

École polytechnique de Louvain

Designing circular household appliances: a proposal

Hands-on proof-of-concept

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LLN - 2094, a distopic future...

Picture a moment a few years from now. Imagine a world where electronic products are designed to last forever. When one just stops working one day, you go to your local fabrication laboratory to repair it yourself or even with your very own tools you already have at home. If a part breaks, you just replace it easily with a spare part you can even reproduce yourself. But maybe all of that is not possible every time and your favorite local shop will take your object back. Then, the product is disassembled into its very basic components. The ones which are still usable get reused for the same or other purposes and contribute to the making of new goods, while the broken ones are recycled into new materials, offering them a new life.

On the way back home from the fabrication laboratory, you realize that this process forms a global supply of parts and materials which are compatible with each other, and which can be forever turned into new products, locally. All of these fields full of electronic waste have stopped growing and the rusty remaining is getting treated. In a few years there will be not much as an abandoned nut left to find.

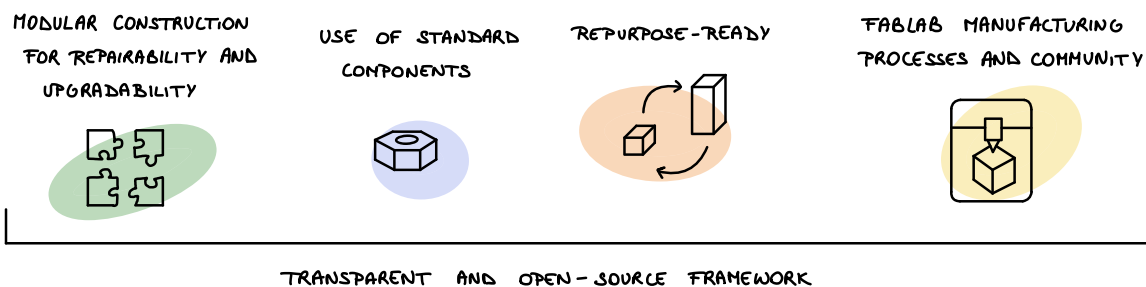
You find yourself to like this new emerging system of decentralised production based on locally repaired, reused and recycled goods and materials. You realize it also brought you -a user- together with the producers, repairers and other diverse communities of people you didn't know of before, but who take an essential place in the electronic products you use daily and thus, a place in your life as well.

With time, the old make-use-dispose model becomes an dusty memory from old times, being replaced by this new workflow benefiting the people, and the planet.

Abstract

The ever-increasing amount of e-waste (53.6 Mt generated in the world in 2019 and 74 Mt are expected by 2030) has drastic social and environmental consequences (soils pollution, precious materials extraction, open-air landfills, greenhouse gas emissions,...). Irreparable failures, planned technological obsolescence or even fashion trends are at the source of the early disposal of these objects. However, the linear economy in which we live in today can't be compatible with these emerging challenges. This project aims at investigating one of the many ways to solve the e-waste problem. The research objective was to propose an alternative electronics economy, by enhancing repair tendencies of household appliances thanks to distributed design and local manufacturing processes within a 'FabLab' (a fabrication laboratory). The goal is to give the object as many life cycles as possible (with repair, refurbishment, remanufacturing and recycling) to lower the energy consumption and materials extraction associated with the fabrication and use of these appliances. Design has proven to be the major cause of primary disposal and disassembly hindering. As a proof of concept, a hand blender was completely redesigned after the functional and disassembly analysis of a product on the market, turning the latter idea definition into a tangible object. After the construction of a reparability and reproducibility grid destined to designers, manufacturers, repairers and consumers, its repair and distributed design performances were evaluated. The environmental impacts embedded in the production of the object were assessed thanks to a life cycle analysis which proved the need for local materials, recycling options for End-of-Life and educated consumption on raw materials.

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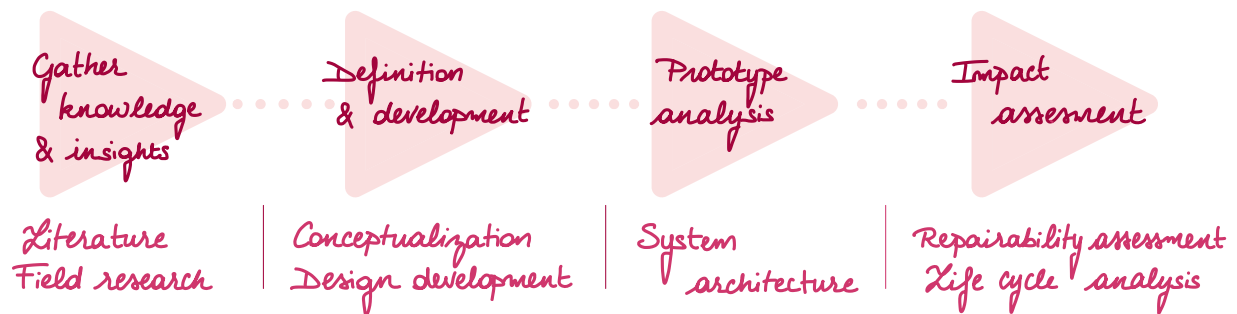
Terms and Abbreviations

3DP	Three Dimensional Printing
CAD	Computer Aided Design; method of designing 3D objects digitally.
CE	Circular economy
Component	Part of a product that cannot be taken apart without destruction.
Disassembly	Process whereby an item is taken apart in such a way that it could subsequently be reassembled and made operational.
FabLab	A space with tools and facilities where makers can go to build their projects and where they help each other.
EEE	Electronic and Electrical Equipment
EoL	End-of-Life; final stage of a product's existence.
FDM	Fused deposition modelling; a common 3D printing technique where a plastic filament is melted and extruded through a nozzle, building up the desired shape.
LCA	Life Cycle Analysis
Maintenance	Set of procedures to ensure the serviceability of a product.
Maker	Someone who makes things as a hobby using modern technologies.
PLA	Poly Lactic Acid, a common 3D printing plastic.
Spare part	An interchangeable part which can replace a faulty, failed or worn-out replaceable part.
Repair	Process of returning a faulty product to a condition where it can fulfil its intended use. (From ISO 14000 family of standard)
Reusability	Characteristic of a product that allows all or some of its parts or the product as a whole to be used again for the same purpose.
Upgradability	Characteristic of a product that allows all or some of its parts to be separately upgraded or replaced without having to replace the entire product.
SLA	Stereolithography (SLA) is a 3D printing technology using UV lasers as a light source to selectively cure a polymer resin.
WEEE	Waste from Electrical and Electronic Equipment

Project approach

The main goal of this project is to propose an alternative workflow for household appliances, enhancing repair and local manufacturing through distributed design. This is done by redesigning objects to ease disassembly as well as ensuring reproducibility in FabLabs environments.

After getting to know the environment and answering the primary questions in the first chapter, the conceptualization of the new framework will take a defined shape, along with the analysis of a case study appliance. Next, a third chapter will focus on developing a functioning realistic prototype integrating all the challenges drawn earlier. The last phase will put repairability to the test through an adapted grid and a life cycle analysis, allowing to have metrics for evaluation of the proposed work.



Research questions

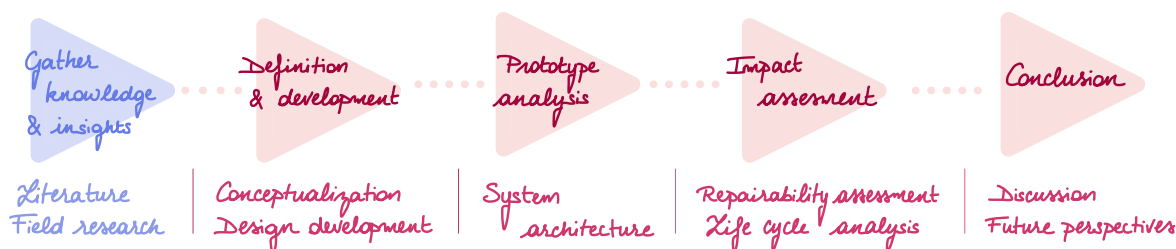
How does the design of a household appliance influence the repair process ?	How does current appliances hinder repair ?	How and where can the concept turn into a tangible object ?	What would be the best tool to evaluate repairability and reproducibility ?
How do end users with limited repair experience and repairers interact with household appliances ?	Which design strategies could ease repair ?	How to make the solution technically feasible ?	What is the environmental impact of this prototype and in which conditions ?
What are the key opportunities for manufacturing in a Fablab ?	Where should each stakeholder be involved ?		

Sub tasks

Explore the context	Define the perimeter of the project	Explore fabrication techniques	Assess the prototype's repairability and FabLab reproducibility
Extract design guidelines	Select a case study and identify the role of each stakeholder and design requirements	Develop a physical prototype	Perform a life cycle analysis

1

Gathering knowledge and insights



In this chapter, the context is explored through literature and some field research. The results are split up into the following sections: the context of e-waste in the current economy, the different paradigms of design fighting against the WEEE problem, a context on repair tendencies and manufacturing within a FabLab, how can distributed design support the wished outcome of previous sections and the realities of additive manufacturing.

Main research questions

The following research questions were formulated as guidance for this chapter.

- How does the design of a household appliance influence the repair process and recovery opportunities?
- How do end users with limited repair experience and repairers interact with household appliances?
- What are the key opportunities for manufacturing of a Fablab?

During this context analysis phase, the questions were answered thanks to a few research methods. Literary sources recalled the history of the repair community, the use of 3D printing as well as design paradigms rooting for a more circular economy. Some field research took place naturally thanks to the Repair Studio (a pilot project of a Repair Café within the University) which took place in the Makilab (a Fablab in Louvain-la-Neuve, Belgium) hosted by the OpenHub (a hub for entrepreneurs). Different communities were present during the elaboration of the project and their interactions could be observed. This was central to have a meaningful overview of the available skills, personal motivations, limitations and other potential insights for this project.

1.1. Closing the loop of valuable goods

1.1.1. Where do broken electronics go?

The Global E-waste Monitor (GEM, [18]) stated that in 2019, the world generated a striking 53.6 Mt of e-waste, representing an average of 7.3 kg per capita. In the same study, the GEM also estimated an amount of e-waste generated exceeding 74 Mt by 2030, making the rate of increasing e-waste extremely alarming with a value of almost 2 Mt per year. The demand for short-lived high-tech consumer products is high and still growing. Unfortunately, no effective systematic recycling and material recovery infrastructures are in place [24]. And surely, the recycling activities already in place are not expanded enough to keep pace with this global growth of e-waste with growing urbanization and mobility, higher levels of disposable incomes, and further industrialization [18].

What does WEEE mean ?

Electronic and Electrical Equipment (EEE) is defined as "any household or business item with circuitry, or electrical components with power or battery supply" (including products from basic kitchen appliances to computers and cellphones). After its use, EEE is disposed of, generating a waste stream that contains hazardous and valuable materials which is referred to as e-waste, or **Waste Electrical and Electronic Equipment (WEEE)** [18] [19].

In EU countries, small-size electronics and equipment represented 17.4 Mt in 2019, witnessing an increase of 5 % since 2014 [18]. From this amount, 8% end up in normal waste bins and are subsequently land-filled or incinerated. The majority of undocumented domestic and commercial e-waste is usually mixed with other waste streams, such as plastic waste and metal waste. This situation implies that only easily recyclable fractions might be recycled but without the recovery of all valuable materials [18].

The accumulation of e-waste is often called an 'urban mine' as it contains several precious, critical, and other non-critical metals that, if recycled, can be used as secondary materials. The need to enhance secondary resource mining and lessen the demand for newly extracted virgin materials has arisen as a result of issues relating to primary mining, market price changes, material scarcity, availability, and access. Only 17.4% of e-waste is recognized as being formally collected and recycled globally [18], so there is still a long way to go.

Basel convention

Unfortunately, e-waste is not only a national problem. When discarded goods are still repairable or reusable, they are frequently exported as used goods from high-income to low- or middle-income nations (where e-waste is likely to be managed by the informal sector). But a sizable proportion of e-waste is being illegally exported, exported while being intended for reuse, or exported while appearing to be scrap metal. These transboundary movements are assumed to be between 7 and 20 % of the total amount of electronic garbage produced which are moved across international borders [18]. To suppress these trading patterns, the Basel Convention, made effective in 1992, requires a written notification and approval process for all cross-border movements of hazardous wastes. This regulatory exemption is undoubtedly necessary given the current situation, but preventing tremendous e-waste fluxes from the start should be the command for long-term resource conservation.

1.1.2. Planning EoL scenarios from the start

To reverse this tendency, repair and reuse come first place to prolong the functionality of electronics, diverting the need for recycling and disposal. Since the growing amount of e-waste is mainly fueled by higher consumption rates of EEE, short life cycles, and few repair options [18], new alternatives are rising. When combining these ideas, it is clear that all converge to adapting the current workflow to a circular economy. Due to raw material scarcity, the environment's limited bearing capacity to absorb residues and emissions, and the evolving consumption needs of a growing population, it is necessary to promote a transition from traditional economic activities to more sustainable business models. The increasing numbers of government directives and legislation dedicated to environmental impact reduction form testimony of this fact [10].

As stated in Fairphone's report on recyclability, recycling has been viewed for a long time as the panacea of sustainability [20]. Recycling (instead of throwing away) something we don't need anymore might just seem to solve the problem. It might be the case for single material products where the process can be as simple as melting it down to reusing it. However, complex products are much trickier and electronic device recycling requires several procedures, including disassembly, size reduction (shredding), physical sorting, and additional processing. Not only recycling is energy-intensive, but every step of the process involves the inevitable loss of materials, and the total effectiveness of recycling also depends on the design of the goods, the characteristics of the materials they are composed of, the collection and sorting of the waste (and more) [20].

Instead of only recycling, important opportunities at the end of a completed use phase are numerous and a concept recognized decades ago proposes an ecological hierarchy of these EoL strategies, called the 'Lansink ladder' (see Figure 1.1). The main EoL recovery strategies that can be identified are direct reuse, reuse after small repairs (also known as refurbishment), remanufacturing (both of products or their components) and materials recycling [10]. The goal of the ladder is to preserve the functional value of products or components since that can contribute to the minimisation of the total environmental impact. But in recent years some questions have been raised on the generic applicability of this hierarchy. [27], [28] and others, proved that some products have a clear optimal ecological lifetime, implying that reuse of the product or components is not necessarily beneficial for the environment. This is especially true for products or components with deteriorating characteristics or if new generation products are more eco-efficient [10].

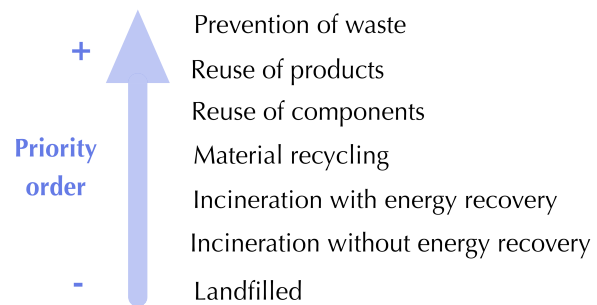


Figure 1.1: Lansink's ladder: ecological hierarchy of end-of-life options. Original figure from [10].

