for this modular system were developed.

Another topic that gained attention was the product's packaging system. Currently, mop heads are typically sold wrapped in a plastic bag. Although this material is technically recyclable, it does not align with the project's vision of an absolute sustainable product. For this reason, the team reached a consensus that the packaging should not only use a more environmentally appropriate material to protect the fibers, but it should also visually communicate the core values of the product. At first glance, the packaging should reflect the idea that this is not just an ordinary mop, but rather it is a product specifically designed with the planet in mind, one that stands out through its purpose and its thoughtful, eco-conscious design.

The last highlighted idea was the efficiency with which the floor is cleaned. It is evident that a considerable amount of water is used when mopping, and for this reason, the possibility of designing a system that supplies the precise amount of water and the necessary detergent was also explored, to avoid any waste. This idea emerged during the first activity but evolved during the second one, as the feasibility of implementing a setup with such characteristics would significantly increase the number of materials and the complexity of the system, while also limiting its potential for reuse. Therefore, in the second activity, after sharing the ideas, it was concluded that it would be better to first look for studies to support this concept and assess its viability.

It was found that most studies focus on ergonomic or biomechanical aspects, emphasizing the importance of the mop handle while overlooking the efficiency of water or detergent consumption [66]. Nevertheless, these studies also state that the perception of cleanliness and water usage varies depending on the user and the type of surface, and there is no clearly superior method [67]. For these reasons, it was decided not to pursue the development of an automatic dosing system and instead focus on all the other ideas that had emerged.

As a result, several paths were identified to develop different possible solutions. In order to group all the ideas and work with them effectively, a conceptual mapping tool called the House of Quality was used. This method originated in 1972 at Mitsubishi's Kobe shipyard site and has been successfully applied in various fields such as the manufacturing of consumer electronics, clothing, construction equipment, and agricultural engines, among others [68]. The House of Quality is defined as a product planning matrix that is built to show how customer requirements relate directly to the ways and methods companies can use to achieve those requirements. It serves as a tool for interfunctional planning and communication. For engineers, it provides a way to summarize key data in a usable format, and for marketing executives, it represents the voice of the customer. This is achieved by listing the *'What'*, the customer requirements, each assigned a specific weight, and the *'How'*, the technical responses, and mapping the relationships between them. In this way, if all objectives cannot be met, it is clear which ones are related and what weight is associated with not fulfilling them. The result of this exercise is presented in *Figure 13*.



WHATS	WEIGHTAGE (1-5)	Strong handle-to-head connection	Modular and fuctional design	Fiber absorption	Sustainable materials	Manufacturing cost	Fewer materials	Packaging	Ease of recycling
		HOWS							
Cleaning Efficiency	5	●		●●●	●				
Priced Affordably	4			●	●●	●●●	●●	●●	
Floor dryness after use	4			●●●					
Durability and Resistance	2	●●●	●		●●		●		●
Ease of use	4	●●	●●●	●					●
Absolute Sustainability	5		●●●	●	●●●	●	●●●	●●	●●●
Attractive product presentation	3		●●			●		●●●	

									TOTAL
Importance Weight	35	92	94	68	44	59	54	51	497
Relative importance weight	7,04%	**18,51%**	**18,91%**	13,68%	8,85%	11,87%	10,87%	10,26%	

Figure 13. Application of the House of Quality in the design of an absolutely sustainable mop

Therefore, in this case, the most important actions to be carried out are that the mop ends up using a material with highly absorbent fibers and that the design is modular, with an importance of 18.91% and 18.51% respectively.

4.3 Preliminary Designs

Once all relevant criteria were known and the most important needs had been identified, the design phase could begin. It was observed that the most critical factor was the quality of the fibers, which depends strictly on the material used. However, other characteristics, such as a modular structure, had to be addressed directly through the design itself. At this point in the project, as a new design had to be created, a second brainstorming session was carried out.

This brainstorming session was conducted with a team of three students from the Universitat Politècnica de Catalunya and followed the typical brainstorming methodology, where each participant could freely share any ideas they had in mind. The main goal of this session was to explore a wide range of potential solutions without immediately judging their feasibility, encouraging creativity and open discussion.

After compiling all the suggestions, the ideas were discussed in more detail to identify those that best aligned with the project's goals. Below are the main ideas that were generated during this creative session.

Concept 1

This initial concept was inspired by the mechanism of a peg or a binder clip. The goal was to develop the simplest possible design in order to minimize the use of different materials, while still ensuring that the mop fibers could be securely clamped in place. The force created by the clamping action was intended to be sufficient to hold the fibers without the need for additional fasteners or complex parts.

With this idea in mind, it was also considered how the mop handle could play an active role in generating this clamping force. By designing the handle to apply pressure to the connector, it becomes possible to use a less rigid material for the connector part, thus further reducing the need for heavy-duty components or resource-intensive materials.

Another key advantage of this design is its simplicity in terms of modularity. The system consists of only two main pieces, and the fibers can be easily removed and replaced. This makes the product highly functional and easy to disassemble, facilitating maintenance, cleaning, or replacement of parts.

The designed concept is illustrated in *Figure 14*, which shows different views of the proposed solution in order to better convey the intended mechanism and structure.

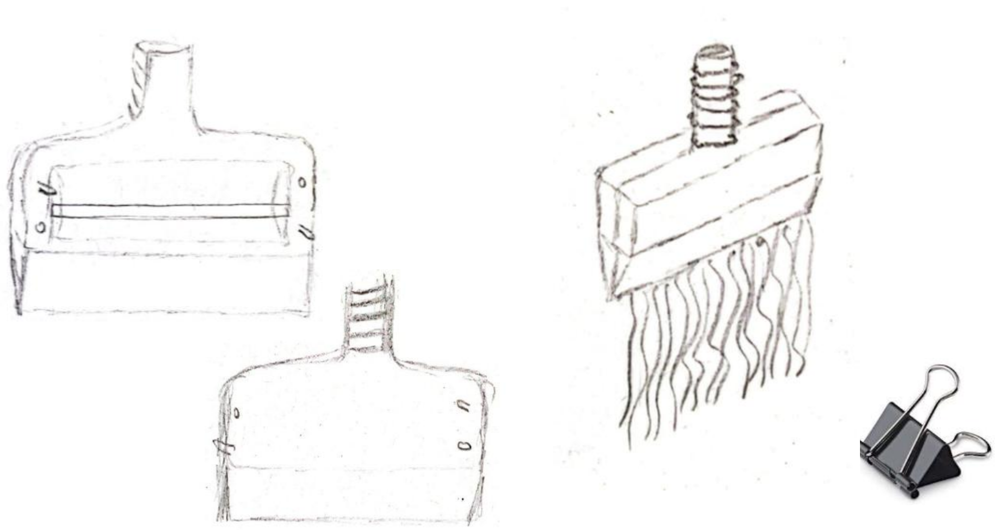


Figure 14. Sketch of the first concept developed during the brainstorming session

Concept 2

In this second concept, the goal was to join the fibers by clamping them between two components using a sliding joint. The idea is based on a guiding mechanism, similar to a wooden groove system, where a main piece connected to the handle features lateral tracks or rails. These guides allow a second piece to slide into place, pressing the fibers against the first component.

At the end of the sliding path, a small rod or stopper must be inserted to prevent the parts from separating unintentionally. This element is essential to ensure that the fibers remain firmly held by the pressure created between the two joined components.

The use of sliding guides and a mechanical lock improves ease of assembly and disassembly, making it easy to replace or recycle the fiber section when worn out.

The concept is illustrated in *Figure 15*, showing the sliding connection and how the fiber block is secured between the two main elements.

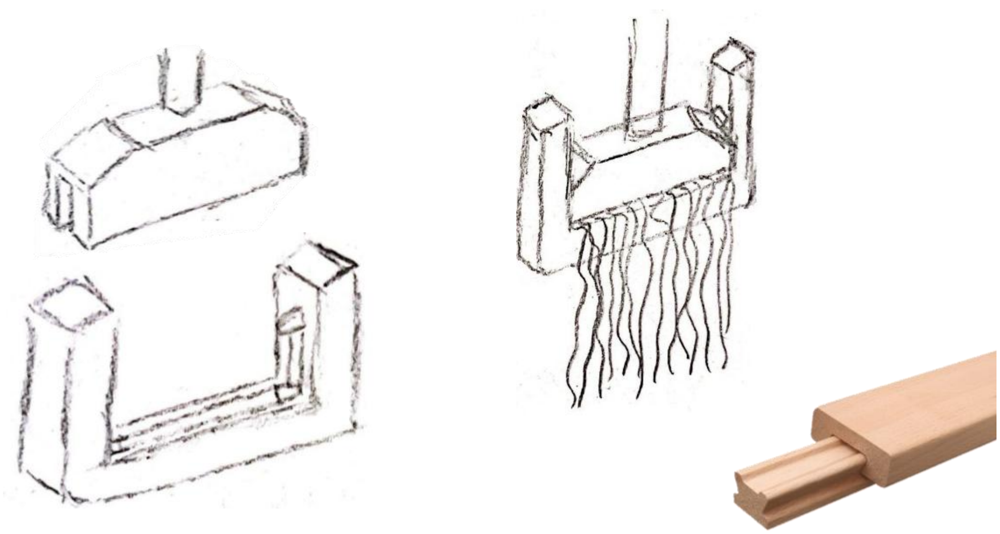


Figure 15. Sketch of the second concept developed during the brainstorming session

Concept 3

The third concept is inspired by the mechanism of a document binder. While it is not identical, as the fibers have significantly more volume than paper sheets, the idea is to replicate a similar clamping principle. The design consists of a mechanism that, when the handle is slightly lifted along with the upper part of the head, causes the fiber-holding section to open slightly. This small movement allows the user to insert or remove the fibers with ease.

Once the fibers are in place, releasing the handle brings the two components back together, securing the fibers in position through mechanical pressure. This method requires only a simple motion, one that most users are already familiar with, and eliminates the need for screws, clips, or additional locking systems.

It should be taken into account that this system requires materials that are not only more resistant but also slightly elastic, in order to allow the controlled movement of the clamping mechanism. The components must be able to flex without breaking, ensuring that the opening and closing action can be repeated multiple times without compromising the durability or functionality of the product.

The intention behind this concept is to maximize simplicity and user-friendliness while maintaining modularity and functionality. The concept is shown in *Figure 16*, which includes sketches of the locking mechanism and its operation.