Following the idea of a circular economy, many concepts have been proposed for EoL treatments or priority levels. Still, the shape that first comes to mind is a circle. A circle in which all materials would magically recycle themselves into a brand new product. The reality is much more nuanced and does not yet meet the utopia of a perfectly closed loop (which would oppose the typical 'produce-use-dispose' workflow recognized to be the source of much pollutions and resource depletion). But, what shape should be chosen instead? The Ellen and Mac Arthur foundation [25] chose a butterfly-like diagram to represent both a technical cycle and a biological cycle. Both regenerating collected goods after the end of the chain to keep them in circulation.

Another representation, more focused on materials, is the 'Comet circle' (available on Figure 1.2). It focuses on prioritising the highest value opportunities. In the diagram, approaches such as reuse, sharing, remanufacturing, and refurbishment sit closer to the centre of the multiple material loops, while recycling sits farthest away. It underlines that efforts across the entire product life cycle are pivotal to reducing environmental impacts. As a rule of thumb, the closer the loop is to the centre of the diagram, the more valuable the approach [21].

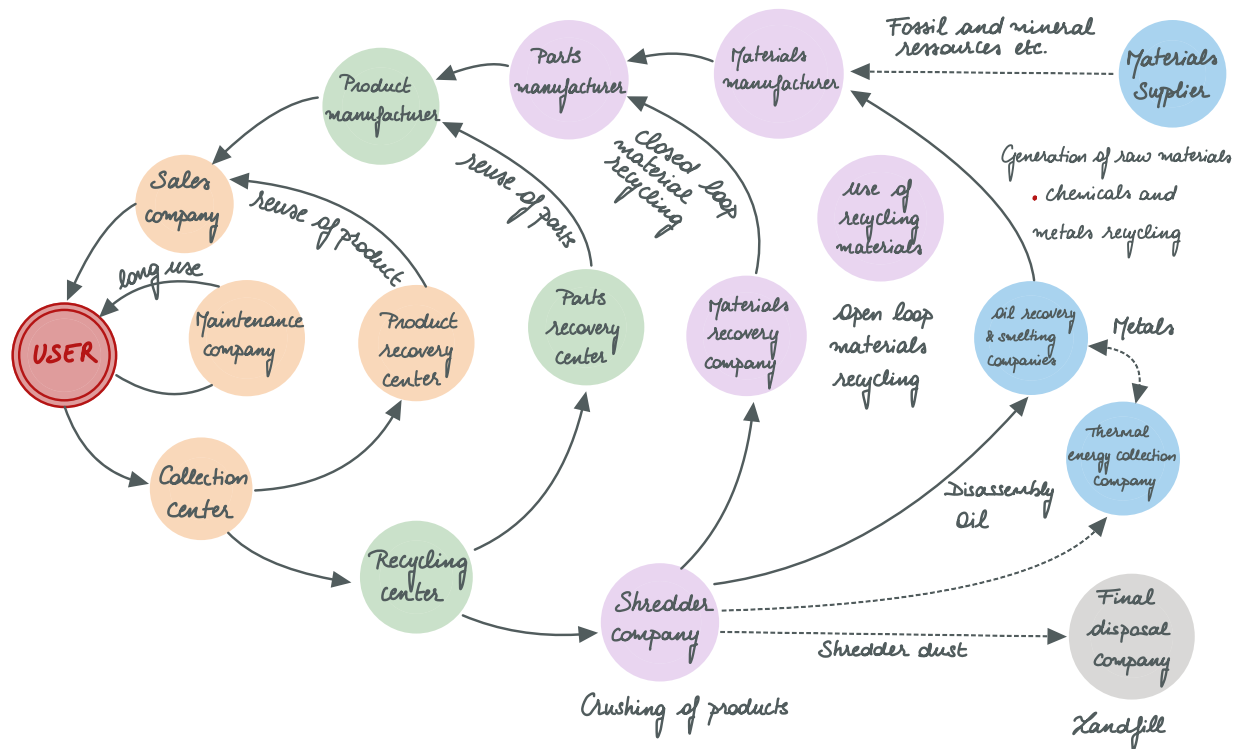


Figure 1.2: Concept of a Sustainable Society: The Comet Circle™ (created in 1994). (Comet circle is a trademark of Ricoh, Co., Ltd.) Each orbit in the figure corresponds to a life cycle option, such as prolonged use by means of maintenance, product reuse, part reuse, recycling, and energy recovery. To realize closed-loop manufacturing, the product life cycle should be managed by selecting proper life cycle options. Original Figure from [26].

As the diagram highlights, product maintenance and reuse are the preferred scenarios since they preserve high value with minimal environmental impacts and costs. This perspective of life cycle management for close-loop manufacturing shakes up classical business models and brings transformation of the companies from product providers to service providers [11]. If this business transformation goes further, companies will sell utilization and customers will pay for that only. This effect has benefits on both sides. On the one hand, achieving effective maintenance could be of benefit to companies, which can increase their profits by reducing maintenance costs, as well as to customers who can enjoy improved service quality [11]. On the other hand, designing long-lasting and circular products will spare them efforts and money as well as doing better for the environment by staying longer in the inner loops of the Comet Circle. The final aim would be to provide functionality rather than to sell products [11].

1.2. Today's context on repair and product design

Although repair and reuse have long been touted as a successful technique to lengthen product life and improve resource efficiency [35], this depends on the product category and the procedures required to restore the product to a usable form. Also, it is only until these last years that ideas and studies came into action on a larger scale. This next section will cover a brief overview of the main game-changer steps in this field.

1.2.1. Right to repair

Consumer electronics and home appliances are currently designed to lean towards hindering product repairability by conventional product users [6]. The testimony of iFixit developed for the Congress on Repair Restrictions 'Nixing the Fix', gives examples of how manufacturers purposely hinder repairs by design [41]. And as [6] stated in its literature research, "a product's design influences how time-consuming, and complicated the repair will be, as well as how economically viable". Therefore, many authors agree that repairs could be facilitated if they were considered during the design process. It is not only evident for producers and designers but also for end-users whom generally take repair decisions based on the convenience and ease of accessibility of repair as designed into the products [42].

Due to barriers at the system, product, and service levels, the consumer product repair industry is declining in Europe, and specifically, its profitability is hampered by the high labor costs [43], [6]. At the systemic level, repair techniques currently encounter commercial and legal barriers, such as violations of contract and intellectual property agreements, unfavorable consumer and tax regulations, and unfavorable customer impressions of repaired goods [43]. Eventually, the infrastructure available is decisive in facilitating repairs as well [6], and consumer repair decisions are influenced by technical, value-based, and emotional considerations [44]. Not only their repair is ineffective, but product lifespans of electric and electronic products are in decline, with detrimental environmental consequences [30]. This trend can have numerous potential causes. A shortened product lifespan in particular product categories directly benefits manufacturers, hence "planned obsolescence" is observed on purpose. Improvements in technology or changes in legislation might render obsolete the other product categories. Additionally, markets can compel producers to alter their goods in order to keep up with the competition and meet consumer expectations [30]. This decline in product lifespans lead to increasing material throughput and waste, making environmental impacts of materials production and processing rapidly critical.

Right to Repair is a campaign fighting to remove the barriers to repair by wanting design practices which support ease of disassembly, information on product repairability from the purchase, access to spare parts and repair manuals for the entire lifetime of a product. The aim is to push Europe to adopt legal guidelines promoting repair and not preventing it. They will also push for a EU-wide repairability index [8] in the near future. The most common argument against the right to repair is repair safety. Some might be afraid that opening broken appliances might hurt the inexperienced repairer. However, [60] believes that there's no such thing as security through obscurity. Making repair manuals and spare parts data public won't undermine an already sound appliance. Repair fosters security in homes, communities, governments and businesses. Indeed, when manufacturers erect barriers – whether monetary or logistical – to owners and their agents to repair, they create conditions where repairs or maintenance will be delayed or put off entirely [60]. Right to repair and its recommendations should also provide the right repair frame as opposed to back-market firmware updates or unfit components replacement sometimes happening when documentation and repair are proprietary.

1.2.2. Evaluating repair tendencies

In their studies, [6] found that end users generally need expert guidance to successfully diagnose common faults. At *iFixit*, a wiki-based self-repair platform, end users asked experts for help to locate the faults in their appliances and how to resolve them. This comes in very handy since end users very often need hints to be able to disassemble the appliance otherwise they might not even begin or continue the process [6]. The same study showed that "manuals generally advise a cause-oriented route to diagnosis rather than a component-oriented route". Thus, the support provided for end users is generally limited to the diagnosis of overdue maintenance faults.

Recently, many studies have been conducted on the subject of assessing products' repairability, with the hope of defining standards, protocols and scoring systems that could both help establishing a new labelling system and guiding the redesign of more durable consumer goods [14]. [15] developed an indicator to measure the repairability of electronic products, [40] explored how to improve repair through design. In the work of Flipsen et al. [56], 20 key criteria were included in a "Design for Repairability" tool, related to the ability of consumers to repair a product by themselves. A Benelux study [54] also provided an overview of relevant criteria for the repairability of products according to three categories: information provision, product design, servicing. The repair operation they investigated was divided into steps: products identification, failure diagnosis, disassembly and reassembly, replacement of spare parts and restoration to working condition. On a more global point of view, [55] explored policy options to enhance repairability after the analysis of barriers to repair and the potential impacts resulting from the implementation of repairability requirements on four product groups; washing machines, dishwashers, coffee machines, vacuum cleaners. They also performed a socio-economic analysis of the repair sector in EU.

Summarizing the findings of these studies, it is clear that the overall repair sector is fragmented and consists of repairers differing in type and size. Still, there is a general tendency to centralisation of repair services [53], especially for mainstream brands. The repair sector depends greatly on product category and represents a general higher share in terms of number of companies, employees and turnover for computers and communication equipment. Behavioural aspects (e.g. preference for new products, mistrust and lack of awareness towards repair) is a key barrier, along with the cost [55]. There is evidence that some products are not intended to be fixed, and there is a common propensity to replace products or components rather than repair them. This decision also depends on many factors, including the device's design, the availability of spare parts, as well as manuals and tools. To increase repair rates, an extension of the legal guarantee period to five years and competitiveness could help decreasing repair prices. All these assessment methods and studies recognized challenges in; the objectivity and reproducibility, the ease of understanding the system and reported information and fair applicability to a broad scope of strategies [53].

Initiatives that took repairability further

Kippit [69], a start-up launched in 2021 developed a kettle that could be repaired by owners to avoid replacement after a failure. They produce all components in France except for electronics and plan on putting more appliances with the same spirit on the market. Born in 2014, "L'increvable" ("The indestructible") [70] is a washing machine that is made for easy maintenance with simple software and physical updates. It is still under development but has prompted many interests. [14] concretized the concept of a disassembly map, which is a visual representation of the disassembly process and can be a powerful tool when making design decisions. For them, insights into product disassembly and reassembly are critical to the repairability of products. Many more initiatives made their proof but these ones are representative of market evolution towards circular products.

French repairability index

The French repairability index [8] was a key milestone for the Right to Repair in Europe since France established a repairability index on 5 categories of electronic devices in 2019. It regulates the mandatory display of clear information for consumers on the repairability of electrical and electronic equipment [8]. The index's goal is to persuade consumers to select more repairable products and manufacturers to make their products easier to repair. It covers five product categories, including smartphones, laptops, televisions, washing machines, and lawnmowers, that are sold in France [8].



Figure 1.3: The index has to be displayed near the product in shops, and online next to the price of the product using the following logo, with the colour corresponding to the level of repairability in 2 point intervals. Picture from [?].

The index assesses 5 main criteria: documentation, assembly, availability of spare parts, price of spare parts, and product-specific aspects (the last one looking into product-specific properties like software aspects). The final grade is determined by adding the points assigned to each weighted criterion and then proportioned over 10 [8]. The index takes into account all pertinent target groups. Points are awarded if specific documents are available to repairers, and extra points are given if they are made public to customers. Similar to this, the availability of spare parts for manufacturer-in-house repairs, spare part dealers, independent repairers, and consumers earns the same number of points.

Cradle to Cradle certification

Conceived in 2002, the eco-design of a C2C (Cradle to Cradle) product requires that a manufactured good must be able, once recycled, to be used to create one or more further items, with the potential for a single addition of renewable energy. Thus, the waste is entirely reincorporated into the production process. The certification and its 5 evaluation criteria, aim at having a positive ecological impact through the design of products that are either biodegradable or recyclable [9]. The five categories of sustainability performance cover; ensuring safe materials for humans and the environment, enabling circularity through regenerative products and process design, protecting clean air and promoting renewable energy, safeguarding clean water and healthy soils and respecting human rights [9]. The third-party product certification program is independent from the manufacturer.



Figure 1.4: Cradle to Cradle Certified assesses the safety, circularity and responsibility of materials and products across five categories of sustainability performance. From [9].

1.3. Exploring the repair and FabLab communities

1.3.1. Local maker communities

As [3] and others put into light, a networked approach to design and small-scale production is growing in popularity. This is in line with the growing accessibility of digital design and fabrication tools at the domestic scale and the understanding of distributed manufacturing practices. Digital platforms act nowadays as nodes which not only transfer data but also connect like-minded collaboration. More local approaches and even at the domestic scale allow hyper-local and hyper-customised design solutions with a diversity in materials, techniques and crafts. The digital layer offers communication, tools and platforms, pushing the limits of physical design and production spaces by opening possibilities for collaboration at distance with open access to design-to-production processes and education. Networks and digital applications are driving dematerialization and the exchange of intangible knowledge, while on the other hand a meaningful connection between a designer and the most material aspect of creation is recreated when putting the accent on digital fabrication as new informal way of collaborating with production [3]. In that context, the prototype and the space in which the process evolves become two central features.

What is a FabLab ?

A **FabLab** (fabrication laboratory) is a small-scale workshop. It is a place which provides access to the environment, the skills, the materials and the advanced technology to allow anyone anywhere to make (almost) anything [2]. It is a place where people gather, socialize and share/produce *knowledge-by-doing* with a variety of tools and materials.

1.3.2. The Makilab

The MakiLab is a FabLab located in Louvain-la-Neuve. After a tour of the workshop, featuring two laser cutters, a few 3D printers, a CNC milling machine and the necessary material for electronic crafting, the fab-manager introduces the context around the laboratory. A majority of students are present in the public but also start-upers and hobbyists participate as well, the local population being a minority. Depending on the public, skills and abilities vary in a wide range. CAD modelling, a necessary step in design, is not accessible to most people. Nevertheless with the help of experienced people or if they already own a CAD model they easily blend in and become independent quickly from a manufacturing point of view.