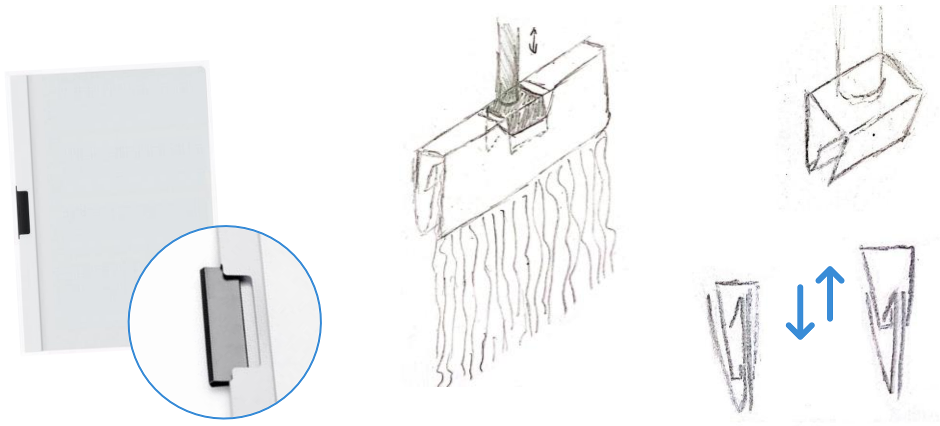


Figure 16. Sketch of the third concept developed during the brainstorming session

Concept 4

The fourth concept takes inspiration from the common plastic bag clip used to seal food packaging. The idea is based on a hinged mechanism composed of two complementary arms that close tightly over the fibers to hold them in place. One arm contains the locking pin, while the other includes a matching hole or slot, ensuring a secure fit when closed. This system is simple, intuitive, and requires very few components.

Unlike the other concepts, this solution would consist of a single molded piece with an integrated hinge, simplifying manufacturing and reducing assembly steps. This also presents an opportunity to use a single material, preferably a durable and slightly flexible bioplastic or recyclable polymer, to ensure both functionality and environmental responsibility.

Figure 17 illustrates the concept, showing the clamping action, the internal locking detail, and how the fibers would be secured once the piece is closed.

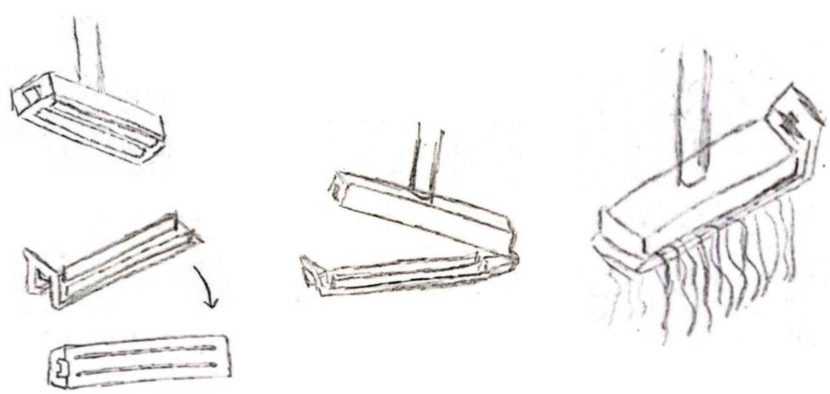


Figure 17. Sketch of the fourth concept developed during the brainstorming session

Concept 5

The fifth concept is based on a mechanical latch mechanism, similar to those used in door locking systems. The main idea is to create a secure locking system that holds the fiber module in place through the action of a rotating latch. This latch is activated with a simple rotation, allowing the user to open or close the system quickly and reliably.

The mop head includes a cavity where the fiber block is inserted. Once in position, the latch is rotated into the locking position, causing a small plate to move down and apply pressure to keep the internal module firmly secured. When the user needs to remove or replace the fibers, the mechanism can simply be unlocked to release the part.

This mechanism ensures a very strong hold, which can be especially useful for more demanding cleaning tasks where higher forces are applied. However, this design would require more precise manufacturing and materials with sufficient mechanical strength to ensure the durability and reliability of the moving parts.

The concept is shown in *Figure 18*, which illustrates the locking mechanism in both open and closed positions, as well as how the fiber block is secured within the system.

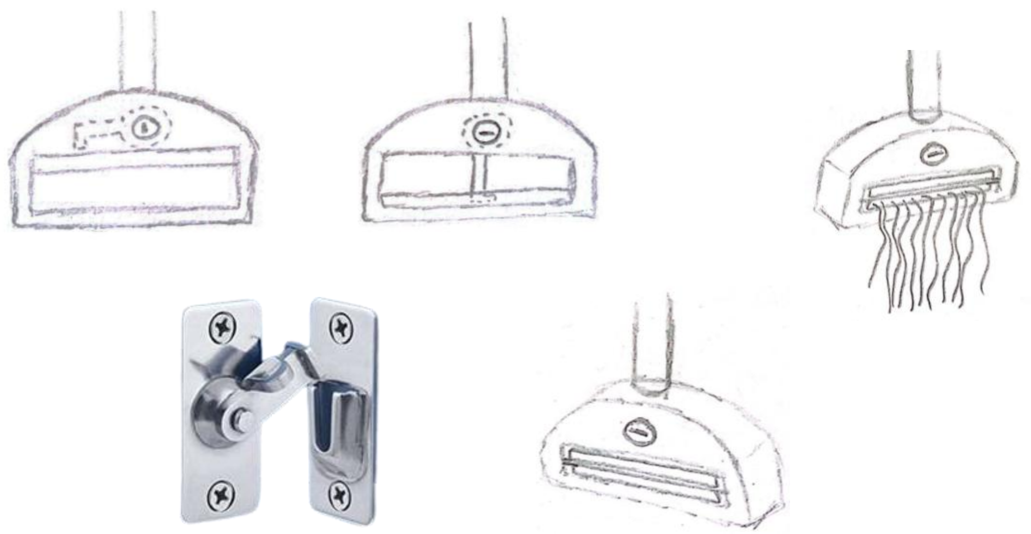


Figure 18. Sketch of the fifth concept developed during the brainstorming session

4.3.1 Concept selection

Once all the concepts were generated, it was necessary to narrow down the options through a structured evaluation process. To achieve this, a concept selection methodology was applied based on a set of predefined criteria. This allowed each idea to be assessed objectively and identify the most suitable one for further development.

The transition from divergent ideation to a more convergent decision-making phase involved evaluating the concepts according to technical feasibility, manufacturing ease, environmental impact, and other strategic factors. This process ensures that the development effort is aligned with sustainability goals and practical constraints.

The evaluation was conducted using a criteria-based selection matrix. Each criterion was weighted according to its relevance to the project objectives, and each concept was later rated based on how well it satisfied those criteria.

The criteria were carefully chosen to balance key aspects critical to the success of the product, including manufacturability, user experience, environmental sustainability, durability, aesthetics, and cost. These factors collectively ensure that the selected concept is not only feasible and economically viable but also aligns with the project's sustainability goals and meets user needs effectively. The criteria used in the selection were as follows:

- Ease of manufacturing: the simplicity of producing the component, taking into account required processes and complexity.
- Ease of use: how intuitive and user-friendly the concept is in everyday cleaning tasks.
- Absolute sustainability impact: the environmental performance of the design including factors such as the number of different materials used and the amount of material required.
- Durability and resistance: the ability of the concept to tolerate physical stress and long-term use without failure.
- Aesthetic appeal: the visual quality and overall design perception of the product.
- Cost: the expected cost of producing the component, considering materials and processes.

It is important to note that not all requirements are directly represented within these criteria. For example, the absorbency of the fibers is a critical aspect of performance, but it depends primarily on the material used for the fibers themselves. Since the current focus of the design phase is on the mechanism that connects the fibers to the handle, absorbency is not included as a scoring criterion in this stage. The selection process aims to evaluate only the connector design, independent of the final fiber material.

The criteria were selected to reflect the most relevant functional, environmental, and economic aspects of the design. However, the final choice also acknowledges that some requirements are inherent to future material decisions, which will be addressed in subsequent phases of development.

The following *Table 12* presents the importance of the different criteria compared to other criteria.

Table 12. Comparison of Criteria Importance

	Ease of manufacturing	Ease of use	Absolute Sustainability Impact	Durability and Resistance	Aesthetic appeal	Cost	S+1	Pond.
Ease of manufacturing		0	0	0,5	1	0	2,5	0,1190476
Ease of use	1		0	1	1	0,5	4,5	0,2142857
Absolute Sustainability Impact	1	1		1	1	1	6	**0,2857143**
Durability and Resistance	0,5	0	0		0,5	0	2	0,0952381
Aesthetic appeal	0	0	0	0,5		0	1,5	0,0714286
Cost	1	0,5	0	1	1		4,5	0,2142857
						Total	21	

This weighting was used to compute a weighted score for each concept, which allowed an objective comparison of alternatives. While the individual scoring tables for each concept can be found in Annexe A 06, the final selection is included below in *Table 13* to show the outcome of the evaluation and highlight the winning concept.

Table 13. Concept Selection

	Ease of manufacturing	Ease of use	Absolute Sustainability Impact	Durability and Resistance	Aesthetic appeal	Cost	Total	PRIORITY
Sketch 1	0,040	0,057	0,086	0,032	0,024	0,071	0,238	23,809524
Sketch 2	0,020	0,036	0,067	0,013	0,007	0,043	0,142	14,206349
Sketch 3	0,028	0,021	0,019	0,013	0,017	0,029	0,098	9,7619048
Sketch 4	0,024	0,071	0,076	0,013	0,007	0,057	0,191	19,126984
Sketch 5	0,008	0,029	0,038	0,025	0,017	0,014	0,117	11,666667

After evaluating all five proposed concepts using the weighted criteria selection matrix, Sketch 1 achieved the highest overall score, with a total priority value of 23.81, clearly outperforming the other alternatives. This makes it the selected concept. Consequently, further development efforts will focus on refining and detailing this design, moving forward with prototyping and validation.

4.4 Detail Design

Once the final concept has been selected, the next step involves developing the detailed design. This phase focuses on refining the chosen concept in order to define all the specific elements that will allow the product to meet the established requirements.

The aim is to analyse and define all the technical and functional aspects of the design to ensure its feasibility, performance, and sustainability. At this stage, it is essential to determine dimensions, materials, mechanisms, assembly methods, and other critical characteristics that will shape the final solution.

By working through these details, it becomes possible to move forward with prototyping and testing, and to ensure that the final product satisfies the initial objectives. In this way, the goal of this stage is to transform the selected concept into a fully defined, functional, and testable design, ready for evaluation and further validation.

4.4.1 Prototype Development

After selecting the concept that aligns the most with the specifications, attention turns to developing a functional prototype as a key step in validating the design and preparing it for implementation. This phase represents the transition from the initial sketches to physical reality, enabling hands-on testing and refinement of the proposed solution. The selected concept was modelled in 3D using SolidWorks, a Computer-Aided Design (CAD) tool well suited for precision and iteration.

Turning designs into tangible objects not only allows for a detailed visualization of how the components fit and interact, but also makes it possible to evaluate factors such as ease of assembly, ergonomics, and accessibility. Unlike virtual models, physical prototypes reveal subtle design issues that are not immediately visible in CAD, such as interferences, excessive material use, or assembly misalignments. In addition, SolidWorks enables quick adjustments throughout the process and provides a clear foundation for future fabrication.

Thus, this iterative cycle between CAD modelling and 3D printing enables fast and efficient improvements. Each version of the prototype incorporates insights from the previous one, progressively refining the design toward an optimal solution. This methodology proves particularly effective for testing and adjusting the product before advancing to final production stages.

The first step in this process was to create the actual concept idea that had been chosen. In order to do this, the dimensions and specific technical characteristics of the handle and the fiber section from various types and brands of mops and even brooms were studied. Based on this research, an initial design was recreated using approximate measurements to gain a first impression of the proper proportions.