1.3.3. Repair Studio in Louvain-la-Neuve

Hosted by the Makilab, the Repair Studio takes place every week to offer citizens the chance to not only repair their appliances but also get to know the opportunities in the location and the population of volunteers present on that day. Other conclusions stood out during these sessions. Repair processes for advanced devices require experience and expertise and even with the right tools the repair can be difficult sometimes, given the design of these appliances; including for example broken snap-fits when disassembled, glued parts hindering the inside components and requiring the breaking of the device,... Given the possibilities in the location, 3D printing was often cited on the table when needing spare parts for repair. Often, it will bring a customised solution to the faulty device but it can't be used systematically.

PLA and ABS (most used plastic filaments in FabLabs) don't behave well under temperatures above 60 °C, they can't equal structural properties of metals and the size of the parts is limited by the volume of the 3D printer. An important factor to add is that the part needs to be remodelled in 3D with appropriate softwares. If the user can't do it, some engineers or hobbyists draw models voluntarily online but often to reach a big audience with mass-produced products. A CAD engineer costs around 40 to 70 euros per hour and that price can't be worth repairing most products.

For simple designs or low structural and heat requirements, 3D printing for repair has made its proofs. Nevertheless expectations of non CAD drawers are too high and they think an object is quickly 3D modelled and reproduced physically. The technologies of the FabLab interested many people but often unfeasible requests were made. To overcome this problem and allow FabLabs to be limited by the printing time only, manufacturers should be compelled to publish their CAD files online.

1.4. Manufacturing within a FabLab

With the ever-increasing availability of technology, design opportunities kept emerging in recent years [3]. New production processes with the help of digital technologies allow designers to approach projects in a more informed and holistic manner [3]. These technologies no longer serve firms only and allow to envisage a landscape of democratization within design practices. Moving beyond academia, these practices embrace the process of involving making as part of the semantic principle [3]. The individual becomes a proactive subject of the realization of an object, integrating various skills and being motivated by doing, as to "constantly learn and refine the project path" [3].

1.4.1. Distributed manufacturing

Since the turn of the century, manufacturing has concentrated on mass production models to increase productivity. Low or no customer-specific features and components allowed faster assembly, reducing the costs and increasing production rates [49]. Its advantages are clear however, it releases significant amounts of emissions and waste depending on the energy and materials required during the production processes. By putting the place of production closer to the point of sale (and repair), DMS give the customer higher freedom to influence the design and production process of the product they wish to buy [50]. A local network of manufacturing resources connected by a cloud-based manufacturing system can simplify the supply chain or even partially substitute it by a regional hub of manufacturing resources.

DMs against CMs

Distributed manufacturing systems (DMS) could potentially reduce pollution through the **reduction of global transport** as opposed to centralized manufacturing systems (CMS) implying high global flows of goods and materials, and thus higher waste of energy due to global transportation [50], [49].

Additive manufacturing (AM)¹ predominantly supports the unit process level and production line in a DMS². The creation of affordable 3D printing gear has given customers access to technologies that let them shape the development of new products and manufacturing procedures. Social media and crowdsourcing data networks, along with open source and inexpensive commercial 3D printers, are rapidly combining to enable consumers to produce [49]. But as 3D printing rapidly matures, it will

¹AM is defined as "the process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies, such as traditional machining" [51].

²In this work, the focus on AM will stay on fused deposition modeling (FDM) techniques

account for a significant product output in the future, implying significant environmental impact as well [49]. However, not only DMS and its associated technologies will redefine material supply logistics, it also implies the emergence of new business models [50], product development processes, and production processes [49]. Indeed, energy consumption hotspots will undergo a relocation throughout the life cycle of a product, diversifying the mix of energy embodied in products [49]. A point of attention when talking about DMS is the drastic changes in quality that could occur as it allows more participation of consumers within the manufacturing processes. Postprocessing operations of 3D printed products for example could be quite different from a user to another. Nevertheless, some products found the market show surface quality representative of 3D printing but the high degree of personalization and small batch size potential override this element which even becomes aesthetic [49].

1.4.2. Distributed design for replicable manufacturing

An important question that arises after the topic of distributed manufacturing is how to distribute and share designs in a way they could be manufactured anywhere equally. The FabLab revolution already revolves around this challenge and encompasses the questions of accessibility of tools and manufacturing skills [3]. However, reproducibility also depends on external factors such as user former experience, settings, and working environment. Adding another layer to this with the availability of materials one can place itself on the distributed design radar on Figure 1.5. The goal is to broaden the triangle as much as possible. The local-to-global potential of distributed design is seen as possibly humanising production processes and providing a more sustainable alternative to complex global supply chains. This could lead to a possible solution to over-consumption and mass production [3].

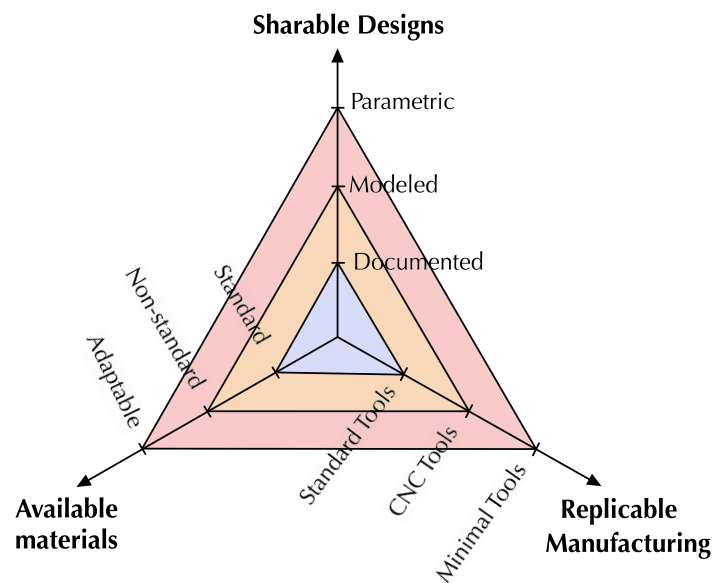


Figure 1.5: Distributed design radar as introduced by Fab City Store [3]

FabLabs can host a great variety of technologies depending on their capabilities and budget, but they all have a common ground of small scale machines. For some, users can become independent very quickly and for others the help of an experienced person is needed. An overall of these technologies and their assistance needs can be observed in Annex F.

1.4.3. The 3D printing ecosystem

After its invention in the early 1980s, the place of 3D printing technology in manufacturing evolved significantly. At first, the hype was mainly concentrated in households but it is not until recently that it shifted from consumer markets to a more widely applied industrial manufacturing process [13]. It seduced many since 3D printing has a unique capacity to quickly adapt to production and supply chain needs, a feature clearly highlighted during the Covid-19 pandemic period [13]. During that period, manufacturers and makers used 3DP to rapidly produce protective equipment and medical devices to combat shortages and supply chain issues. As parts and goods may be manufactured locally and on-demand, 3DP emerged as a viable solution to both new and persisting challenges. Now, during the downhill slope of the pandemic, 3D printing has fewer immediate uses related to Covid-19, but more people now recognize the technology's agility and production potential.

What is 3D Printing ?

In 3D printing, the machine reads in data from a CAD drawing and lays down successive layers of liquid or powdered material, and in this way builds up the model from a series of cross sections. These layers are fused automatically to create the final shape. The primary advantage to this type of **additive manufacturing** is its capacity to create almost any geometry.

3DP answers to a lot of different considerations. In 2022, the main applications were still prototyping (62%), one-time orders for end-use parts (17%), repeated orders for end-use parts (11%), jigs and fixtures (tooling) (8 %) and lastly for aesthetic parts (2%) [13]. Nowadays, fewer barriers to 3DP remain and the price in particular, inducing many engineers to choose 3DP along with the main driving factors such as faster lead times and improved geometric complexity [13].

1.4.4. Going beyond prototyping - 3DP as final manufacturing

Production of a 3D printed spare part can take anywhere from minutes to hundreds of hours depending on the machine. Since the technology is built for on-demand production and therefore is not bound by the same economies of scale as traditional manufacturing [13], it migrates away from the prototyping field to become a final manufacturing method. AM can be cost-efficiently manufactured as it reduces the amount of raw material consumed, and becomes a viable means of manufacturing parts in quantity [12]. 3D printed parts are now the biggest competitor for injection moulded parts and might even tend to replace them [5]. Indeed, simply from a complexity cost point of view, AM tends to stay constant whereas conventional manufacturing processes have to trade costs for complexity. However, the mechanical and thermal performance of 3D printed copies still can't match IM ones [5]. Nonetheless, extreme performances do not represent a majority of cases, design can be adapted knowingly and AM has a chance to occupy a large place on the market. Many industries including healthcare, aerospace, automotive, energy, motorsports and sporting goods, are today using the technology to produce functional end-use parts, showing an increase in end-use 3D printing adoption [13]. They have found the design freedom and production agility for final products seducing enough and now, current trends show three prevailing production applications for 3D printing: low-volume production, mass customization and serial production [13]. This is possible because of the recent availability of advanced materials including polymers, metals or composites, driving the creation of new applications [13].

Thanks to the rise of AM, a new economy-of-one production paradigm, where personalized products govern instead of replaceable parts produced in large quantities, has altered the competitive dynamics of traditional economies-of-scale production. Every model has its own economic variables and competitive advantages but AM is a competitive and viable option compared to economies of scale which support commodity and high volume production, as it offers unique customization at small volumes [4]. According to the same source, the emerging dynamics of economies-of-one have five likely outcomes:"

- There will be few clear boundaries in the design-build-deliver paradigm.
- Design and production will be tightly coupled through experimentation.
- Competitive advantage will reside in both designs that are simple to manufacture and assemble and designs that are highly customized and complex; the challenge will be in arenas where manufacturers are seeking simple designs, and customers are seeking customized, complex products.
- Proximity between supplier, manufacturer, and customer will matter, and localized production will be not only more feasible but more desirable.
- Planning will go from long term to real time." [4]

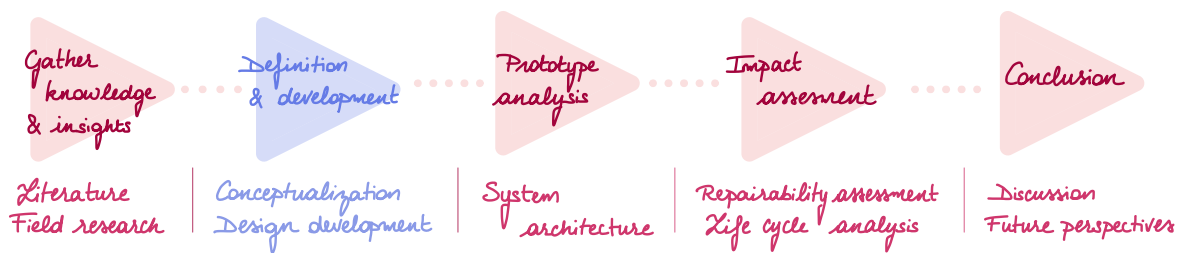
The ability of collaborative printing technologies to considerably speed up the manufacturing process justifies their popularity. However, defects and non-uniformity caused inherently by the variation in the way the material is layered impact the functions of the parts and can sometimes become more significant in "collaborative printing systems where multiple printing nozzles co-create the same model" [48]. It is a reality that needs to be accounted for, but that could also turn into an advantage (the layers add friction between two pieces and that could be advantageous in some cases). Surface finish can also be enhanced with post-processing but in many cases, the exterior look of these pieces satisfy users as they enjoy the 'homemade' finish look.

1.5. Conclusion on main findings

Summarizing the insights of this state of the art chapter, one can conclude several main findings. The demand for short-lived electronic products are high, resulting in an increasing amount of electronic and electrical waste which has many environmental consequences. As a solution, products are advised to be redesigned for as many life cycles as possible (including, reuse, repair, repurposing and recycling) in order to limit primary raw material extraction, and toxic fluxes induced by EEE. In recent years, many movements on the topic of repair emerged. The Right to Repair fights to remove the barriers to repair, by support design practices with ease of disassembly, information on product repairability from the purchase, access to spare parts and repair manuals for the entire lifetime of a product. The repair sector is currently fragmented and consists of repairers differing in type and size but industrial brands tend to centralize these services. The repairability depends greatly on the product category but the greatest barriers are cost, guarantees limiting self-repair and behavioural aspects like preference for a new product, mistrust and lack of awareness towards repair. The French repairability index wishes to score a product's repairability assessing 5 main criteria : documentation, assembly, availability of spare parts, price of spare parts and product-specific aspects. Distributed manufacturing also has the possibility to reduce pollution through the reduction of global transport. This idea is to prefer a local network of manufacturing resources connected through cloud-based platforms rather than centralized manufacturing system implying high flows of goods and materials and thus higher waste of energy due to global transportation. Additive manufacturing has evolved from its prototyping label to a final manufacturing technique recognized by many industries. Its customization possibilities and fast production tightly couple design and production through experimentation.

2

Definition and development



The goal of this chapter will be on the one hand, to extract from literature design strategies, guidelines and product features that enhance a product's potential to have multiple or/and long-life cycles, and on the other hand, to complete these guidelines by experiencing the design strategies directly through prototyping within a FabLab. Therefore answering the question, "How can product design ease the process of recovering functionality from products?". Next, a concept generation phase takes place and once the best option regarding the specifications is chosen, the making of the prototype can begin.

2.1. Methodology and process

After having a better understanding of the context thanks to the insights from Chapter 1, it is now time to define the tangible approach this project will take and define the framework in which it wishes to evolve. The general workflow aims at targetting all small EEE home appliances however, the specific case study of a hand blender will be taken into further detail. This will allow a deeper comprehension of the concept at a small scale as well as the development of a practical prototype. But before the prototyping stage, an analysis of an off-the-shelf market hand blender and its requirements will be performed to identify "hotspots" and design requirements. On Figure 2.1, a diagram shows the general reflection behind the prototype making timeline, covering Chapters 2 and 3. After understanding the scope of the case study, the goals and specifications will be evaluated accordingly. Then, comes the time of the making and testing to get the best fit within the amount of time given. The general implementation when prototyping a new device has to be iterative and will both integrate design aspects oriented towards reparability and user interaction as well as engineering aspects on a strictly

functioning point. Once the prototype starts to take a final form, a step back is needed to evaluate its reparability and reproducibility fit. Eventually, room for improvement will be further developed.