During this process, the thread detail quickly became an important point of attention. Initially, a flat-crest thread was considered, as it is one of the most common profiles, but it was observed that most commercial mop handles use a rounded thread. For this reason, a comparative study of the required thread type was conducted. Since part of the handle had to be modelled anyway, a single piece was created with a rounded thread on one end and a

Figure 19. 3D-printed and CAD models of the mop handle with both thread types

flat-crest thread on the other. Additionally, the upper geometry of the two fiber-holding parts was also included to verify thread compatibility without printing the full component. *Figure 19* shows the CAD design and printed prototype of this step.

In this test, it was confirmed that both thread types were compatible with current mop handles. This also revealed that this piece could potentially be commercialized as a separate adapter, allowing users to reuse their existing handles rather than purchasing a new one, thus supporting modularity and reducing unnecessary waste.

Once it was confirmed that either thread would be suitable, the design proceeded with the flat-crest thread, as it provides better axial force transmission in static conditions. *Figure 20* shows the CAD and 3D-printed prototype of this first concept.

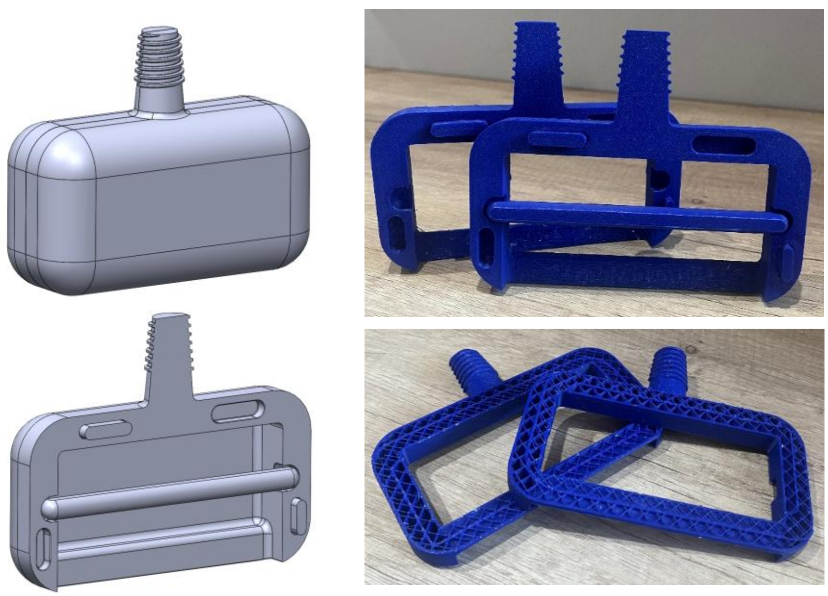


Figure 21. Initial CAD design and the corresponding 3D-printed prototype

During the first print attempt, the model lacked adequate support structures, which led to printing instability and failure. However, the interruption occurred at an ideal point: the thread and key notches had already been

Figure 20. Complete assembly including the sewn fibers, the first 3D-printed piece, and the mop handle

printed, as shown in the image. At this stage, mop fibers from another product were sewn together and tested with the piece, which revealed an additional benefit. The design required less material and was more aesthetically pleasing. *Figure 21* shows the assembled prototype with the fibers included.

Despite this progress, several adjustments were still needed. The lower section, which is responsible for pressing the fibers, was too narrow and became deformed. Since the fibers are already held in place by the internal pin, this section does not require excessive pressure. To improve durability and reduce stress concentration in the

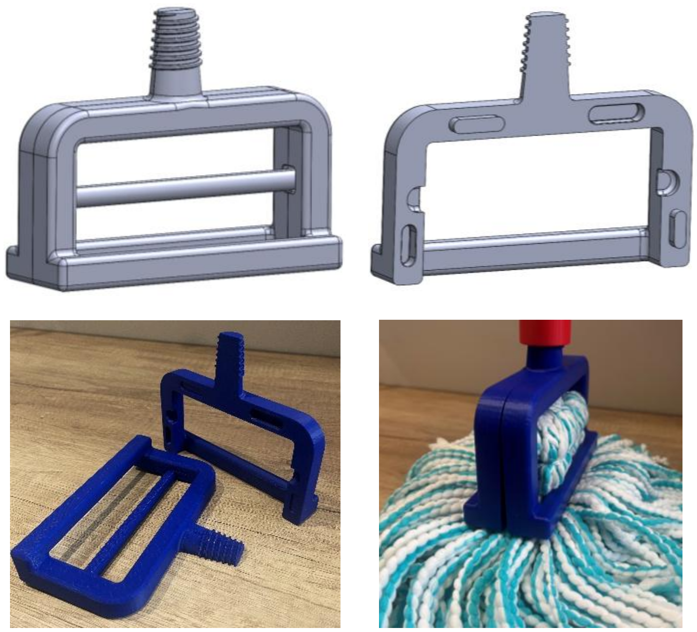


Figure 22. Second prototype version: updated CAD model and 3D-printed result

lower section, the geometry was modified by creating a small protrusion and a hole to reduce the pressure applied to the fiber-holding parts. This change aimed to avoid deformation while maintaining functionality and ensuring the longevity of the piece. Additionally, the key notches were enlarged and deepened to enhance longevity. *Figure 22* shows the updated design in CAD and its printed version.

After printing the revised piece, further tests with the fibers revealed that the two parts slightly opened at the bottom. To further reinforce the structure and increase durability, a small guiding system was added to connect the bottom sections. Since the guides now handled the centring, the previously included key notches were removed.

To assess functionality, the mop was tested for compatibility with different types of buckets, but it was observed that the piece did not fit properly in all bucket models, which prompted a new iteration. The fiber alignment was modified to achieve a more cuboid shape, improving compatibility and compactness. *Figure 23* illustrates the CAD model and printed version of this design, including the full assembly with fibers.

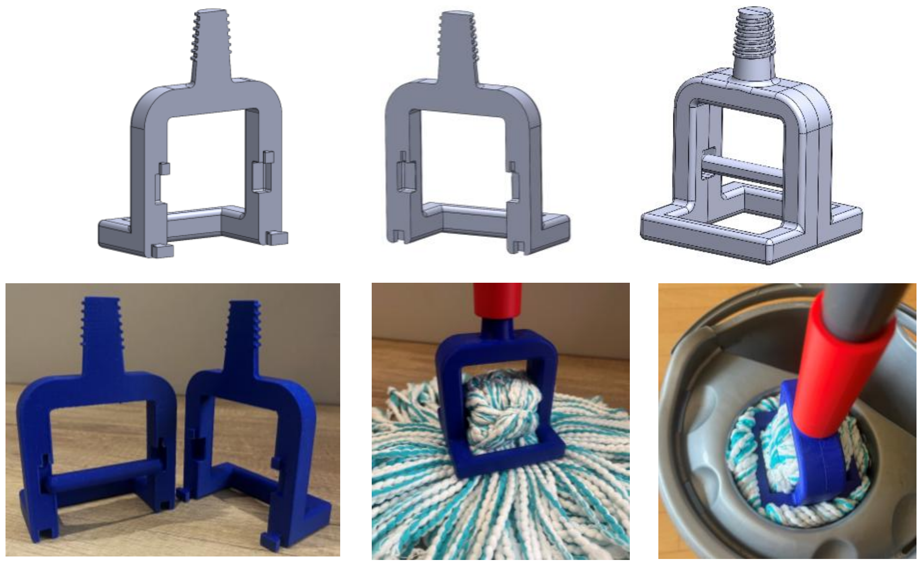


Figure 23. Third prototype version: updated CAD model and 3D-printed result

Once this new version was printed, several aspects requiring improvement were identified. Firstly, it was observed that the guide located next to the hole for inserting the stick that holds the fibres was difficult to position. This issue made assembly more complicated and reduced the practicality of everyday use, leading to a reconsideration of its necessity. Since the piece already separated at the lower section and had an effective guide there, and the handle at the top secured the assembly, a central guide was deemed unnecessary and subsequently removed, thereby improving ease of use.

In addition, during a usability test with a standard bucket, it was found that although the piece fit inside the bucket, it did not rotate properly to allow efficient wringing of the fibres. This obstructed the removal of excess water and compromised functionality. To address this issue, the bottom of the piece was redesigned with a circular geometry to better adapt to the shape of the bucket and allow smooth rotation during the wringing process.

Finally, it was also identified that the overall height of the piece was greater than necessary. There was a visible gap between the piece and the point at which the fibres are fixed, which resulted in excess material and unnecessary bulk. This separation negatively affected the efficiency and compactness of the design, so the height was reduced to optimise both size and material consumption without compromising functionality. *Figure 24* below shows the prototype with all these issues corrected.

Figure 24. Final prototype version: optimized CAD model and 3D-printed result

Once this version was completed, it was thoroughly reviewed to ensure that all previously established requirements were met. Through a combination of physical testing and visual inspection, the prototype demonstrated compliance with the intended functional, structural, and usability goals. The modularity of the system was confirmed, the fiber attachment was effective, and the adjustments made throughout the prototyping process successfully addressed the design flaws detected in earlier versions. As a result, this version of the design was considered fully aligned with the functional needs of the project and with the original design vision. While a more in-depth environmental impact analysis and additional technical detailing are still pending, the prototype already meets the core expectations in terms of usability, modularity, and manufacturing feasibility, making it a solid foundation for the following stages of detail design.

In order to ensure the viability of the solution from an industrial and commercial perspective, expert feedback was essential. For this reason, the design was presented to the company Fapil. Their technical team reviewed the concept and responded positively to the proposed solution. The design was well received and validated in principle, with the main recommendation being to test it using the appropriate plastic injection process and final materials. Since the current prototypes had been produced using 3D printing and alternative materials, the company highlighted the importance of replicating the model with production-grade polymers to fully assess its performance, durability, and adaptability in daily use scenarios. Despite this pending step, the feedback confirmed the product's strong potential and affirmed the decision to proceed with the development of this model.

4.4.2 Technical Specifications

With a validated prototype and a concept aligned with the project's functional needs, the next phase involves defining the technical specifications that will guide the final development of the product. This stage focuses on the key areas of the selection of material and manufacturing process and the definition of a suitable packaging system.

Material Selection

The choice of material plays a fundamental role in the overall success of the product, influencing not only its durability and performance but also its environmental impact. Several material options had already been studied during the early stages of the project, considering absorption capacity, mechanical strength, and recyclability. However, the definitive selection will be based on the results of environmental impact analysis.

The initial approach was to minimize the number of different materials used in the product. Accordingly, the possibility of using recycled nylon across the entire mop was considered, using nylon pellets for the structural parts and nylon fibers for the mop head. However, this option was discarded since nylon fibers have very low absorbency, which is a critical requirement in this application. As the core function of the product is directly related to liquid absorption, such a solution was considered unviable. Moreover, the current design allows for easier separation of fibers from the rest of the structure, so the need for a single-material product becomes less relevant. This means that two different materials can now be used: one for the fibers and another for the handle and connector parts.

For the structural components, including both the handle and fiber-connection parts, the material must be water and humidity-resistant, mechanically strong, and lightweight, while also minimizing environmental impact. As such, only recycled materials are considered, and particular attention is paid to the availability of local suppliers to reduce transport-related emissions.