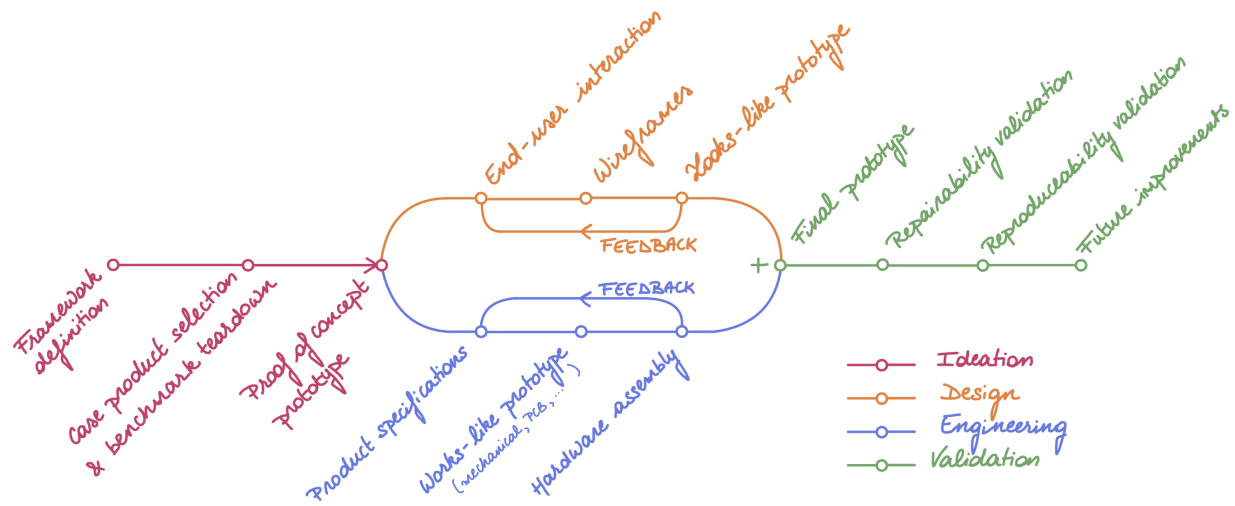


Figure 2.1: Project workflow for the proof-of-concept prototype - covering Chapters 2 and 3.

2.2. Building an alternative electronics economy

Recovery operations -such as repair, refurbishing or remanufacturing (by preferred order)- should be easy to perform and in an efficient manner [7]. This is influenced by product design. Design sits prominently at the heart of the circular economy ([21], [6]) and allows to provide an alternative to premature product replacement. Not only the mechanical design in itself needs to be redesigned but also products in their globality, business models, cities, and the linear systems that have lasted for the past centuries [21]. To stay in line with the latter statements, this section will expose the building blocks of the new workflow of home electronic appliances proposed in this thesis.

2.2.1. Product life extension - Why (re-)design products that last

Over the past years, product design strategies have taken into consideration environmental damage by focusing efforts on redesigning individual qualities, products and industrial processes. This was done by focusing on recycling efforts or (and) reducing the usage of energy and natural resources [31]. However, most of the in-use product design strategies focus on a single product's use cycle. Nevertheless, designing products for one lifespan does not align with CE requirements as its goal is to close the loop of materials and avoid the generation of waste, as a natural ecosystem would do, while promoting economic growth. This implies, as [32] put it, that the resources that enter the economic system must remain accounted for before, during and after their lifetime as useful products. Following that idea, products must be restored to their original state or a similar state after being used. Longer product lifespans reduce the demand for replacement items, which in turn reduces the amount of raw materials required for production processes, the amount of CO₂ emissions emitted into the atmosphere, and the quantity of products that end up in landfills [30]. Nevertheless, products with high use energy compared to embedded energy should be replaced frequently, provided a significantly more energy efficient alternative is available [57]. Laptops, as an example, have a high material density, a relatively short lifespan and low energy consumption and early replacement would not be eco-effective [6].

In his study, [30] defined well this balance; "the optimal product lifespan is the point in time where the environmental impacts that arise from using a product equal the embedded impacts of a (more energy efficient) replacement product." [30]

2.2.2. Aiming at repairability from the start

To keep products' multiple life cycles opportunities, repair is non negotiable. Product repairs require little energy and often few resources to extend products lifetimes, which can slow down the flow of materials, thereby preventing waste. They also reduce emissions from transportation (as they can be done locally) and new product manufacture [45] as they provide an alternative to premature product replacement. As they also run on manpower, repair practices can have an added positive socioeconomic impact by creating jobs at home and boosting economic development [6]. "The smaller the economic loop, the more profitable and resource efficient it becomes" [45]. To allow rapid and affordable repair, design changes should follow and thus translate in better competition against product replacement [6]. The first barrier to repairability is the user diagnostic. The results outlined from [6] show that a difficult disassembly process hinders both fault location and isolation. In contrast with the latter, design cues can guide end users through the diagnosis steps (like textual signals or specific arrangement of components) and increase the feasibility.

2.2.3. End-users interaction with appliances

Current appliances on the market are not designed to make fault diagnosis easy [6]. Component visibility and access are frequently restricted, which makes fault isolation difficult. User manuals frequently omit crucial details, like how symptoms differ from basics error codes. Fault diagnosis is "the process of identifying and characterising a fault when a failure occurs". This step is crucial when aiming at targeting repair from end-users of low experienced repairers. If the fault diagnosis process becomes smoother and transparent, more people could be added to the repair picture and overall repair time will be shortened as it is the most time consuming step in a repair process [6]. Moreover, a successful diagnosis process can positively influence the repair-or-replace decision-making process. If appliances were to be simple and modular, with accessible components, the step would be easier to perform [6].

2.2.4. DfD at the service of product's multiple life cycle

Design for Disassembly ?

Design for Disassembly is a design strategy that considers the future need to disassemble a product for repair, refurbish or recycle.

It is now clear that products should be kept in use for longer. We also know that to do so, repair is crucial but still, to allow this, it is vital that the product is easy to disassemble. "Ease of disassembly is not only necessary for successful recycling, but also for repair, refurbishment, remanufacturing and parts harvesting for reuse [16]." It will enable cost-effective operations and make products fit for all circular strategies [16]. However, for larger products with more intricate designs, the cost of disassembly will

frequently outweigh the value of products and materials recovered, so such products end up being processed by shredding and mechanical material separation [10]. This EoL scenario should be avoided because even if shredding of products is a quick way of retrieving recyclable materials, it usually results in lower-quality material blends.

Before reaching the EoL alternative destination, products should be disassembled to maximize the purity of recovered material fractions, safely dispose of hazardous parts, and recover sub-assemblies for reuse or remanufacturing [10]. It is unlikely that the disassembly of many small products becomes economically viable given current design of the industry [10], and that's why DfD should be implemented.

2.2.5. Modularity

A modular approach makes it easy to remove only part of a product, thus easier to disassemble, lowering the cost and effort to swap out components when they are damaged. Additionally, as stated by [21], modular systems are easier to customise and therefore adapt to the ever-changing needs of users, preventing products from becoming obsolete. Like Lego blocks, every component has qualities that make it simple to connect, integrate, or improve them. This assures that all components, from all manufacturers, are interchangeable, going beyond the product ecosystem of a single producer.

2.2.6. Planning for recovery operations

Value recovery only occurs if components can be easily extracted. A profitable disassembly should include: "identifying the optimal degree to which a given product should be disassembled; development of a product design that simplifies the disassembly of used items; establishing the logistics for collection and distribution of goods and analysis of uncertainty characteristics, including probabilistic returns, incoming part quality, varying recovery rates, and changing demand for components " [10]. The most stated product features from EOL decision and management are: a product's geometry, the linkages between its components and how they are arranged as a whole [6]. The aim is to preserve a product's integrity (i.e. aiming to reuse products instead of recycling them), even though ultimately and unavoidably products will have to be recycled at some point [45]. Recovery process efficiency greatly relies on its earlier planning. To overcome obstacles like high labor costs or storage expenses related to remanufacturing and refurbishment, planning for the recovery activities in accordance with the design methods is helpful. The environmental impact of a product can be decreased through planning by, for instance, taking into account how resource-intensive the maintenance procedures are for a product. Additionally, it aids in preventing undesirable recovery outcomes, such as not being able to access a part or needing a specific unavailable instrument [6].

2.2.7. Distributed design for local manufacturing

The rapid development in now FabLab technologies (3D printing, CNC milling, laser cutting,...) coupled with the maker's movement explosion around the globe makes it possible to produce locally (again) at competitive prices. Not only being great for the creation of local jobs and activities, this also benefits the planet, as less transportation and emissions are needed. Ultimately, repair and refurbishing of products will become more affordable.

2.2.8. Safe and circular material choices

Not all materials are fit for a circular economy. Some contain chemicals that are hazardous to humans or the environment. Additives are often used unintentionally or for performance reasons - such as improving flexibility or durability - but there are ways to design them out. By choosing materials that are safe and circular, you can build a better offering for your users, while ensuring that the products and services you create fit within a circular economy [21].

Summary of the redesign goal

The first barrier to repair might be the hardest one to break. When an appliance breaks, a majority of users might not be wishing to even open the lid of their broken techno-companion and check what's happening. Of course they have good reasons to do so. For some brands, guaranties sometimes have a limited range of operation and won't apply when the objects has been disassembled, which discourages a majority, and a lot of people are not familiar with repair and won't risk to try it themselves. The goal here is to go past repair barriers and allow end-users to reconnect with the technology they use everyday and be able to repair it themselves or with the help of experienced people, in their local fabrication laboratory. Being manufactured in a FabLab, the object will allow replicability in any part of the world equipped with the associated manufacturing technologies thanks to an open source framework. Design choices will allow **quick assembly, disassembly, upgrading and repair, using common tools**, without the use of harmful adhesives and expensive industrial machinery. Repurposing will be kept in mind, shall the appliance be used for building other home electronics in the future. **Standard components** will be chosen with the aim of being widely available and easily replaced when broken. Parts should be replaceable by anyone, with the help of a simple screwdriver. For more tangible guidance, design guidelines on Table 2.1 were extracted from literature and will serve as guide throughout the whole process.

Table 2.1: Design for Disassembly guidelines extracted from literature [6], [61], [62], [63], [64].

		Set center-elements on a base part.
		Aim at self-locating interfaces.
		Mark parts which must be removed first.
		Avoid multiple directions and complex movements for disassembly.
Assembly configuration	Sequence	Avoid the need for specialized disassembly procedures.
		Locate parts with the highest value in easily accessible positions.
		Avoid long disassembly sequences: consider part order, part disassembly directions and number of re-orientations.
		Locate parts with the highest value in easily accessible positions.
		Find an optimized disassembly plan.
		Find an optimized disassembly stopping point.
		Create modular sub-assemblies which do not require further disassembly operations.
	Reversibility	Plan for a reversible assembly process.
		Avoid permanent fasteners that require destructive removal.
		Allow for non-destructive disassembly using snap-fit types of connections, active disassembly using smart material and heat-reversible.
	Tools	Consider number of tool changes.
		Prefer standard screwdrivers and tools.

Fixtures	Type	If destructive removal is necessary, ensure that damage to the core does not happen. Reduce the number of fasteners prone to damage and breakage during removal. Use fasteners rather than adhesives. Use fasteners that are easy to remove or destroy. Use reversible joints or connectors with fracture points. Easy detachable connections. Avoid welding and jamming of parts. Ensure screw threads are sufficiently robust.
	Quantity	Reduce the total number of fasteners in the unit. Reduce the number of press-fits. Minimize the number of joints and connections.
	Wear	Increase corrosion resistance of fasteners.
	Placement	Reduce the number of fasteners not in direct line of sight. Make joints visible and accessible, avoid hidden joints. Provide easy access to disjoining, fracture or cutting points.
	Variety	Standardize fasteners by reducing the number of different types of fasteners and the number of different sized fasteners. Use the same fasteners for many parts.
	Product geometry	Create geometry and shape with the purpose of facilitating handling operations. Modularize valuable modules. Increase product accessibility by eliminating visual and physical obstructions. Merge components, whenever possible, with the aim to minimise the number of components and to reduce the number of assembly and disassembly operations. Develop standard interface for the connection of different modules. Ergonomic handle to support one hand usage.
Tools		Provide good documentation of specifications and clear installation manuals. Avoid need for specific tools.
Aesthetics		Color coding or textual guidance. Style should be suitable for display in the kitchen.

2.4.1. Identifying critical components through HotSpot Mapping

Now that the components are disconnected from each other, one should locate the critical parts. To do so, the HotSpot Mapping method [16] was followed. By logging each step of the dismantling process in a spreadsheet, target components and requirements will be easily extracted. Inserting each step of the dismantling process, five critical factors were determined (general properties, activity properties, difficulty of access, functional sensitivity and material properties). The completed grid can be consulted on Figure 2.3 but the main findings are summarized on Table 2.2.

Table 2.2: Target components identified with the HotSpot mapping method [16].

Part	High failure/functional importance	High embodied environmental impact	High embodied economic value
Motor	Target	Target	Target
PCB	Target	Target	Target
Power cord	Target	Target	Target
Shaft coupler	Target		
Push pull-out module	Target		

The target indicators from the HotSpot Mapping show that these components present either a higher failure rate compared to the others but also (or either) have a high embodied environmental impact and economic value. That is exactly the definition of critical parts, which should be easily accessible with low effort to enable cost-effective recovery processes when at EoL. Other than that, the logging process gave an objective metric to compare the ease of disassembly of two products as this approach depends on product-related aspects, such as the type of tools used and their availability, and on context-related aspects (like the availability of a repair manual) [16]. The tools needed during the disassembly are classified according to the EN45554 standard where hand or basic tools are defined as class A, B specifies product group specific tools, class C is other commercially available tools and proprietary tools as class D (this classification will be a bit more detailed in Section 4.1.1 and Table 4.1). In this case, only category A and B tools were needed.

2.4.2. Target consumer

Given the configuration of the object, it is clear that the accent is put on the product's buyer only. The design prevents an easy tear-down and understanding of the object. The first step of the disassembly is representative of this as a flat tool needs to be inserted inside the top cap to act as a lever and unclip the cap, which might harm it. No guidance on disassembly is provided by the manufacturer and the appliance manual only focuses on use and never on repair.

Repairers are also consumers

During the redesign phase, the above conclusion is wished to be avoided and the repairer will be considered as much an end-user as the product buyer. This alternative business model proposition is a central statement as it breaks the barriers between manufacturers, end-users and repairers, sitting them all at the table when conceptualizing a product, to make it as much 'circular' as possible.