Based on the comparative analysis shown in *Table 10*, the two most suitable material candidates for the structural parts are recycled nylon (PA6) and recycled polypropylene (rPP). Both materials offer relevant advantages in terms of performance, sustainability, and industrial feasibility.

Recycled nylon stands out for its high mechanical strength, abrasion resistance, and excellent durability under cyclic loads. These properties make it especially reliable in tough conditions, although its tendency to absorb water can compromise dimensional stability over time. In addition, recycled nylon requires higher processing temperatures and longer injection moulding cycles, which increase energy consumption and production costs.

Alternatively, recycled polypropylene offers good structural performance for the expected application, while being lighter and more resistant to water and chemicals. It is also easier to process, with lower melting temperatures, shorter cycle times, and lower tooling wear, which makes it highly suitable for cost-effective mass production. From a sustainability perspective, rPP typically has a lower carbon footprint and is widely available as a recycled material, making it easier to source locally and reducing transport impact. In terms of usability and lifecycle considerations, the reduced weight of rPP can improve handling comfort, lower transportation emissions, and reduce material consumption overall. Additionally, its hydrophobic nature contributes to long-term durability in wet environments, which is essential for cleaning tools.

Taking all these factors into account, recycled polypropylene emerges as the most balanced and suitable material choice for the structural components of the product, combining adequate technical performance with superior sustainability and manufacturing efficiency. The manufacturing process for these parts will continue to be injection moulding, as it is the only viable option for working with plastic in complex geometries. Other alternatives, such as extrusion or compression moulding, are not suitable due to the specific structural and functional requirements of the parts.

On the other hand, the fiber material is a key component of the product, as it directly affects cleaning performance, absorption capacity, and user experience. Based on the comparative evaluation shown in *Table 11*, several candidate materials were identified, but seaweed-based fibers and recycled nylon were discarded due to their lack of absorbency, which is a critical requirement for mops. Each of the remaining candidates presents a different balance of properties in terms of absorbency, sustainability, mechanical behavior, and industrial viability.

Recycled cellulose fibers are highly absorbent due to their naturally porous structure, making them an attractive option for cleaning applications. They are biodegradable, plant-based, and widely available through established recycling processes, which contributes to their environmental appeal. However, their main drawback lies in their mechanical performance: when wet, cellulose tends to weaken, which could compromise durability. In addition, the texture can be rough and less aesthetically appealing, with limited resistance to friction and wear over time.

Recycled bamboo fibers offer a more balanced profile. They provide good mechanical strength and flexibility, even in moist conditions, and have a naturally smooth and pleasant texture. Bamboo is a rapidly renewable resource and offers inherent resistance to fungi and bacteria, making it a hygienic option for cleaning tools. Nevertheless, bamboo fibers generally have slightly lower absorbency than cellulose or cotton and can be more difficult to process at an industrial level unless properly treated. Their availability in recycled form is also somewhat more limited, and cost can be higher.

Recycled cotton fibers demonstrate excellent absorbency and a soft, familiar touch that is well suited for cleaning products. They typically offer better wet strength than cellulose and are derived from textile waste, supporting circular economy principles. However, the environmental footprint of cotton, as already observed in the analysis of Fapil's current mops, is the highest among the materials considered. Additionally, processing recycled textile fibers may be more complex if the source materials are not well separated or prepared. Over time, cotton fibers may also lose structural integrity with repeated use and washing.

Finally, nappy factory waste fibers originate from industrial diaper production waste, which is repurposed into mop strips and stored in large rolls with minimal energy input. This fiber stands out for its excellent absorption capacity, as the original material is specifically designed to retain liquids. Additionally, the reuse of internal manufacturing waste contributes positively to circular economy goals and reduces environmental impact by eliminating the need for additional processing or virgin material sourcing. Another advantage is that it is already being used by Fapil in the production of its ecological mop. However, one potential drawback is that its durability is moderate. The fibers may also have a less refined aesthetic appearance, but this is less critical for their intended functional role.

Considering the functional requirements of the product, especially the need for high liquid absorption and the environmental impact, selecting a single optimal material remains a complex decision. Both nappy factory waste and recycled cellulose fibers present strong advantages in terms of sustainability and absorbency, which are key priorities for this project. However, based on real-world validation, practical handling, and reduced environmental processing requirements, nappy factory waste fibers emerge as the most balanced and realistic solution. The material is already being used effectively by Fapil in similar applications, and its circular reuse further reinforces its suitability from an absolute sustainability perspective. Nonetheless, recycled cellulose remains a promising secondary option, particularly for future iterations or in scenarios where full biodegradability is prioritized over mechanical robustness.

Packaging Concept

Packaging plays a fundamental role in how a product is perceived. It is the first physical interaction the consumer has with the product, and therefore it must communicate the essence of what the product stands for. In this case, where absolute sustainability is at the core of the design, the packaging must immediately reflect this value. It should catch the eye, spark curiosity, and clearly convey the product's environmental commitment, all before the product is even touched.

For this reason, the typical plastic bag commonly used in mop packaging must be rethought. A more meaningful and eco-conscious solution has been proposed: a flowerpot-shaped container made from recycled plantable seed paper. This innovative packaging not only protects the mop fibers during transport and display but also serves as a strong visual metaphor. The fibers rise from the "pot" like blooming flowers, symbolizing growth, nature, and regeneration, which is exactly what can happen if the paper wrapping the product is planted.

Once the product is unpacked, the packaging itself can be planted directly in soil, allowing flowers or herbs to grow from it. In this way, the consumer not only receives a high-performance cleaning product but also takes part in an act of environmental restoration. The packaging becomes a small, tangible gesture toward biodiversity and sustainability, aligning perfectly with the values the product seeks to represent. *Figure 25* shows a possible prototype of this concept.

Figure 25. Possible prototype packaging

More than just a functional element, this packaging transforms into a message, a statement, and an invitation to care. It ensures the product stands out on the shelf not with flashy colours or plastic, but with a story that connects emotionally and ethically with the consumer. Furthermore, once planted, the packaging leaves no waste behind, further enhancing its environmental impact.

4.5 Evaluation of Results and Discussion

After completing the design and development process, it is essential to evaluate the final outcome to determine whether the proposed product meets the established objectives. This stage involves validating the performance of the design, assessing its alignment with functional and sustainability criteria, and drawing conclusions based on objective data and testing.

The first step in this evaluation is to assess the environmental impact of the newly developed mop. This is crucial to confirm whether the design decisions made, such as the choice of materials, packaging, and manufacturing process, were appropriate. The study was conducted using a Life Cycle Assessment (LCA), following the same methodology as the previous one, which compared the different existing mop models from Fapil. To carry it out, an inventory was also compiled, and the same three selection parameters were applied: cost, emissions, and energy consumption. With this, the three ASRs were calculated and are shown in the following *Table 14*.

Table 14. LCA, SOS, and SoSOS and ASR for each SP category of the redesigned mop

DAMAGE CATEGORY	UNIT	LCA	SOS	PRICE		EMISSIONS		ENERGY	
				SoSOS	ASR	SoSOS	ASR	SoSOS	ASR
Acidification	mol H+ eq	0,002760559	1,00E+12	1,87E-02	0,147782	1,16E-02	0,238078	1,15E-02	0,239933
Climate change	kg CO2 eq	0,533125051	6,81E+12	1,27E-01	4,19088	7,90E-02	6,751571	7,84E-02	6,804163
Ecotoxicity, freshwater	CTUe	3,27607039	1,31E+14	2,45E+00	1,338767	1,52E+00	2,156775	1,51E+00	2,173575
Particulate matter	disease inc.	2,49999E-08	5,16E+05	9,64E-09	2,593652	5,98E-09	4,178413	5,94E-09	4,210961
Eutrophication, marine	kg N eq	0,00061861	2,01E+11	3,75E-03	0,164757	2,33E-03	0,265426	2,31E-03	0,267494
Eutrophication, freshwater	kg P eq	0,000226523	5,81E+09	1,09E-04	2,08718	6,74E-05	3,362479	6,68E-05	3,388672
Eutrophication, terrestrial	mol N eq	0,005097206	6,13E+12	1,15E-01	0,044514	7,11E-02	0,071712	7,05E-02	0,072271
Human toxicity, cancer	CTUh	4,99259E-10	9,62E+05	1,80E-08	0,027783	1,12E-08	0,044758	1,11E-08	0,045107
Human toxicity, non-cancer	CTUh	1,74037E-08	4,10E+06	7,66E-08	0,227238	4,75E-08	0,366084	4,72E-08	0,368936
Ionising radiation	kBq U-235 eq	0,083675004	5,27E+14	9,84E+00	0,0085	6,11E+00	0,013693	6,06E+00	0,0138
Land use	Pt	6,588858886	5,21E+15	9,73E+01	0,067701	6,04E+01	0,109067	5,99E+01	0,109917
Ozone depletion	kg CFC11 eq	8,43186E-09	5,39E+08	1,01E-05	0,000837	6,25E-06	0,001349	6,20E-06	0,00136
Photochemical ozone formation	kg NMVOC eq	0,001689716	4,07E+11	7,60E-03	0,22225	4,72E-03	0,358049	4,68E-03	0,360838
Resource use, fossils	MJ	5,734319899	2,24E+14	4,18E+00	1,370431	2,60E+00	2,207785	2,58E+00	2,224983
Resource use, minerals and metals	kg Sb eq	1,38735E-05	2,19E+08	4,09E-06	3,391288	2,54E-06	5,463416	2,52E-06	5,505974
Water use	m3 depriv.	0,237665324	1,82E+14	3,40E+00	0,069907	2,11E+00	0,11262	2,09E+00	0,113498

Climate change remains one of the most critical planetary boundaries already exceeded ([3], [45]) this study reaches the same conclusion, as this category consistently shows the highest ASR ratio. Moreover, although the environmental impacts of the new design are significantly lower across all three evaluation dimensions (cost, emissions, and energy consumption), some absolute sustainability thresholds are still exceeded. This outcome highlights the broader challenge of staying within planetary boundaries, even when more sustainable design strategies are implemented [45].

Examples of this were observed in studies exploring absolute sustainability in battery production, where environmental impacts were calculated using LCA, and even with modifications (such as using alternative materials or new production locations) the products did not remain within the planet's safe operating space [44]. Similarly, in the analysis of the laundry sector, even though scenarios such as using more efficient washing machines and renewable energy reduced impacts, the final results still exceeded planetary boundaries in several categories [45].

These examples, together with the findings of this project, suggest that while product-level design modifications can bring significant improvements, they are often not enough to fully achieve absolute sustainability targets ([45], [44], [40]). Consequently, more transformative strategies are needed, such as promoting responsible consumption patterns and integrating end-of-life practices like reuse and recycling, to achieve true absolute sustainability [40]. These strategies, although beyond the scope of this thesis, represent essential avenues for future research and practical action. Overall, this study provides a clear step forward in aligning with the principles of absolute sustainability, while recognising the need for deeper systemic changes to operate within the safe operating space that the Earth can provide.

In addition to environmental performance, the product must also be evaluated against the set of functional and design requirements defined at the beginning of the project. These requirements reflect the key needs of the user and the product's intended context of use. The following analysis provides an integrated evaluation of how the final design meets each of these specifications.