HotSpot Mapping Datasheet

General project information

Brand name	Bosch MaxoVlxx
Product category	Hand Blender
Authors	Justine Lebrun
Date	April 2022
Location	Louvain-la-Neuve

Overall HotSpot Results

Total	350	(5min50)
Time of disassembly [s]	26	
Number of tasks	21	
Number of steps	4	

Average	0.391	[0 = low (<5 N) ; 1 = moderate (5...20 N) ; 2 = heavy (>20 N)]
Force	0.652	[0 = clear access, 1 = recessed access, 2 = obstructed access]
Accessibility	0.565	[0 = no/low precision, 1 = moderate precision, 2 = high precision]

General properties				Activity properties				Difficulty of accessibility				Functional sensitivity		Material properties		HotSpot indicators							
Step number	Name	Subassembly		Part of...	Activity	Required tool	Tool size	Task frequency	Time to disconnect (sec)	Force	Accessibility	Positioning	Maintenance	Functionality (failure risk)		Material group	Weight [g]	Time	Activity	Priority part	Environmental	Economic	
		Yes	No											Yes	No								
1	Blender's foot	Yes	No	Foot assembly	Disconnect	Hands	1	5	0	0	1	1	1	1	1	Stainless steel	195						
2	Bottom screws	Yes	No	Main assembly	Unscrew	Screwdriver	TR8	2	20	1	1	1	0	0	0	Stainless steel	2						
3	Bottom lid	No	No	Main assembly	Remove	Hands	1	20	1	0	0	0	0	1	1	PP/TPE	7						
4	Metal enclosure	No	No	Main assembly	Remove	Hands	1	10	0	0	0	0	0	0	0	Stainless steel	51						
5	Top cap	Yes	No	Lid	Remove	Flat tool	1	30	1	1	2	0	0	0	0	PP/TPE	4						
6	Lid screws	Yes	No	Main assembly	Unscrew	Screwdriver	TR8	2	20	1	2	1	0	0	0	Stainless steel	2						
7	Top cap support	Yes	No	Top assembly	Remove	Hands	1	20	0	1	1	0	0	0	0	Stainless steel	16						
8	Middle part of lid	Yes	No	Top assembly	Remove	Hands	1	20	0	0	0	0	0	1	1	PP	4						
9	Lid support	Yes	No	Top assembly	Remove	Hands	1	15	0	2	0	0	0	0	0	PP/TPE	8						
10	Superior housing	Yes	No	Main assembly	Remove	Hands	1	20	0	0	0	0	0	1	1	PP/TPE	52						
11	DC motor	Yes	No	Motor assembly	Remove	Hands	1	5	0	0	0	0	0	1	1	/	395						
12	Shaft coupler	Yes	No	Motor assembly	Remove	Hands	1	10	2	0	1	1	1	1	1	ABS	2						
13	Push pull-out clip	Yes	No	Push pull-out	Remove	Hands	1	30	1	2	1	1	2	1	2	ABS	20						
14	Coupler ring	Yes	No	Push pull-out	Remove	Hands	1	5	0	0	0	1	2	1	2	ABS	8						
15	PCB	No	No	Main assembly	Remove	Hands	1	10	0	0	0	0	1	3	1	/	19						
16	Inferior housing	No	No	Main assembly	Remove	Hands	1	10	0	0	0	0	0	1	1	PP/TPE	58						
17	Power cord	No	No	Main assembly	Remove	Hands	1	15	0	0	1	1	1	1	1	Copper and rubi	80						
18	Potentiometer gear	Yes	No	Top assembly	Remove	Hands	1	10	0	1	0	0	0	1	1	ABS	1						
19	ON button	Yes	No	Buttons assembly	Remove	Plier	1	30	1	1	2	0	1	2	0	1	ABS	2					
20	Turbo button	Yes	No	Buttons assembly	Remove	Plier	1	30	1	1	2	0	1	2	0	1	ABS	2					
21	Buttons springs	Yes	No	Buttons assembly	Remove	Hands	2	5	0	1	0	0	0	0	0	Stainless steel	1						
22	Top spring	Yes	No	Top assembly	Remove	Hands	1	5	0	1	0	0	0	0	0	Stainless steel	1						
23	Ball	Yes	No	Top assembly	Remove	Hands	1	5	0	1	0	0	0	0	0	Stainless steel	2						

Figure 2.3: Completed spreadsheet of the Hot Spot Mapping method [16].

2.4.3. Functional diagram

To understand the operation of the studied appliance, a functional diagram of the flow functions is available in Figure 2.4. This abstract structure is the starting point so that the redesign won't affect the functionality of the product. The different flows comprising the correct operation of a hand blender are, electricity (signals and control), manpower (for the commands), released heat, noise and rotational energy to move the blades.

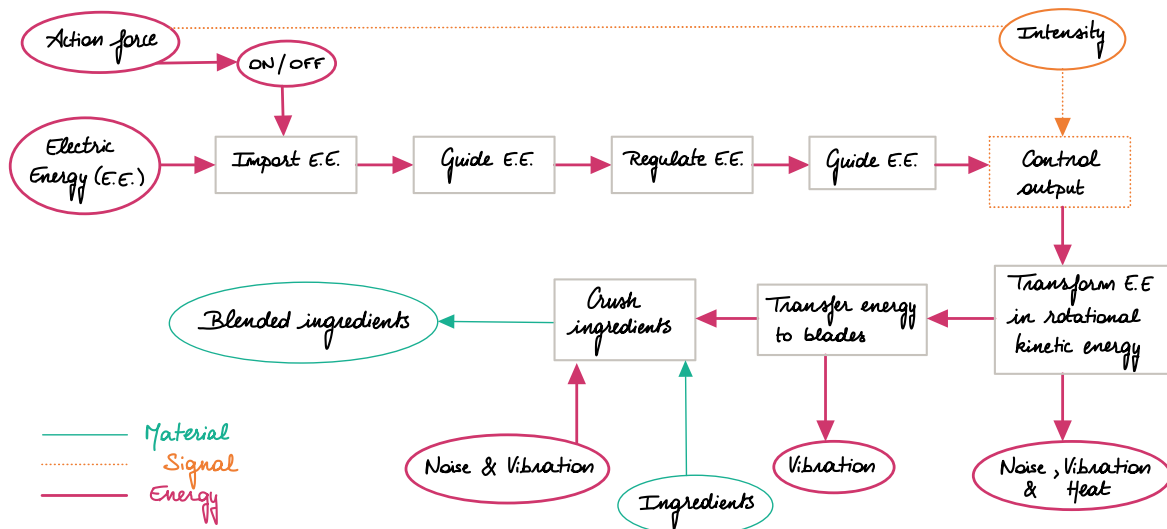


Figure 2.4: Abstract functional diagram of a hand blender.

2.5. Modular approach for design iterations

The two aspects of user-friendliness for repair and EoL considerations work well together. Considering the main mechanical and electronic components as modules, it can both break the barrier of preconception about the complexity of the object as well as ease the after-life treatment process. Using this *Lego*-like approach has the goal of reviving the children's instinct in users' hearts and allowing them to play to repair or assemble their objects. They won't necessarily need to know everything about the technology behind each module but they will have enough guidance to picture the links between them.

Since the goal is to manufacture all possible spare parts in the workshop of a FabLab, the according processes will interfere with design from the start. Nevertheless, for standard components, power and electrical ones, FabLabs can't beat the reliability and precision of the industry. Therefore these spare parts in particular - in our case, electronics components and circuit boards, cables, and a DC brushless motor - will be either bought or upcycled from other objects in EoL. The Repair Studio was the perfect opportunity for these kinds of application and small brushless DC motors were retrieved for later use. This actually makes sense as the lifetime expectancy of a DC motor is between 5 000 and 10 000 hours while hand blenders for example are only used 8,3 times per month on average [35], making a total of 16.6 hours of use per year if we consider 10 minutes per use. It is very unlikely that this kind of component is the reason for failure so their reuse makes complete sense.

The developed prototype went through many versions, Figure 2.5 shows three of them. Starting from the easiest made casing with just acrylic plates press fitted together with notches on the side, it evolved with a 3D printed rack hosting each acrylic plate with the aim of easing the sealing and disassembly questions. Attaching the components to the housing lead to individual casings and tailored apertures to press fit into place. This rectangular version was however not ergonomic at all, inducing a new housing design that could fit into the hand. Pieces were missing to able quick coupling and decoupling of the foot to the rest of the assembly while engaging the shafts of the motor and the blades together. Several design solutions were investigated. The final version that will be presented in the next Chapter tried to simplify spare parts as much as possible while offering a clear disassembly instinct when looking at the object as well as taking the most advantages of the manufacturing machines present in the FabLab.

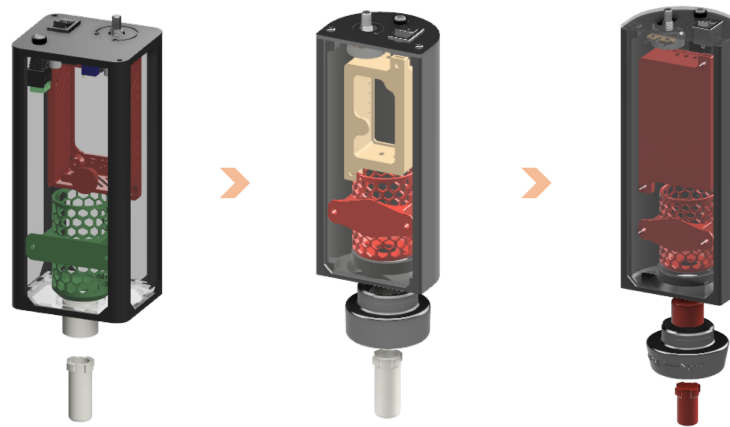
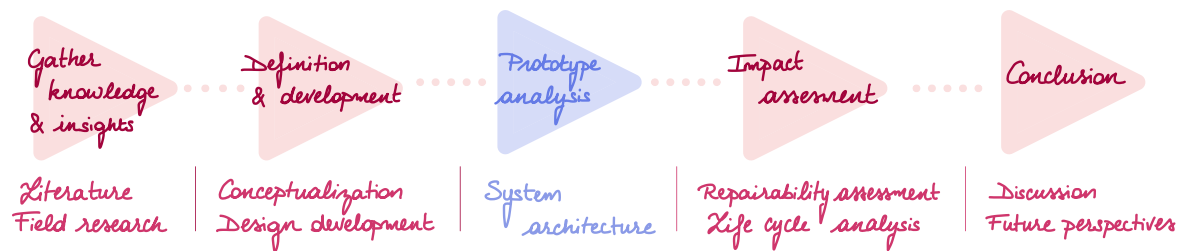


Figure 2.5: Design evolution of the hand blender prototype. From an acrylic box enclosed by a 3D printed rack to an ergonomic design.

3

Prototype analysis



This chapter presents the final prototype, its components descriptions and design choices.

With the framework exposed and the functional analysis in mind, the prototype making could start from scratch. After a get-to-know phase of familiarization of 3D printing processes (see Annexes and A and B for more details), CNC milling and laser cutting, ideation could begin. The prototype has evolved in many versions until coming up with the functional final draft described in the first next sections. The design appropriation possibilities were investigated as well as cost considerations. Lastly, an example on how to reuse critical spare parts to give them a second life cycle was presented.

3.1. Prototype overview and components description

A tear-down top view of the prototype is shown on Figure 3.1 and an exploded view is provided in Annex C as complement. Each of the components' roles and designs are shortly defined in the next sections.



Figure 3.1: Prototype of the FabLab hand blender tear-down.

3.2. Materials

3.2.1. 3D printing material

Due to its low price, and easiness of operation (no toxicity), PLA is the most common material for 3D printing. Polylactic acid (PLA) is a biopolymer produced from natural resources with good mechanical and chemical properties, making it widely used in packaging, agriculture, and biomedical industries [39]. It is also a biodegradable material with less greenhouse gas (GHG) emissions than fossil-based plastic [39]. With its widespread availability in FabLabs, PLA was the only printing material used for the prototype. Other materials with different mechanical properties could have been used (ABS, PETG, TPU, Nylon...) but given the toxicity or the experience required, and the willingness of the project to be user-friendly and easily replicable, they weren't used in the prototype.

Planning for reuse in the case of PLA parts can be done for low-functioning parts but for the others, it is most likely to be the less realistic option when the object is at its EoL. The high functioning parts are highly customized for a specific purpose and will be likely not be as good as new after a good number of use even if they are still operational. Planning for effective recycling nevertheless, can be done systematically. To facilitate that process from the start, heaviest printed parts will bear a symbol as on Figure 3.2 to indicate the type of plastic (miscellaneous category with the number 7 in this case) it is made of and keep a traceability of the materials when at EoL.



Figure 3.2: To plan for recovery and recycling, a recycling symbol is included in heaviest 3DP spare parts.

3.2.2. Flat surfaces

3D printing a flat surface would be a shame considering the exorbitant time needed to do so compared to the time of simply cutting a raw material. To follow that spirit and get the most benefits of both manufacturing processes, some parts of the final prototype were simply laser cut or CNC milled in acrylic. In a foreseeable future, these plates could be replaced by recycled plastic plates, closing the loops of materials by reusing broken or failed 3D printed parts.

3.2.3. Materials composition comparison with the reference case

A complete bill of materials of the prototype is available on Table 3.2. It is significantly different from the reference case product as one can observe on Figure 3.3. The PP/TPE housing is replaced with PLA and acrylic, and all smaller parts of ABS are replaced by PLA. The motor used is slightly lighter as it is a different model. The blender's foot, screws and nuts accounting for the 'Steel' part are similar in mass. The 'Electronics' mass is simply higher in the prototype as it now includes not only a PCB but also a few electronic components. The mass of the category 'Others' in the Fab Lab hand blender is significantly higher as a power cord and transformer were used instead of a simple power cord directly connected to the PCB as in the reference product.

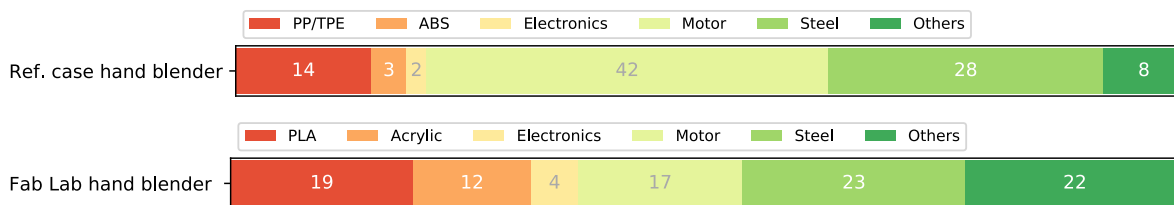


Figure 3.3: Materials composition comparison between the reference case hand blender and the FabLab prototype expressed in mass percentage [%].

3.2.4. Spare parts

Housing - For ergonomic reasons, the housing had to fit into the hand and therefore components had to align vertically to allow a narrow grip. This piece is the most critical one from a manufacturing point of view as it took 9 hours and 20 minutes to print and weights 120 grams. Still, this observation was concluded acceptable as it should not undergo great loads and the purpose is only for enclosure and handle. The choice for a one 3D printed enclosure seemed to be the best option compared to the discomfort of an acrylic box grip and the fragility of a multiple pieces enclosure. A CNC milled enclosure was also envisaged but the idea was quickly dismissed given the amount of material it would be necessary to subtract from the primary raw block. Also, primary material blocks that thick are now easily available in FabLabs and the risk of manufacturing failure is very high. As the hand doesn't need to go across the whole diameter of the handle, a flat plate lays behind the curved housing. Its aim is that after unscrewing the top plate, the only step left to access critical components would be to glide, together with the top part, the lateral plate of the housing. At the bottom of the housing is a annular part that will house the blender's foot adaptor while still allowing quick coupling and decoupling of the foot.

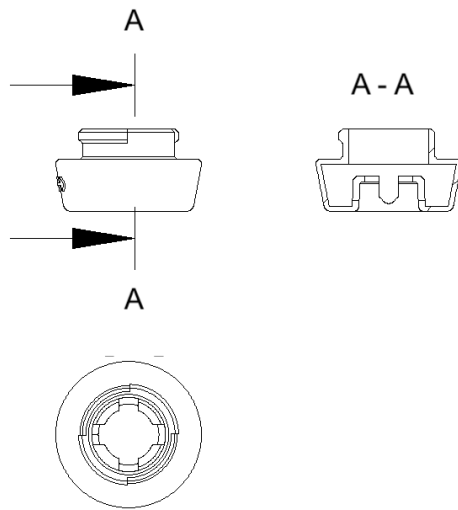


Figure 3.4: Side view, top view, and sectional view of the housing to foot coupler.