One of the most important criteria is cleaning efficiency. The mop head is made from highly absorbent fibers sourced from nappy factory waste, a material specifically engineered to retain liquids. These fibers are already used successfully in similar products, ensuring a high level of cleaning performance. Furthermore, the material is resistant to household cleaning chemicals, maintaining structural integrity and cleaning capacity over time.

In terms of affordability, the choice of recycled materials such as polypropylene for the structural parts and nappy factory waste for the fibers contributes to keeping production costs low. Additionally, the use of injection moulding (a highly efficient mass production method) helps minimize unit costs. This ensures that the final product remains competitively priced, making it accessible to a broad range of consumers without compromising performance.

Another functional aspect is the product's ability to ensure dryness. The fiber material used in the mop has been validated for its excellent absorption properties, which allow it to capture a large volume of water and release it efficiently when wrung. The mechanical design ensures that excess water is effectively removed during use, contributing to faster floor drying and better overall cleaning results.

Regarding compatibility with existing bucket systems, the head and connection system were tested with different types of buckets. Adjustments to the geometry during the prototyping phase ensured that the mop fits comfortably and securely in standard bucket wringers, guaranteeing wide compatibility.

The requirement for durability and resistance has also been carefully considered. During the design phase, this requirement was taken into account by incorporating features such as guiding systems to improve alignment and reduce mechanical stress on the components. The structural parts of the mop, made from recycled polypropylene, provide high resistance to bending and impact during regular use. The fibers, while not the most mechanically robust, are supported by a design that distributes pressure evenly, reducing deterioration. Together, these elements create a durable product that can withstand repeated cycles of use without degradation.

From an ergonomic and usability perspective, the mop has been designed with lightweight materials, particularly the use of rPP for the handle, which reduces user fatigue during extended use. The proportions of the handle and head ensure comfortable operation, while the overall balance of the product allows for effective force application without strain. The grip areas have been considered in the design phase to ensure secure, slip-resistant handling.

The connection between the handle and the head has been engineered to guarantee strong and secure attachment of the fibers. The final design incorporates an interlocking geometry that holds the fiber block in place firmly while still allowing for easy disassembly when replacement is needed.

As previously discussed, absolute sustainability has been addressed through multiple facets of the project: the use of recycled materials, local sourcing, a plastic-free and compostable packaging solution, and the integration of a Life Cycle Assessment to measure and reduce environmental impact. Although some planetary boundaries are still exceeded, the product represents a clear step forward in aligning with the principles of absolute sustainability and provides a strong foundation for future improvements.

It is also important to note that the environmental impact study was carried out based on the product's life cycle without a defined expected lifespan, as the exact durability has not been formally studied by the company. Anyway, with the current design, the mop is expected to last significantly longer than conventional models. Moreover, the modular construction allows users to replace individual components rather than the entire product when damage occurs. This not only extends the useful life of the mop but also further reduces its environmental impact, reinforcing its commitment to sustainability.

The results of this validation confirm that the product successfully meets all functional and design requirements set out at the beginning of the project, supporting its viability as a user-oriented solution with enhanced sustainability aspects. While the product has not yet fully achieved the absolute sustainability target, the design represents a significant step towards reducing its environmental impact.

5. CONCLUSIONS AND FUTURE WORK

This project aimed to address a major challenge: the application of absolute sustainability principles in the design of a real, functional consumer product. Despite the complexity of this objective and the lack of pre-existing methodologies in this field, the project successfully developed a design approach that integrates these principles and provides a foundation for further research and application.

Through a structured and rigorous design process, the project achieved a final prototype that not only meets the functional and aesthetic requirements but also significantly reduces the environmental impact compared to current market alternatives. While it is true that the mop does not yet qualify as absolutely sustainable in strict terms, since some planetary boundaries are still exceeded, the reduction in impact has been substantial, particularly when taking into account the use of recycled materials, modular construction, and plantable packaging. It should also be noted that the environmental impact assessment did not take into account the product's expected lifespan. The current design is intended to extend the useful life of the mop significantly, particularly due to its modular nature, which allows users to replace only specific parts instead of the entire product. Including the product's extended lifespan in the analysis would likely reveal an even greater reduction in long-term environmental impact.

Additionally, it is important to highlight that certain constraints were beyond the scope of this redesign. Key elements, such as the necessity of compatibility with existing buckets and the requirement for the product to remain a wet mop, were non-negotiable. These constraints limit how far sustainability can be pushed under current product definitions. A more radical shift, such as rethinking the product typology altogether, might be required in the future to truly reach absolute sustainability.

Nevertheless, this project represents a significant first step and offers a clear methodology for approaching sustainability from an absolute perspective. It provides a framework that other designers can build upon and adapt. Applying planetary boundary thinking to product design is still a novel and complex task, but the lessons learned here point toward a more structured and effective process in future iterations. Indeed, it became evident that designing without any predefined constraints, technological, functional, or market-based, might be necessary to reach fully sustainable solutions.

Looking ahead, future work should prioritise exploring additional approaches and solutions to achieve absolute sustainability, which remains the ultimate goal. This may involve investigating alternative design strategies and materials that do not rely on current constraints or requirements, thereby enabling more flexible and innovative pathways towards truly sustainable products. This includes validating the design under real industrial conditions by manufacturing the product with the final selected materials using intended processes, such as plastic injection moulding, and conducting performance testing to evaluate functionality and durability in real-use scenarios. These steps will be essential to confirm that the product performs as expected beyond the prototyping stage.

In addition, long-term testing should be conducted to evaluate the actual lifecycle and resilience of the product, particularly considering its modularity. Monitoring the wear of replaceable components, user experience feedback, and disassembly processes will provide valuable insights for further improvements.

Ultimately, this project represents an initial step towards addressing absolute sustainability in real-world product development. While the perfect solution remains a long-term ambition, this work demonstrates that measurable progress is possible, even within a complex and evolving context. Overall, this study constitutes a clear step towards aligning with the principles of absolute sustainability, while also recognising the need for deeper systemic changes to operate within the safe operating space that the Earth can provide.

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A. ANNEXES

A 01. Key Interviews with Fapil

Product Design and Quality Manager

1. ***What are the main components of the mop, and how were the materials selected?***

   The main components of the mop are the plastic cap (which consists of two parts the star and the white cover), the cleaning head, the metal handle, and the packaging. A table with the different mop models and material components for each part has been provided.

2. ***Which parts are most likely to break or get damaged during use?***

   The parts most likely to be damaged are, on the one hand, the mop fibers, which tend to accumulate dirt and are exposed to chemical products, and on the other hand, the metal handle, which, despite having a plastic coating, may rust due to prolonged exposure to water.

3. ***How is the durability and functionality of the mop tested? What are the key quality indicators?***

   There are no specific quality indicators or formal durability tests, as these depend largely on consumer usage. However, the quality of the materials used, and the absence of significant customer complaints mean that strict quality controls are not deemed necessary.

4. ***What quality tests are performed, and what percentage of products fail?***

   Visual inspections and weight control are the only common practices currently performed to determine quality. There is no data on the percentage of products that fail. Issues detected during production are immediately addressed, and most products are believed to meet standards.

5. ***Has there been any design, feature, or project idea that was not implemented or released? If so, what was it, and why was it not pursued?***

   One idea was to add an abrasive fiber to one side of the mop to help scrub harder surfaces. However, it was not implemented due to a lack of time and the need to invest in a new production machine.

Sustainability Manager

1. ***Have sustainability principles been integrated into the production process?***

   Yes, some sustainability principles have been integrated, such as using recycled materials from other industries and reducing the thickness of plastic film used for packaging from 40 microns to 25-30 microns. Replacing plastic film with cardboard is also being studied.

2. ***How do you measure the environmental impact (e.g., carbon footprint, waste)?***

   The environmental impact is not formally measured yet. However, it is noted that production generates very little waste, as most materials can be recovered.

3. ***Are there any initiatives to reduce waste or adopt circular economy principles?***

   Yes, initiatives include replacing plastic film with cardboard and using recycled materials. However, components such as pins cannot be reused, as they become irreparable once disassembled.

4. ***What challenges have you faced in promoting the recycled-material line (Ocean line)?***

   The main challenge is the higher cost of recycled materials, which discourages retailers from purchasing these products, even though end users might be willing to pay more. However, once the retailer barrier is overcome and the products become accessible to consumers, they sell just as well as those that are not part of the Ocean Line, highlighting that end users value sustainable options.

5. ***Are suppliers and supply chain decisions influenced by sustainability goals?***

   The company is beginning to evaluate suppliers' policies and practices to ensure sustainability criteria are considered, although the process is progressing slowly. Local or regional suppliers are preferred when possible to reduce transportation impact.

Production Manager

1. ***Could you describe the production process for the mop from start to finish?***

   The production process begins with raw material extraction and transportation to the factory. Once at the factory, the process starts with the production of the plastic components, such as the star and the white cover. These are followed by the assembly of the mop head, which may or may not include packaging at this stage, depending on whether the mops are sold with the handle or not. Finally, the product is packaged into boxes, typically containing 12 units, and placed onto pallets for shipping. The pallets are then transported to warehouses or directly to stores, where consumers can access the product. The end-of-life for most mops involves disposal in landfills or incineration.

2. ***How is waste generated and managed during production?***

   Waste generation during production is minimal, as most processes are highly efficient. Waste is considered nearly zero, and any defects identified are corrected immediately.

3. ***How many units are produced daily, and what are the main bottlenecks?***

   The production line operates at a speed of 1,500 units per hour, over two shifts of 16 hours daily, producing around 24,000 mops per day. The main bottleneck occurs during the final packaging stage, where carton boxes must often be prepared manually to keep up with the machine's speed. Additionally, the machine occasionally encounters issues with placing the refills into the boxes, requiring manual intervention to complete the packaging process.

4. ***Are there initiatives to minimize waste or reduce environmental impact through circular economy principles? Does the production process follow any environmental regulations?***

   No specific environmental regulations are followed, but ideas have been proposed to improve sustainability. These include simplifying packaging by using less material or selling mops without packaging. Circular economy principles are lightly integrated, focusing on extending product life and reducing waste wherever possible.

Marketing and costumer Manager

1. ***What specific requirements or features have customers requested most frequently?***

   Customers primarily request a mop that cleans effectively, is priced affordably, and leaves the floor dry after cleaning. These features are particularly valued and drive product demand.

2. ***Which mop has the highest demand, and why is it so popular?***

   Mops with microfiber cleaning heads are in the highest demand because they clean better and dry floors more effectively than other types.

3. ***How does the Ocean line compare in terms of sales and customer response?***

   The Ocean line receives positive feedback from customers, but its higher price makes it difficult to persuade retailers to stock the product. Promotions and special events are the primary ways this line is successfully sold.

4. ***Who are the main competitors, and how do our mops stand out?***

   The primary competitor is Vileda. When both products are available on shelves, the choice depends on the customer, as both brands sell well.

5. ***Are there any customer-driven design changes implemented recently?***

   No significant customer-driven design changes have been implemented recently.

6. ***What trends or demands do you foresee impacting mop design in the future?***

   Trends such as robotic cleaning devices and products like the iRobot or Dyson models, which can wash, clean, and dry surfaces, represent a major challenge for traditional mop designs. These innovations may shift customer preferences away from manual mops.