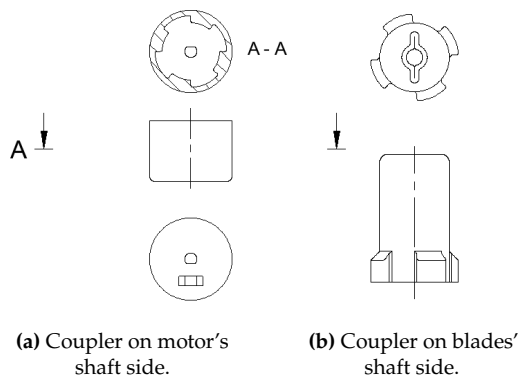
Housing to foot coupler - This piece is directly fixed on the blender's foot to allow coupling and decoupling of the foot blades housing to the main housing. To do so, on half the external diameter, a partial annular will engage in the female counterpart of the housing and after rotating the part by 90° this external annular will be supported in the main housing, finishing the coupling. Disengagement is only the reverse process. As seen on the sectional view in Figure 3.4, an annular snap fit (with 4 gaps around the diameter to improve the flexibility of the snap fits) attaches to the protrusion of the blades' housing. The design of this annular snap fit was tricky given the rigidity of PLA. Once the piece is in place, the link is very sturdy however, if one wishes to remove this part, the risk of breaking one part of the snap fit is high. Many designs were investigated to avoid this outcome but as the small annular retraction of the blades housing protrusion is the only attach area possible, snap fits were the only option. Also, this piece should not be removed during use thus, disassembling it would already mean that the piece is broken. Eventually, this serves as an adaptor of an industrial spare part and will surely differ depending on the blender's foot chosen.

Motor casing - To protect the DC motor and attach it to the housing, a honeycombed casing with two threaded inserts (see Figure 3.5 for visualization) on the sides was 3D printed. Instead of a plain enclosure, this pattern allows cooling down and prevents overheating failure in the motor. Operational temperatures of the motor in this kind of application will safely stay under the glass transition temperature and avoid plastic deformation.

Electronics box - To protect the electronic boards, a robust but see-through casing encloses the PCB and buck converter with textual signals for wiring to guide the user when (dis-)assembling the product. Four threaded inserts are needed to house the threaded screws that will fix the boards.



Figure 3.5: Picture of a positioned threaded insert on the motor casing.



Shaft coupling - Not only the foot should be assembled to the housing but the blades shaft should also be engaged to the motor shaft. A small piece (visualisation on Figure 3.6a) is inserted on the motor's shaft. A nut is inserted on top of the shaft's hole (right above the sectioned part of the shaft, normally for a key placement) in order for a pressure thread screw to robustly fix the piece.

Slicing settings and printing duration times for the 3D printed spare parts are reported in Table 3.1. The total time needed to print all parts adds up to 33 hours. This number is quite significant and will limit production capabilities of the FabLab for the object. A smaller layer height was set for parts needing more details or tolerance precision (FDM has an unavoidable dimensional accuracy of ± 0.5 mm). Infill percentages were increased to 15 or 20 % along with wall line count to 5 (or even 6 for the housing) to increase robustness of high functioning parts.

Table 3.1: Slicing guidelines for the 3D printed spare parts of the FabLab hand blender and their needed time of print.

Part name	Time	Weight [g]	Layer height [mm]	Infill [%]	Wall line count	Support
Housing	18h40	125	0.15	20	6	None
Electronics case	5h50	37	0.15	10	4	None
Foot to housing coupler	3h	23	0.1	20	5	None
Coupler pin motor side	0h53	3	0.1	15	5	None
Coupler pin blades side	1h05	4	0.1	15	5	None
Motor casing	3h36	14	0.15	10	5	Touching build-plate, overhang angle 72°

Enclosure plates - An acrylic lateral wall hosts the printed circuit boards and motor casings. After unscrewing the two screws fixing the top plate, the lateral wall simply glides from the housing, making all components easily accessible after only 2 steps of disassembly. The top plate is also made from acrylic and finishes the enclosure as well as supports the rocker switch, potentiometer and power plug, which are pressed fitted or screw to it.

Power supply - To able the prototype to be plugged in a 220 V socket, a transformer and power cable are used. The transformer allows to feed the appliance directly with 24 V DC current. This module is reused from a former appliance.

DC motor - A brushless direct current motor will transform electrical energy into rotational kinetic energy to move the blades. The one used for the prototype has a 24 V and 4500 rpm rating.

Table 3.2: Bill of materials and their respective proportion and function for the FabLab hand blender.

Part name	Qty	Mass [g]	Mass [%]	Material	Manufacturing	Primary function
Top plate	1	20	2.1	Acrylic	Laser cutting	Top enclosure and buttons support
Housing	1	103	13.1	PLA	3D printing	Enclosure and handle
Wall	1	81	8.49	Acrylic	Laser cutting	Enclosure and components support
Electronics box	1	33	3.46	PLA	3D printing	House the PCB and buck converter, guide user for wiring
Electronics box top	1	14	1.47	Acrylic	Laser cutting	Box enclosure
PCB	1	16	1.68	/	Purchased	PWM DC motor speed control
Buck converter	1	11	1.15	/	Purchased	Regulate the voltage supply
Motor casing	1	14	1.47	PLA	3D printing	Support the motor and attach it to enclosure
DC motor	1	160	16.82	/	Purchased OR reused	Provide torque to drive the blades when powered
Motor shaft coupler	1	5	0.31	PLA	3D printing	Engage the blades shaft and motor shaft
Blades shaft coupler	1	5	0.42	PLA	3D printing	Engage the blades shaft and motor shaft
Foot to housing coupler	1	23	2.4	PLA	3D printing	(De-)couple blender foot to housing
Female plug	1	6	0.63	/	Purchased	Supply power from the power cord to the rest
Power cord and transformer	1	210	22.01	Copper, rubber	Purchased OR reused	Power connection to a 220 V socket
Rocker switch	1	3	0.31	/	Purchased	Switch power on and off
Potentiometer	1	5	0.52	/	Purchased	Control the PWM signal/intensity of torque drive
Potentiometer button	1	1	0.1	PP	Purchased (IM)	Handle for potentiometer
Cables	9	5	0.52	Copper, rubber	Purchased	Link the electronic elements
Screws	10	5	0.52	Stainless steel	Purchased (Thread-rolling)	Fasten components to housing
Nuts	4	1	0.1	Steel	Purchased	House screw threads
Heat sets	6	2	0.21	Brass	Purchased	House screw thread

3.2.5. Wiring architecture and motor control

Figure 3.7 displays how the electronics and other components inside the prototype will be hooked up. To supply the appropriate voltage to the board and the motor, the intention was to use an of-the-shelf component that could tune the incoming voltage to a desired value. This is specifically the role of the buck converter. The latter will power the printed circuit board designed for controlling the speed of the DC motor. Directly related to it, is a potentiometer, which will later be used as a control of the torque intensity.

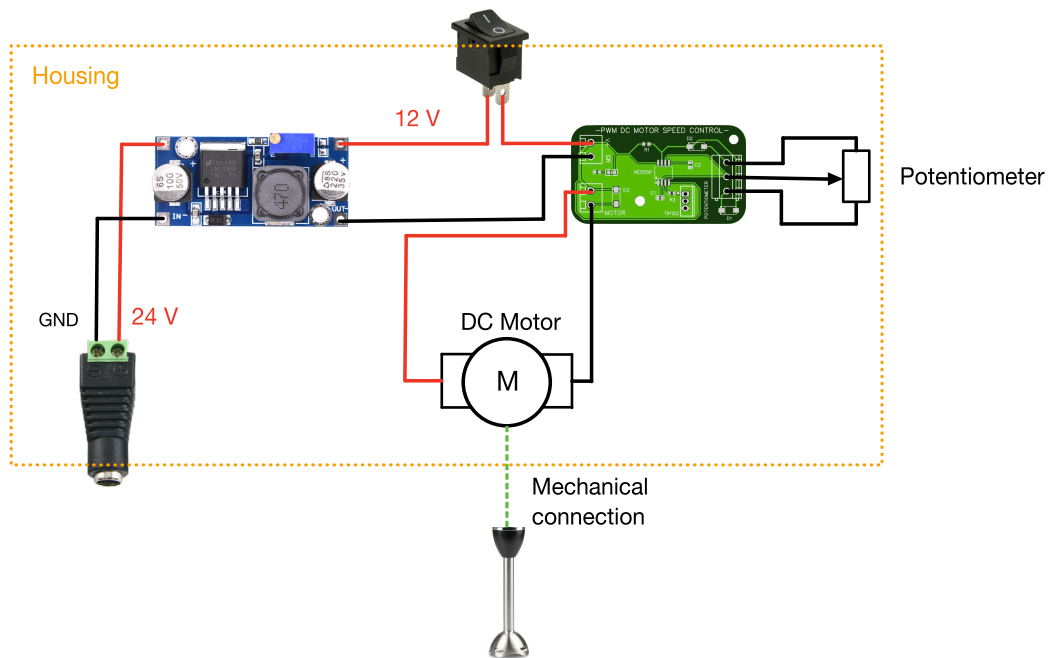


Figure 3.7: Diagram of the architectural layout of the prototype.

Motor control

The DC motor converts electrical energy into mechanical energy and will be controlled with the help of a 555 Timer Pulse Width Modulation (PWM) generator circuit. The aim of the circuit is to generate variable voltage by turning on and off the power that's going to the electronic device at a fast rate. The average voltage will be representative of the motor behavior and will depend on the duty cycle of the signal, or the amount of time the signal is ON versus the amount of time the signal is OFF in a single period of time.

Using the potentiometer it is possible to control the speed of the DC motor, meaning, the PWM signal produced by the 555 timer IC. For the final version of this circuit, a PCB was designed in order to fit in the new prototype. A 2D view of the final PCB can be seen on Figure 3.8 and the circuit schematics are available in Annex D.

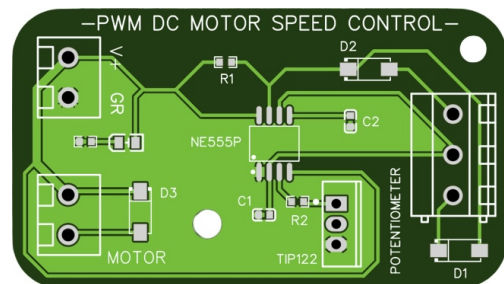


Figure 3.8: Printed circuit board view of the PWM speed controller for the DC motor.

3.3. Future design appropriation

Different household appliances have different mechanical and thermal requirements, inducing appropriate material choices. For the case study application of a hand blender, 3D printed PLA and acrylic made their proofs but they surely won't be fit all for all products. For other applications, different materials like ABS, or even higher quality ones like ABS, Nylon, Onyx (a Nylon 3D printing filament reinforced with carbon micro-fibres) can be envisaged. The 3D printed spare parts could also be made from a SLA printer using resin and therefore increasing the performance of the parts. Once the reproducibility within a FabLab environment is proven with cheap and widely available materials, the designed spare parts can move to stronger material choices.

The dimensions of each spare part can also be easily assimilated to other similar components as the CAD models are designed to be parametric. After choosing reference edges on the part, the rest of the dimensions were placed relatively to these reference edges. Therefore, by simply changing the values in the dimensions table of the CAD model, it can easily adapt to the wished configuration. This parametric design is also necessary if the goal is to go towards bigger production and repair lines. Even if the manufacturing concentrated in a FabLab during the study, it can be imagined that once the prototype is validated for safety, ease of repair and disassembly, and reproducibility, the fabrication models and design guidance could be send to bigger production lines. This would make sense as the production capacities of FabLabs are limited (the necessary time to print the 3D spare parts described in the previous are representative of that) and it could therefore not satisfy the whole demand on the current market. This new workflow doesn't wish to stay marginal to the industrial market but could also work next to it.

3.4. Cost considerations

The total price of the new object will depend on many parameters. Firstly, the price of spare parts like electronics components or product related spare parts (like the blender's foot in this case) depends greatly on quality and brand. Secondly, if the person making the 3D printed and laser cut part is a beginner, they might add some cost to the bill with a few failed tries, adding a couple euros. Finally, electricity cost could be a small driver. In the case presented above, the final prototype costed **39.7 €**. This low price is due to the fact that the DC motor, power cord and transformer as well as the blender's foot were recuperated from disposed products, therefore adding no contribution to the bill. However, if one was to buy these components as new, it would cost **92.7 €** in total. A bill of materials for cost computation is developed into more details in Annex E. The price of the Bosch hand blender studied before is currently 91.99 € on the market. Obviously, the local and customizable processes used in the making of the prototype can't compete with the costs of bigger scale production lines. Nevertheless, this equivalent price compared to industry will be amortised with its longer lifetime thanks to repair and upgrade possibilities. Also, electronic components were bought separately and in very small quantities but buying those in higher amount in association with other local hubs could reduce costs.

3.5. Second life cycle example for priority parts

When considering the critical components of the hand blender - meaning: the motor, PCB, power cord and transformer - it is clear that their lifetime under normal use are above the ones of the rest of the spare parts. Repurposing functional critical components whether an appliance should be broken, undesired or obsolete can offer a second life cycle to these spare parts and therefore minimize their embedded environmental impact due to their high value in raw materials extraction and production.

This principle was applied and allowed to recreate a new object from the internal components of the hand blender. With the help of 3D printing and laser cutting, fan blades, a new motor coupler and casing were built. Adding in the electronics box and motor inside, along with the other components (rocker switch, potentiometer, plug, power cord), a fan could be created (see Figure 3.9 for an overview). The outer casing walls are made of acrylic and a PLA 3D printed rack holds everything together. The idea behind this, is that the user will only have to unscrew the top and then glide the walls to get access to any components. The 2 simple steps severely reduce disassembly time compared to a typical similar appliance and thus enhancing the first step of repair.

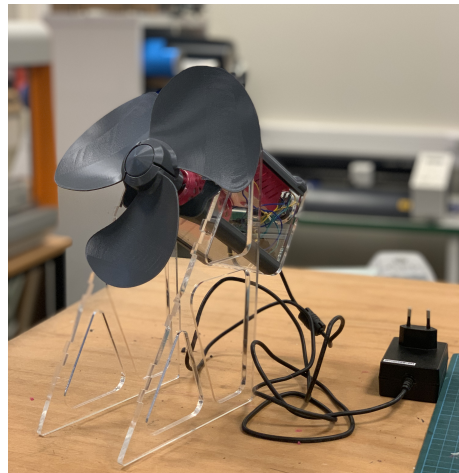
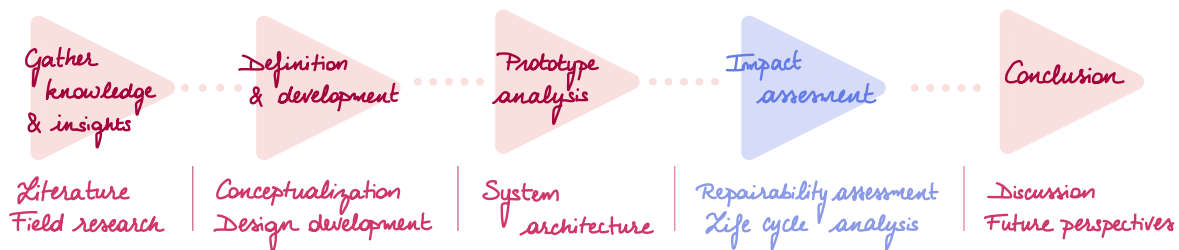


Figure 3.9: Turning the priority spare parts of the hand blender into a new object, a desktop fan.

4

Impact assessment



This chapter will evaluate repair possibilities and environmental impacts of the prototype. This is done by constructing a repairability and reproducibility evaluation grid and later by performing a life cycle analysis on the prototype.

4.1. Repairability and reproducibility grid construction

As mentioned in Chapter 1, more and more certifications and scoring systems start emerging on the thematic of repairability. Nevertheless, none has included FabLabs in the game yet. This section aims at proposing a new evaluation tool for this purpose, mostly taking inspiration from the French repairability index ¹ [8], the analysis study on a scoring system for repair and upgrade of products carried out by the European Commission [53] and European standards on repairability [36], [37]. Not only this scoring system wishes to encourage repair initiatives amongst product designs but also reproducibility. It aims at evaluating how fit a product would be for a reproducible, repairable and repurposed model in a FabLab. The grid targets small-sized electromechanical household appliances. It is directed to designers, manufacturers, repairers and even customers. The grid was made for a user-friendly purpose, so that not only experienced repairers could fill it in but also end-users. A limited number of technical parameters (covering design characteristics and operational aspects) have been selected to keep the length of the grid reasonable while still referencing important aspects.

¹The French repairability index only provides repair grids for smartphones, laptops, washing machines, TV, vacuums, mowers, pressure washer and dishwashers but the methodology is very holistic and is a perfect fit as base inspiration for this new grid.

4.1.1. Criteria

After the first version of the French repairability index, several have pinpointed challenges, especially from the way it is computed. Indeed, the ambition changes between categories and for bigger machines that already score high, manufacturers do not feel they need to make additional efforts. Also, the grades announced by manufacturers are computed by them but no mandatory detailed justifications are requested, sometimes leading to higher biased scores. Furthermore, the current grading system allows a product to still get a decent grade, despite performing poorly on the disassembly, availability or cost of spare parts criteria even if that means repair is almost impossible. The criteria weighting should not allow compensating in other evaluation areas [47]. In this proposed alternative grading system, critics of existing indexes will be taken into account, trying to make the insights embedded in the final score more representative.

Documentation

The first step is to evaluate the manufacturer's commitment making technical documents available free of charge, in number of years, to customers and repairers. Documentation on the product should include: product identification information, a disassembly map or exploded view, wiring and connection diagram, electronic board diagrams, a list of the necessary repair and test equipment, a technical manual of instructions for repair, component and diagnosis information, guidance for self-repair, accessibility to the nearest FabLab, user maintenance instructions and eventually easiness of access to the documentation. For reproducibility, CAD models (other than industry-owned standard components) should be available as well as the appropriate guidelines and settings to manufacture the spare part. Each of these aspects is separated into a sub-criteria. When completing the grid, four choices will appear in the box of each sub-criteria, as seen in Figure 4.1, representing the duration of availability of the mentioned documentation. To obtain the maximum score, the duration of availability should be over 7 years, otherwise, the score is simply the number of years in question and under 4 years, the score drops to zero.

Duration of availability
x ≥ 7 years
Select a choice
Not available or x < 4 years
x = 5 years
x = 6 years
x ≥ 7 years

Figure 4.1: Drop-down list when evaluating the duration of availability of necessary documentation.

Disassembly

Number of steps needed to disassemble the spare part
#steps < 6
Select a choice
Not available or #steps ≥ 16
11 ≤ #steps < 16
6 ≤ #steps < 11
#steps < 6

Figure 4.2: Drop-down list when evaluating the number of steps needed to disassemble a critical spare part.

After listing the possibly broken or malfunctioning priority parts, the accessibility of these critical components, necessary tools for the disassembly and fastener characteristics are evaluated. For circular strategies (i.e. repair, refurbishment, recycling), it is vital that the product is easy to disassemble to allow energy and cost-effective operations. To do so, the critical parts should be easy to reach and the tools used for dismantling should be of the highest class according to Table 4.1. The top category on the Table scores the maximal grade while the rest respectively score, three, two, one and zero points out of ten.

These number of steps to access critical parts should remain under 6 to get the maximum score of 10/10 for the accessibility sub-criteria, and for the rest of the available choices as seen in Figure 4.2 can score 5, one or zero points if the number of steps increases. Fasteners also play an important in the disassembly of a product [53]. The quantity and kind of fasteners, as well as their visibility, can be utilized as a proxy for the time required to repair or update a product. However, if repair instructions are available and fasteners are physically accessible, their visibility (e.g., by labelling and marking) is not as critical. More essential factors for evaluating fasteners are their reversibility and re-usability. Three levels of fasteners evaluation can be chosen, from the least score to the best: C - Neither removable nor reusable (0/10), B - Removable but not reusable (2/10), A - Removable and reusable (10/10). The component is considered reusable for the same object and/or other functions.

Table 4.1: Classification of tools as defined in the EN45554:2020 standard [36].

Category description	Class
Feasible with the use of no tool, or a tool or set of tools that is supplied with the product or spare part, or basic (common) tools	A
Feasible with product group specific tools	B
Feasible with other commercially available tools	C
Feasible with proprietary tools	D
Not feasible with any existing tool	E

Availability of spare parts

This next criterion focuses on the spare parts that are needed to create the object but can't be manufactured in a FabLab (a small brushless motor or a power cable for example). A score will represent how their manufacturer commits to make spare parts available for the product and for how long. Similarly to the documentation criteria, the availability over time for spare parts should be over 7 years to score the maximum and won't score a point if under 4 years. Another sub-criterion evaluates whether alternatives to the original advised industry spare parts are mentioned. If three or more alternatives are cited, the score is 2/2, if one or two are cited, the score will be one and otherwise becomes null.

Price of spare parts

Price of spare parts can be a major barrier to repair and this criterion evaluates the ratio of the sale price of spare parts compared to the price of the product. This criterion is strictly the same as in the French repairability index [8], and the calculation is based on three parameters:

- The price of the most expensive spare part x
- The average price of the other spare parts y
- The price of the product z

Once that is known, the ratio $\frac{x+y}{2z}$ is computed and points are awarded scale linearly from full points if the ratio is less than 10%, to zero points if the ratio is 30% or more [8]. This percentage limit is also validated by [53].

FabLab environment

The last criterion will score the product depending on its reproducibility within the scope of FabLab. It means that every part -other than electronics, power components and other standard components impossible or unreasonable to manufacture in a FabLab- should be produced through the machines available in this environment (on overview of the machines and manufacturing processes available in FabLabs is available in Annex F).

To start with, an open-source framework should happen to be in place. The information on existing corrective updates or upgrades scores a point if provided and none otherwise. Repairing or updating a product may necessitate certain technical skills, which contribute to the operation's complexity and cost. Such skills include the capacity to identify and localize a fault, access a part within the product, handle parts and tools securely, and manage any risk related with the product and the environment. As a result, certain procedures may necessitate suitable technical capabilities that the majority of consumers lack, and thus may be practicable only for particular target groups [53]. Therefore, the next criterion wishes to reward a safe environment of work. If a description of repairs operations are provided (level of skills required, risk associated, safety precautions) a point is added, otherwise none. Also, if the repairer requires just a general basic knowledge of repair with no specific qualifications, it'll score 10/10 on this sub-criterion. However, if a specific experience of the product category to be able to handle risks properly is needed, the score is dropped to 6. And if only the manufacturer can perform the repair, a score of 3/10 is awarded.

The reproducibility of spare parts is evaluated. All spare parts other than the standard ones should be replicable through FabLab manufacturing techniques. This will again be evaluated as a proportional scoring system. If no more than 50% of spare parts is replicable, no points are awarded. The second option visible on Figure 4.3 will score 2 points out of 5 and the maximum score is awarded if more than 90% are replicable.

Figure 4.3: Drop-down list when evaluating the proportion of replicable spare parts.

The next criteria might seem logical is actually necessary considering redesigns of existing objects as the manufacturing techniques are different. All spare parts should fit within the requirements of the machines (a 3D printed part should fit within the building volume or a CNC machined part should accept the precision level of the offered milling cutters for example). They should also obviously match their requirements with the mechanical and thermal properties of the limited panel of materials proposed in FabLabs. Both of these sub-criteria use the same proportion scoring system as the previous one.

Eventually, a criteria rewards the presence of a take-back program. When the object finds itself to be at its End-of-Life, a take-back system should be in place to organize the reuse of the functioning components and the recycling or responsible handling of the broken ones. One point is awarded if such a system is established and none otherwise. This choice to reward a take-back program comes from the assumption that it should encourage users to envisage a repair/upgrade process as they would go to the FabLab in any case, therefore finding a solution whatever the outcome.

4.1.2. Weighting system and final scoring

Even if each criteria should be individually optimized, they can't all get the same importance on the final score. Therefore, the final score was computed as a weighted sum of all the mean criteria grades. The biggest scoring weights were attributed to the disassembly and FabLab manufacturing steps. The accent was put there because the availability of spare parts or the maintenance instructions for example stop making sense when a product can't even be disassembled or its spare parts can't even be reproduced or easily found. To emphasize this, the grading on the sub-criteria is stricter than the French repairability index which for example attributes a linear grade from 0 to 4 depending on the position on Table 4.1 for tools category. In the calculation presented here, the maximal grade is 10 for category A but from the B category, points directly lower to 3/10. Next in the weighting importance comes the documentation availability and finally, cost considerations. The first distribution of weights was inspired from the French repairability index and then was adapted so that the final score could not be biased by other categories if the product doesn't perform well on the disassembly and reproducibility categories. The weights distribution is available in Table 4.2 and was attributed per global criteria therefore the sub-criteria were not included in the Table.

Table 4.2: Weights distribution for the repairability and reproducibility grid criteria.

Documentation	Availability of the technical, manufacturing user instructions documentation	1
	Availability of CAD models and manufacturing guidelines	1.5
	Ease of access to documentation	0.2
Disassembly, accessibility, tools and fasteners	Accessibility of the critical components	1
	Necessary tools for disassembly to get the critical components	1.2
	Fasteners characteristics	0.5
Availability of standard spare parts	Availability over time of standard spare parts	0.3
	Replacement of standard spare parts	0.3
Cost considerations	Price of spare parts	1
FabLab environment	Open-Source framework	0.5
	Skills and safe working environment	0.5
	Reproducibility	1.5
	End-of-Life	0.5

4.2. Results and discussion of the constructed grid

The blender prototype described in Chapter 3 will now be put to the test by completing the grid. After evaluation, the prototype performed really well with a score of 9.199/10. In order to nuance this result and give a realistic score idea, two cases were investigated for the FabLab hand blender. One is more optimistic than the second, their main sub-criteria evaluation is depicted on Table 4.3. The optimistic one represents the ideal scenario with target perspectives in place and the pessimistic one, represents more the prototype as it is today. This second case will be representative of the fact that given the restricted time of the thesis, only the hardware part was covered and a complete comprehensive online platform is missing. Instead, a repository on MyMiniFactory with all necessary CAD files, settings and exploded view was created but it is a point of attention which would need improvements in the future. Still, grades about duration of availability were all put over 7 years (scoring the maximum).

As to have a complementary on how a product would score after completion of the grid, two other fictitious scenarios were investigated. A product with good disassembly performances but poor documentation and the other with poor disassembly performances but very good documentation. A short description of these four cases is observable on Table 4.3. The goal of these two scenarios is to reflect the fact that with poor disassembly performances, the pertinence of the rest of the criteria is questionable and the product shouldn't score well. While if disassembly performances are good but no documentation or manufacturing models and settings are provided, reproducibility would be highly affected and thus the final score should be representative of it. Final scoring can be observed on Figure 4.4 and from it, one can validate the weighting distribution as it doesn't allow critical aspects like disassembly and documentation to compensate a bad score with other categories.

Table 4.3: Cases description for repair and reproducibility scores comparison.

Case 1	Prototype optimistic scenario - All documentation is available for more than 7 years, all CAD models and manufacturing settings are provided, accessibility to critical components is under 6 steps, class A tools, standard spare parts assumed available for more than 7 years, electronics and power components are reused, take-back assumed.
Case 2	Prototype pessimistic scenario - Compared to Case 1, Technical manual of instructions for repair, components and diagnosis information, user and maintenance instructions, guidance for self repair are not available, availability of spare parts is above 7 years but no alternatives are cited, all spare parts are bought/made new, FabLab environment scores the maximum but no take-back is in place.
Case 3	Fictitious scenario, good disassembly but no documentation - Documents are available for 5 years, less than half of CAD models and settings are provided, spare parts are available for 5 years and no alternatives are cited, a take-back is in place.
Case 4	Fictitious scenario, poor disassembly but maximum performances for the rest - Documentation scores the maximum, all CAD models and manufacturing settings are provided, between 11 and 16 steps are required to access critical components, category B tools are used, category B of fasteners.

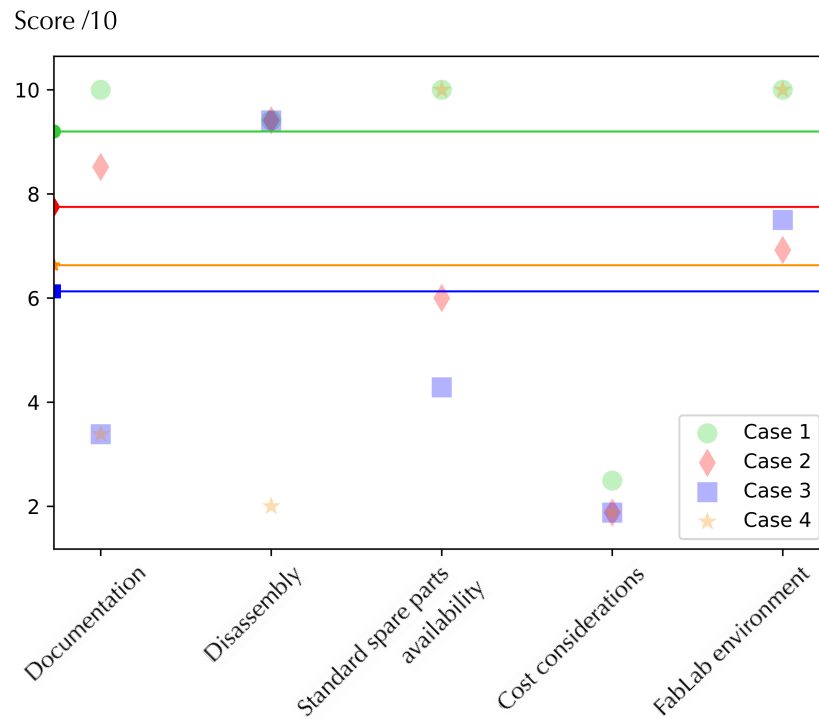


Figure 4.4: Repair and reproducibility scores comparison for the four cases depicted in Table 4.3. Mean score on each criterion for each case represented by points and the lines provide the final score associated with the case. The FabLab hand blender final score oscillates between Case 1 and Case 2 depending on the assumptions. Case 3 and 4 allowed to validate the weighting distribution of the grid.