Supplier Relations Manager

1. ***Are the mop materials sourced locally or internationally? How are they transported to the company?***

   Materials are sourced both locally and internationally. For instance, packaging materials are often sourced locally, while other components like fibers may come from Europe, India, or Asia. All materials are transported to the company via road transport.

2. ***How often do you receive material shipments from suppliers? What is the typical order quantity per shipment?***

   Material shipments depend on the product and the supplier. For example, covers are produced internally by Fapil and depend on production needs, cardboard orders are typically placed annually, and cotton and other fibers are supplied every 2 to 3 months by external suppliers

3. ***What criteria are used to select suppliers (e.g., cost, reliability, sustainability)? Have local suppliers been considered to reduce transportation impact?***

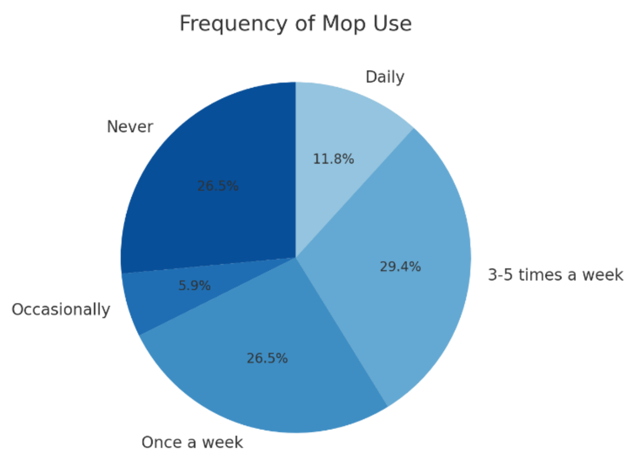
   Supplier selection is primarily based on cost and quality. While sustainability is not yet a mandatory criterion, it may be considered in the future.

4. ***Do your suppliers have any environmental certifications or standards that you specifically require?***

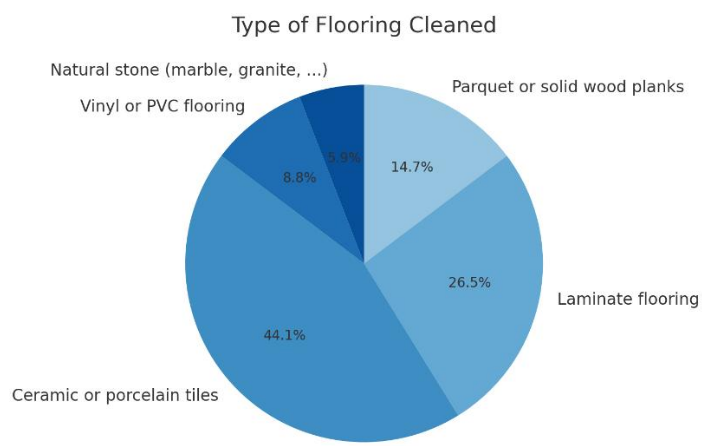
   Currently, no specific certifications are required from suppliers, although some suppliers may already have them. This could become a requirement in the future.

A 02. Customer Survey Results

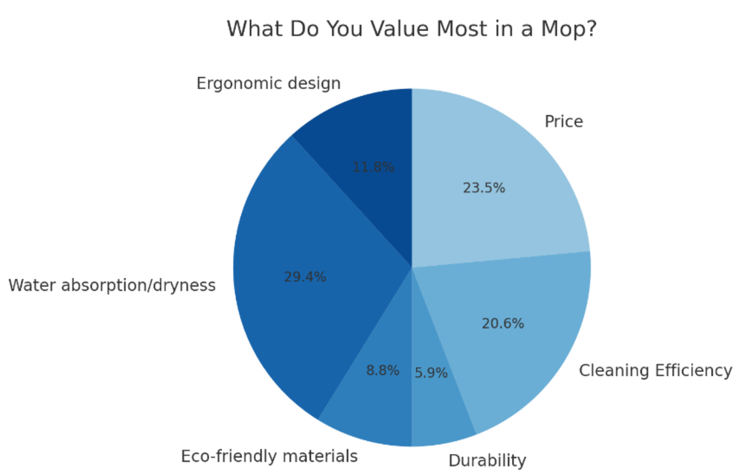
1. How often do you use a mop?



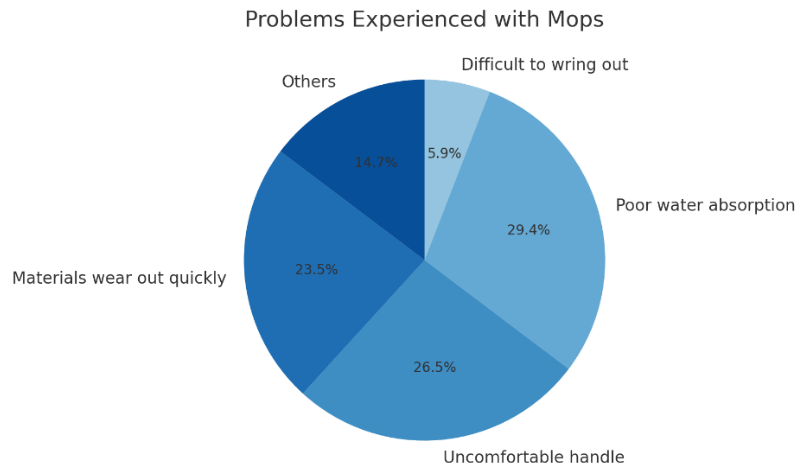
2. What type of flooring do you typically clean with a mop?



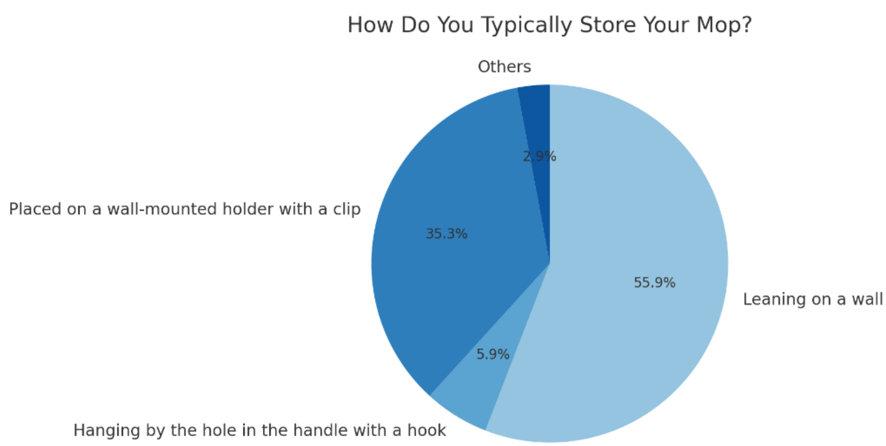
3. What do you value most in a mop?



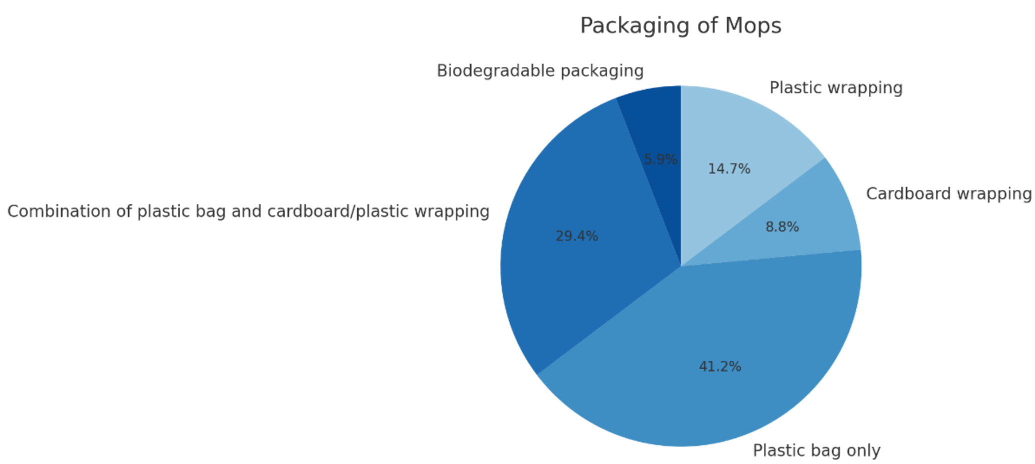
4. What problems have you experienced when using mops?



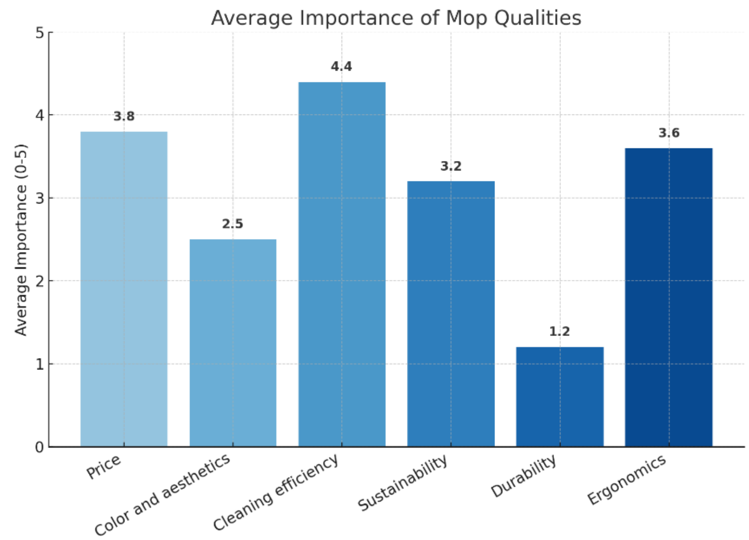
5. How do you typically store your mop?



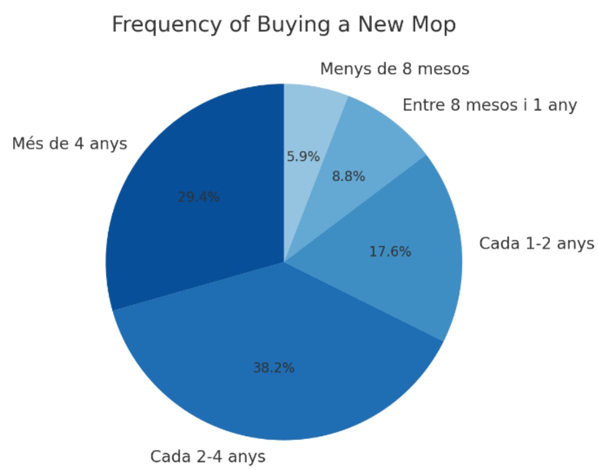
6. What is the packaging of the mops you usually buy like?



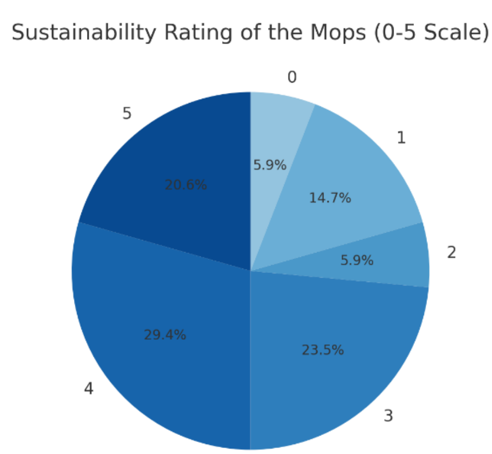
7. On a scale of 0 (not important at all) to 5 (very important), how do these qualities matter in a mop for you?



8. How often do you buy a new mop?



9. On a scale of 0 to 5, how would you rate the sustainability of the mops you use?



A 03. LCA Inventory of the current mop

This annex presents the inventory conducted for each of the Fapil mop models. To avoid presenting numerous tables for each individual model, the inventory has been structured into two main tables. The first table shows the material inventory corresponding to the different fibres used in each mop. The second table contains the inventory for the rest of the process, which is common to all mop models. Below, *Table A 1* shows the material inventory of the different fibres for each mop.

Table A 1. Raw material inventory of the different fibres for each mop. Information provided by Fapil. (a) average value for energy required to cut and roll fabric [69]

	Mop Type	Material Fibers	Ecoinvent	Value	Unit
Fibers Material	Microfiber	Polyester	Fibre, polyester {IN}| polyester fibre production, finished	0,152	[kg]
	Terry microfiber strips	Polyester	Fibre, polyester {IN}| polyester fibre production, finished	0,1032	[kg]
		Polyamide	Nylon 6 {RER}| nylon 6 production	0,0168	[kg]
	Cotton	Cotton	Fibre, cotton, organic {IN}| fibre production, cotton, organic, ginning	0,1581	[kg]
		Other fibres	Fibre, viscose {GLO}| fibre production, viscose	0,0279	[kg]
	Power mop	Polyester	Fibre, polyester {IN}| polyester fibre production, finished	0,08342	[kg]
		Polyamide	Nylon 6 {RER}| nylon 6 production	0,01358	[kg]
		Jute	Fibre, jute {IN}| fibre production, jute, retting	0,0388	[kg]
		Bambu	Fibre, viscose {GLO}| fibre production, viscose	0,0388	[kg]
		Cotton	Fibre, cotton, organic {IN}| fibre production, cotton, organic, ginning	0,0194	[kg]
	Ecological	Nappy fibres	Electricity, high voltage {PT}| market for electricity, high voltage	0,00367 [a]	[kWh]
	Viscose strips	Viscose	Fibre, viscose {GLO}| fibre production, viscose	0,0832	[kg]
		Pes	Fibre, polyester {RoW}	0,0104	[kg]
		pp	Textile, nonwoven polypropylene {RoW}| textile production, nonwoven polypropylene, spunbond	0,0104	[kg]

Table A 2 below presents the complete inventory of the rest of the process, including materials, processes, transport, and end-of-life stages, as detailed throughout the report.

Table A 2. Life Cycle Inventory of the mop. Information provided by Fapil. (a) energy consumed based on [70], [71], [72], [73] (b) energy consumption based on [74], [75], [76]

	Categories	Ecoinvent	Value	Unit
Raw Materials	Fibers	Depends on mop model according to *Table A 1*		[kg]
	Polypropylene	Polypropylene, granulate {RER}| polypropylene production, granulate	0,05084	[kg]
	Steel	Steel, low-alloyed {RoW}| steel production, electric, low-alloyed	0,13455	[kg]
	PVC	Polyvinylidenchloride, granulate {RER}	0,04761	[kg]
	Cardboard	Folding boxboard carton {RER}| folding boxboard carton production	0,03835	[kg]
	Plastic Film	Packaging film, low density polyethylene {RER}	0,00063	[kg]
Transport	To factory and users	Transport, freight, lorry 16-32 metric ton, EURO5 {RER}	*	[tkm]
	To landfill	Municipal waste collection service by 21 metric ton lorry {RoW}	0,01696	[tkm]
Production	PP injection	Injection moulding {RER}| injection moulding	0,04684	[kg]
	Head mop assembly + packaging bag	Electricity, high voltage {PT}| market for electricity, high voltage	0,0042 (a)	[kWh]
	Steel extrusion	Metal working, average for steel product manufacturing {RER	0,13455	[kg]
	Plastic extrusion	Extrusion, plastic film {RER}| extrusion, plastic film	0,05161	[kg]
	Handle mop assembly	Electricity, high voltage {PT}| market for electricity, high voltage	0,03533 (b)	[kWh]
	Factory	Plastic processing factory {RER}| plastic processing factory construction	$3{,}14 \times 10^{-10}$	[p]
End of Life	Waste	Municipal solid waste {RoW}| treatment of municipal solid waste, sanitary landfill	0,99079	[kg]

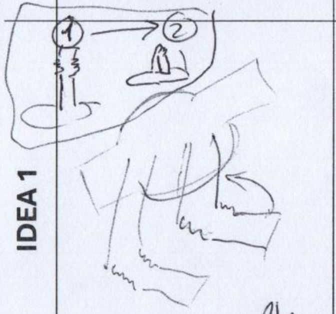
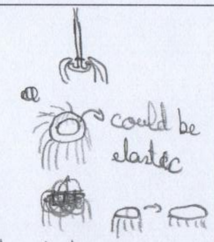
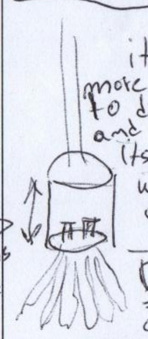
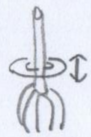
* The tonne-kilometres (tkm) of transport to the factory and users depend on the origin of the raw materials, which also varies for each mop. To protect confidentiality, only the final transport values for each mop will be provided, without disclosing the individual distances travelled by each material to reach the factory. These total values are shown in the following *Table A 3.*

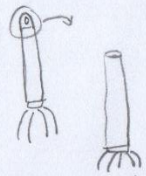
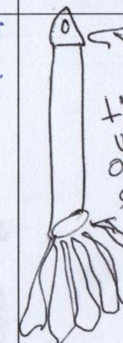
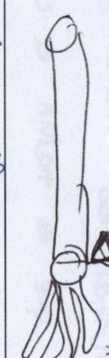
Table A 3.Summary of transport tonne-kilometres (tkm) by mop

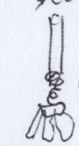
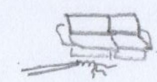
Mop Type	Distance
Microfiber	3,733 tkm
Terry Microfiber Strips	3,283 tkm
Cotton	3,701 tkm
Power Mop	3,951 tkm
Ecological	2,336 tkm
Viscose Strips	3,045 tkm

A 04. Results of the Brainwriting exercise

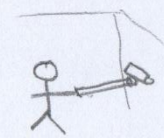
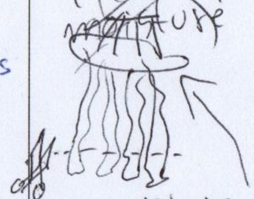
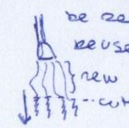
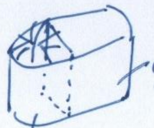
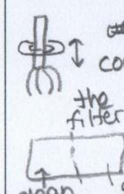
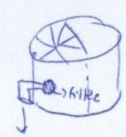
	PARTICIPANT 1	PARTICIPANT 2	PARTICIPANT 3	PARTICIPANT 4	PARTICIPANT 5	PARTICIPANT 6
IDEA 1	Design for Reuse: Easy fix system to hold the fibers in place. The only waste would be the actual fibers. fibers	not sure if I understood ~~What if the mecha~~	all the handle part made by bambu or so other material and the fibers could them be attached by theirselves fibers strips	if elastic system is used it would be easier to disassemble Design for reuse and Design for recycling	This makes possible the reuse of the handle for different kinds of mops (different fibers/shapes) and different purposes (outside of mops)	~~[illegible]~~ How to disassembly only fibers?
IDEA 2	Design for efficiency water + soap dispenser in the mop. Water tank	What if you ~~add~~ a fan blower in the tip? maybe too complex, ~~them~~ its a dry blower, why would you need a mop		There could be some kind of recharge that you could insert in the top of the handle bar. when you press the mob against the floor it spills detergent	You could use the blower at the tip to dry the fibers, not the floor. Then they would more efficiently soak the water of the floor (more efficient for cleaning than blow drying it)	Where the dirt goes? ~~[illegible]~~ Still has a bucket with water?
IDEA 3	Design ~~for reuse~~ with recycled materials: Waste from other industries for the fibers.	build the plastic ~~parts~~ components ~~[illegible]~~ with scrap fibers them when everything goes to ~~the~~ recycling stage, they would be made from the "same" material	use recicled plastic of the bottels or maybe hair for the fibers or clothes that had a lot of uses and they are broken		Recycled plastic from old handles to make new pieces	

	PARTICIPANT 1	PARTICIPANT 2	PARTICIPANT 3	PARTICIPANT 4	PARTICIPANT 5	PARTICIPANT 6
IDEA 1	 ① → ② it this folds and clicks into position it may be eisiest to disassemble/Recycle	maybe with some magnetic part at the end it will click better and it will be easiest to separate	 could be elastic If it is elastic ~~you~~ it would embrace the ~~bucket~~ bottom of the bucket bar and you would need one less		~~Magnet~~ Mechanism in plastic better, magnetic will be weaker and with higher impact elastic didn't understand	Clamp system for ~~individual~~ fibers. Replace only the fibers. snap locks  Sell replacement fibers.
IDEA 2	 it this goes up and down it will be more efficient to drain water and ~~the~~ likely its life will be extended Downside ⇒ more complex ⇒ more materials	 a piece of plastic that humans can use to dry the fibers and the bucket will be more simple		There could be a rotation feature that facilitates the drying of the fibers making it more efficient		
IDEA 3	the pastic part that connects everything could be made out of compressed fibers (same material as the tip of the mop) highly compressing them will give them strength			If the small connection piece could be made out of compressed fibers then maybe so could the whole handle?	In terms of sustainability it is better to easily separate the two parts and do the cable in ~~pl~~ recycled plastic (guessing from other projects)	

	PARTICIPANT 1	PARTICIPANT 2	PARTICIPANT 3	PARTICIPANT 4	PARTICIPANT 5	PARTICIPANT 6
IDEA 1	 most people don't use that part of the handle and it could be fabric with plastic // bambu.	if bambu is used for the whole handle bar it might not need to be painted & less polutants emission.	The top part of the handle could be graspable / holdable to facilitate cleaning instead of being that way to facilitate storage (rarely used)	I think people don't grab the mop from the top. Analyse different cable materials, all without paint. But recycled material have paint already !!	Make the top part optional. Not all people hang the mops. Sell it separate.	 Make this part usable in other contexts ~~sell~~ if separated am this also. Like a keychain or a spring to hang clothes.
IDEA 2	We could use the fibers to put them in ~~chairs~~ the "legs" of the chairs or tables to protect the floor. 	those fibers could also be ~~used~~ used to produce cleaning cloth/or a doormat.	The used fibers could be reused for many applications, using them as they are to hold wet things and protect the surface or as raw material for new textile	All these ideas in a company context need to have a ~~sta~~ scheme for EOL	Make the fibers so they can be used for other cleaning applications after mop life	 this often breaks here. So make the handle stick double sided => if it breaks, you flip it
IDEA 3	 put all fabrics in circles and ~~not~~ in strips to clean a bigger area.	but maybe more plastic would be needed? the coupling between handle bar and	Maybe more difficult to dry!	And to use		

	PARTICIPANT 1	PARTICIPANT 2	PARTICIPANT 3	PARTICIPANT 4	PARTICIPANT 5	PARTICIPANT 6
IDEA 1	use natural fibers or human/animal hair based products	Not sure if animal / human ~~the~~ hair is more sustainable. Maybe natural fibers like plaintain, flax, etc? Not sure if possible	Cotton is one idea of organic fiber, BUT not necessarily sustainable... Composite fibers with ~~the~~ pe + flax (or others) ? Are there mechanical properties relevant for cleaning efficiency?		not sure these are good absorbers. scrap cooth and pillows ? car seats, etc	a bathroom towel that have been used already used. towels ... The packaging with cardboard
IDEA 2	use recycled plastics as the baseline material for the fibers holder	use recycled plastics for the holder as well. make the fibres recyclable -> after end of life can be used to make new fibres	Need for a eoL collection ~~##~~ scheme for that. Maybe free resp if old is returned ?	Not free, but discounted! In this case design the mop for easy disassemble in an industrial setting. Also look for easy to recycle fibers. Prob. synthetic?	New idea. A damper in the handle/plastic section  ⇒ reduces mechanical loads ⇒ increases life	this part could move more easily to the bottom to the sofa or other objects 
IDEA 3					Make the fibers to disolve while they are being used. (releasing cleaning stuff) ⇒ Avoid detergent ⇒ In the end of life, there will be less material to recover/recycle	

	PARTICIPANT 1	PARTICIPANT 2	PARTICIPANT 3	PARTICIPANT 4	PARTICIPANT 5	PARTICIPANT 6
IDEA 1	more dueable handle (wood/metal) that makes it easy to change the "head" more ergonomic and possibility to use for other equipments (e.g. broom)	Develop cheap ~~heads~~ heads for mops, brooms, dry mops, sell in a set	Not really company dependent, but it would be interesting to see a international standard ~~[illegible]~~	what if the handle is designed to force the user to wash in a certain way that it is less "stressful" for the mop, and promotes cleaning efficiency, extending the life of the product	the chemicals are the problem for the fibers so maybe changing to another product like clothes cleaning it will be better	
IDEA 2	~~Poss. Utilize~~ Recycle clothing or textile materials to ~~[illegible]~~ make the fibers	~~[illegible]~~ Use also recycled plastic for the cable ↓ Product merely made of recycled materials	Closed-loop business model! Retrieve old mops and recycle the materials for new mop... Ex: the plastic insert for the fibers	what if the material heats with movement? OR if the mop is self dissolving, therefore avoiding the need of using detergent	fibers with another texture and not simply strips will have more ~~[illegible]~~ and clean better without chemicals	when pressed against the floor the mob moves away; different format/shape of the fibers. a bit more "robust" fibers
IDEA 3	Instead of "separate" fibers, a "full" cloth that is easy to wash and therefore is more durable; instead of	Maybe ~~[illegible]~~ more difficult ~~[illegible]~~ to dry in the bucket?	Combine with an active drying bucket? Water reservoir; Drying side; Fan	more expensive, more materials, less sustainable; does not clean as good → less surface area	could be a fast drying cloth like those Decathlon towels.	

	PARTICIPANT 1	PARTICIPANT 2	PARTICIPANT 3	PARTICIPANT 4	PARTICIPANT 5	PARTICIPANT 6
IDEA 1	Very resistant and more expensive cable → very cheap/~~pee~~ mop ends Cable → Wood / steel / ?		What if the hadle / cable was a universal thing for more than just a mop?	for painting maye they will need for the brush 		
IDEA 2	~~Z~~ Mop made exclusively of recycled materials	Fibers → cotton from textile ind. ex: scrap fibers Plastic parts → scraps from automotive ind.	~~Nylon absorbs a lot of moisture~~  fibers that you cut when used			Instead of replacing the "head" you could pull the fibers and cut the used parts (these parts could be recycled/reused)  new cut
IDEA 3	Two compartments for dirty / clean water  clean water dirty water	→ Maybe water filtration to water plants?  dirty water clean water ~~dirty water~~ filter	very good idea the filters could be made by	if the mop have the plastic peace for it selves to dry the fibers  this could help the 2 deposits filter clean water dirty water	compartment idea is very nice the filtering would need energy? • would need three compartments? filtering is useful at the end of the cleaning.	Dirty water could have filter out of the bucket  filter filtered dirty water

A 05. Notes and outcomes of the SCAMPER exercise

Substitute

- What can I substitute so as to make an improvement?
- How can I substitute the place, time, materials or people?
- Can I substitute one part for another or change any parts? → Replace The Head → Replace/remove Top part
- Can I replace someone involved?
- Can I change the rules? → Redesign/reconside bucket (ex. soap/water dispenser)
- Should I change the name?
- Can I use other ingredients or materials? → Recycled materials → Low water consumption materials → House materials past life (ex: Towels)
- Can I use other processes or procedures?
- Can I change its shape, colour, roughness, sound or smell? → Consider bamboo or other natural mats for the handle.
- Can I use this idea for other projects?
- Can I change my feelings or attitude towards it?

Combine

- What ideas, materials, features, processes, people, products, or components can I combine?
- Can I combine or merge this or that with other objects?
- What can I combine so as to maximize the number of uses?
- What can I combine in order to lower the costs of production?
- Which materials could I combine?
- Where can I build synergy?
- Which are the best elements I can bring together so as to achieve a particular result?

Adapt

- Which part of the product could I change?
- Could I change the characteristics of a component?
- Can I seek inspiration in other products or processes, but in a different context?
- Does the history offer any solutions?
- Which ideas could I adapt, copy, or borrow from other people's products? → Look at the comercial american dry mops
- What processes should I adapt?

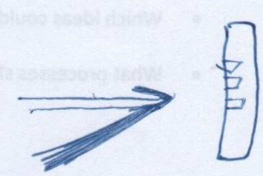
- Can I adapt the context or target group?
- What can I adapt in this or that way in order to make this result?

Modify

- What can I magnify or make larger?
- What can I tone down or delete?
- Could I exaggerate or overstate buttons, colours, size…?
- Could I grow the target group?
- What can be made higher, bigger, or stronger? → Increase durability of the handle
- Can I increase its speed or frequency? or efficiency
- Can I add extra features?
- How can I add extra value? → Detergent dispenser
- → The packaging → Make it just a sticker
- What can you remove or make smaller, condensed, lower, shorter or lighter—or streamline, split up or understate? → The bucket → Remove the top
- What can I change in this way or that way so as to achieve such and such a result?

Put to another use

- What else can it be used for? → Multiple use cable
- How would a child use it?—an older person? → Requirement ??
- How would people with different disabilities use it?
- Which other target group could benefit from this product?
- What other kind of user would need or want my product?
- Who or what else may be able to use it?
- Can it be used by people other than those it was originally intended for?
- Are there new ways to use it in its current shape or form?
- Would there be other possible uses if I were to modify the product?
- How can I reuse something in a certain way by doing what to it?



Eliminate

- What can I remove without altering its function? → Top part
- Can I reduce time or components? → Maybe different ~~cable~~ handle sizes?? smaller people buy less material
- What would happen if I removed a component or part of it?
- Can I reduce effort? → easy dry systems → auto clean system → disolving fibers
- Can I cut costs?
- How can I simplify it?
- What's non-essential or unnecessary?
- Can I eliminate the rules?
- Can I make it smaller?
- Can I split my product into different parts?
- I can eliminate what by doing what?

Rearrange

- What can I rearrange in some way – can I interchange components, the pattern, or the layout?
- Can I change the pace or schedule?
- What would I do if part of your problem, product or process worked in reverse?
- I can rearrange what in what way such that this happens?

A 06. Scoring Tables for Concept Evaluation

The following tables present the evaluation of each design concept (Sketch 1 to Sketch 5) based on specific criteria such as ease of manufacturing, ease of use, or absolute sustainability impact. For each criterion, the concepts are compared against one another to assess their relative performance. The scores are then normalized to obtain a ponderation that reflects the importance of each concept with respect to that criterion.

Table A 4. Weighting of the design concepts based on the ease of manufacturing criteria

Ease of manufacturing

	Sketch 1	Sketch 2	Sketch 3	Sketch 4	Sketch 5	Sum+1	Pondera.
Sketch 1		1	1	1	1	5	0,333
Sketch 2	0		0,5	0	1	2,5	0,167
Sketch 3	0	0,5		1	1	3,5	0,233
Sketch 4	0	1	0		1	3	0,200
Sketch 5	0	0	0	0		1	0,067
				Total		15	

Table A 5. Weighting of the design concepts based on the ease of use criteria

Ease of use

	Sketch 1	Sketch 2	Sketch 3	Sketch 4	Sketch 5	Sum+1	Pondera.
Sketch 1		1	1	0	1	4	0,267
Sketch 2	0		1	0	0,5	2,5	0,167
Sketch 3	0	0		0	0,5	1,5	0,100
Sketch 4	1	1	1		1	5	0,333
Sketch 5	0	0,5	0,5	0		2	0,133
				Total		15	

Table A 6. Weighting of the design concepts based on the absolute sustainability impact criteria

Absolute Sustainability Impact

	Sketch 1	Sketch 2	Sketch 3	Sketch 4	Sketch 5	Sum+1	Pondera.
Sketch 1		1	1	0,5	1	4,5	0,300
Sketch 2	0		1	0,5	1	3,5	0,233
Sketch 3	0	0		0	0	1	0,067
Sketch 4	0,5	0,5	1		1	4	0,267
Sketch 5	0	0	1	0		2	0,133
				Total		15	

Table A 7. Weighting of the design concepts based on the durability and resistance criteria

Durability and Resistance

	Sketch 1	Sketch 2	Sketch 3	Sketch 4	Sketch 5	Sum+1	Pondera.
Sketch 1		1	1	1	1	5	0,333
Sketch 2	0		0,5	0,5	0	2	0,133
Sketch 3	0	0,5		0,5	0	2	0,133
Sketch 4	0	0,5	0,5		0	2	0,133
Sketch 5	0	1	1	1		4	0,267
				Total		15	

Table A 8. Weighting of the design concepts based on the aesthetic appeal criteria

Aesthetic appeal

	Sketch 1	Sketch 2	Sketch 3	Sketch 4	Sketch 5	Sum+1	Pondera.
Sketch 1		1	1	1	1	5	0,333
Sketch 2	0		0	0,5	0	1,5	0,100
Sketch 3	0	1		1	0,5	3,5	0,233
Sketch 4	0	0,5	0		0	1,5	0,100
Sketch 5	0	1	0,5	1		3,5	0,233
				Total		15	

Table A 9. Weighting of the design concepts based on the cost criteria

Cost

	Sketch 1	Sketch 2	Sketch 3	Sketch 4	Sketch 5	Sum+1	Pondera.
Sketch 1		1	1	1	1	5	0,333
Sketch 2	0		1	0	1	3	0,200
Sketch 3	0	0		0	1	2	0,133
Sketch 4	0	1	1		1	4	0,267
Sketch 5	0	0	0	0		1	0,067
				Total		15	