The HotSpot mapping of the prototype as in Section 2.4.1 was not reported here as the conclusions were the same after completing the grid. Attention is brought to the blender's foot to housing coupler enabling the connection and disconnection of the latter to the housing. As the snap-fit attaching the part to the foot handle is made with PLA, it is not fit for multiple uses. It will surely break after multiple uses because of the non-flexible and layered character of the part. It thus scored a 2/10 for its fastener characteristic. However given the difficulty of reusing a proprietary design (the blender's foot was upcycled from another model), the limitations of the manufacturing processes, materials and the fact that this part should actually stay in place during all the lifespan of the object and only removed at its EoL, it was found acceptable.

Due the inherent environment of the FabLab, the prototype did not encounter red flags in the evaluation as it was actually designed in this framework from the start. Careful analysis of the case study product in Section 2.4.1 also avoided major errors for the disassembly and initiated educated concern from the start.

Aspects like emotional attachment, education of consumers, tax exemptions, labour cost reductions are considered out of the scope of the study as they are mainly socio-economic related issues and the goal here aims at staying technical (this same scope definition is inspired from [53]). Many more criteria other than socio-economic ones could be added to complete the picture. However, to stay reachable and widely used, the choice made here was to limit criteria to a sufficient comprehensive level as to ensure FabLab reproducibility and repair but without loosing the reader in hard to understand and long principles.

4.3. Comparing environmental impacts through a life cycle analysis

4.3.1. Goal of the study

As household appliances undergone a worldwide 37% increase in the 2013–2020 period, they represent a core area of consumption and their use is expected to grow notably over the coming years [34]. With the aim of supporting long term sustainability, CO_2 footprint, energy use and other environmental impact factors should be minimized. A life cycle analysis can provide a precise definition of the product and its life cycle with the aim of showing hotspots in the life steps and provide insights for future improvement. This method will be applied to the FabLab hand blender. The scope of this study is a traditional LCA ranging from the obtainment of raw materials to disassembly and disposal. The data used is a combination of literature data and data from the *Granta* Software.

4.3.2. System definition

The focus is on the main contributing steps of the product's life cycle to give an approximate idea of the real values. Four scenarios are evaluated, all taking into account raw material acquisition, transport, manufacturing use and EoL. Figure 4.5 shows a description of the steps taken into account and the fictitious scenarios modelled for this study. Each of the scenarios developed in the next section was modelled by considering local electricity mixes and transportation distances, and manufacturing processes were assumed to be the same in every location. Two impact categories will be covered:

Global Warming Potential (GWP): Global warming or the greenhouse effect, "is the effect of increasing temperature in the lower atmosphere" [72], expressed as CO_2 -equivalents (consequences expressed relatively to the effect of CO_2).

Energy use: The energy use represents the energy needed at each step of the life cycle. It will be expressed in Joules [J].

4.3.3. Scenarios description

Scenario 1: Reference case - A hand blender's lifespan can go from 3 to 10 years, depending on brand quality and user care. We'll further consider a lifespan of 5 years as it is a representative average of the guaranties duration of this kind of product. In the first scenario, the EoL assumption will be that a take-back program is in place at the closest FabLab from the end-user. The object will there be collected, its electronics and power components will be reused and all plastic parts will be sent to a recycling factory.

Scenario 2: First time prototype - The second scenario considers the same EoL assumptions as the first scenario. However, this one wishes to represent the case of an inexperienced person making the product and therefore failing each 3D printed or laser cut part three times.

Scenario 3: Low-tech version - Since the take-back and reuse of critical components were often mentioned, this will be integrated in the third scenario. The upcycled components (motor, power cord and transformer, blender's foot) are considered to be available at the manufacturing location and therefore, all impacts related to their production and transport won't be taken into account. The EoL of the product will be quite different. This time, the product will be recycled in its entirety (differentiating plastics and WEEE).

Scenario 4: Critical EoL - This last scenario takes the same assumptions as the first one for lifespan and manufacturing but a less optimistic EoL is envisaged: landfill.

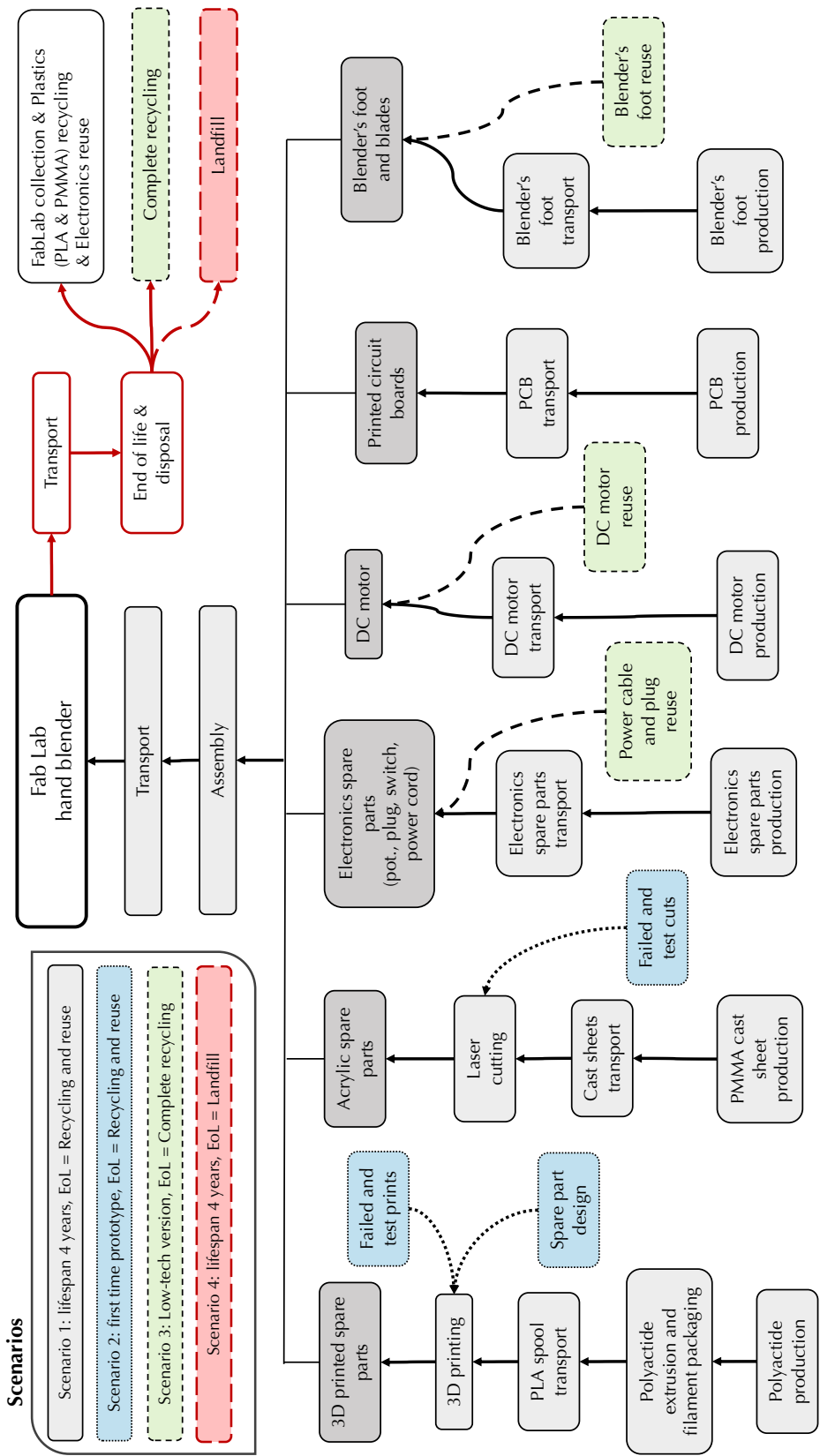


Figure 4.5: LCA scope study in the case of the FabLab blender realized during the thesis.

4.3.4. Raw materials extraction and production

In this sub-section, the data necessary for the raw materials gathering is described. Note that in the case of this study, this step considers consumables as raw materials. As an example, the impacts of the production of a printed circuit board will be resumed in that part as it is considered a primary part for the making of the product. Same applies for 3DP filament, which will be considered a raw material once extruded and rolled on a spool (ready to use in a printer).

After first disassembling the blender and determining the amount of materials used for each component (the materials composition was detailed in Chapter 3 on Table 3.2) their environmental impacts induced before arriving to the manufacturing location can be computed. The foot is the most massive component, at around 22 % of the total mass of the blender. 3D printed spare parts account for 21 %, acrylic ones for 12 %, the rest contains the motor and the electronics.

PLA - PLA primary production data was extracted from the Granta software. After their production, PLA granules are converted into filament through an extrusion process. Commercial extrusion machines have a capacity ranging from 3 to 15 kg of filament per hour with a power rating of 11 kilowatts [49]. Assuming a production of 15 kg per hour [49], 1 kWh per kg of filament is needed. It was assumed that the scrap from an extrusion process is normally reinserted in the process, inducing no material waste. Once the filament is extruded, it is rolled on a spool. This spool was assumed to be made of polypropylene (PP) by injection molding and that its production happens on the same site as the extrusion process [49]. The weight of such a spool is usually around 200 g to carry 1 kg of filament. The data was proportioned to the amount of PLA used during the making (=203 g).

	Energy use [MJ]	GWP [kgCO ₂ eq]
Polyactide primary production	10.69	0.548
PLA filament extrusion	1.17	0.088
Packaging of filament spools (per kg of packaging)	0.5	0.13

Acrylic - For the acrylic, data was obtained from Plexiglass [59], the most popular acrylic cast sheets brand. Provision of raw materials, PMMA production and casting, as well as production-related transport are included in the data.

	Energy use [MJ]	GWP [kgCO ₂ eq]
Cast sheets production (including provision of the precursors, transport of the precursors to site, and production processes)	12.46	0.49

Printed Circuit board - PCB production consists of a two-stage process, namely board manufacturing and assembly. Data for both of these steps were provided by Granta which also provides final numbers on energy use and global warming potential of individual electronics components. The same process was done for the buck converter. The board are single layer/single-sided of thickness 1.6 mm, with a substrate of epoxy resin, glass fibre and copper.

	Energy use [MJ]	GWP [kgCO ₂ eq]
Printed wiring boards production & assembly	82.8	4.86
Components of the boards (1 NE555P, 3 resistors, 2 capacitors, 3 diodes, 1 LED, 1 TIP22, 3 connectors)	82.18	4.05

Electronic components - Again taken from *Granta*, data was found for each electronic components present in the product.

	Energy use [MJ]	GWP [kgCO ₂ eq]
Electronics components (power plug, rocker switch, potentiometer, power cord and transformer, cables)	17.147	1.256

Brushless DC motor - No clear data was found on BLDC motors production. Therefore it was modeled by 9 magnets made of Neodymium, a copper wiring of 10 meters long, a rotor and stator composed of aluminium.

	Energy use [MJ]	GWP [kgCO ₂ eq]
DC motor production	37.86	2.575

Blender's foot - The blender's foot was modeled as 212 g of stainless steel AISI 304. The values in the next table include primary production, foil extrusion and roll forming.

	Energy use [MJ]	GWP [kgCO ₂ eq]
Foot housing and blades production	14.86	1.018

4.3.5. Transport

All transport phases were assumed to be made by truck (16 t), except the object take home which was assumed to be done by car. This category accounts for every transport step needed in the process. The production of PLA was assumed to be made in Thailand and the extrusion process, with packaging production in Hong-Kong. The target FabLab towards which everything is exported is in Louvain-la-Neuve. The PCB and electronics were assumed to come from Hong-Kong, the blender's foot from Germany and the acrylic from Darmstadt in Germany. Transport of the final object was assumed to be 30 km. Values of energy use per km were computed based on the LHV of gasoline (34.4 MJ/l) for a car and of diesel (37.1 MJ/l) for a truck with a consumption of 7 l/100km for the car and 25 l/100km for the truck. Data of GWP footprint for truck freight was extracted from [65] and from EEA [67] for the car.

	Energy use [kWh/km]	GWP [kgCO ₂ eq/km]
Truck freight (16 t)	2.57	106
Car transport	0.66	0.12

4.3.6. Manufacturing and assembly phase

3D printing - In their study, [49] measured the energy consumption of a 3D printer and found that it demands 72 W in set-up state, 75 W in warm-up state, and 71 W in build state. Multiplying these values by the required printing time, we get the final energy use demanded for 3D printed spare parts. The CO₂ equivalent footprint was computed by considering the CO₂-equivalent impact of the Belgian electricity mix, inducing 0.22 [kgCO₂eq/kWh] [68]. No post-processing, such as washing, scrubbing, cutting, or chemical processing was required after printing, therefore adding no contribution. In addition, fifteen minutes of use of a soldering iron (50 W) were considered as to place the 6 threaded inserts in the 3D printed parts of the product.

Laser cutting - With a power rating of 150 W, the laser cutting machine was assumed to be used for 10 minutes, drawing electricity from the Belgian electricity mix (0.22 [kgCO₂eq/kWh] [68]).

4.3.7. Use

The hand blender is assumed to be used 8.3 times per month with 3 minutes per use, those means rates can be found in the work of [35]. Together, these values add up to a consumption of 17.9 kWh/year. The hand blender doesn't produce additional emissions to its electricity consumption during use and GWP was calculated from the previous energy consumption and the Belgian electricity mix.

4.3.8. End-of-life

Based on a case study in Belgium [71], only 32 % of WEEE materials are currently recycled towards high-end applications whereas 68 % is lost in low-end applications, landfill or incineration. This justified the choice for the three EoL treatments investigated. All transport steps in the EoL phase are included in this category and not in the attributed Transport one. This choice wishes to facilitate interpretation when comparing two scenarios of EoL. In that way, looking at one phase only will be necessary to get an idea of the environmental impacts difference while if reported in the Transport category, transport induced by EoL will be mixed with all the other transport steps, making the comparison difficult.

Data for plastic and steel recycling were taken from *Granta*. To model the complete recycling of the product, plastics recycling data were completed with the recycling data of the Fairphone 3 [72] to model the recycling of the PCB, electronics components and internal components of the motor. This assumption can be discussed as it doesn't exactly represent the real case. However, precise data on the recycling of these kind of components could not be found in the literature, therefore, this maximum threshold was chosen since primary materials composition of the Fairphone compared to the PCB and electronics of the prototype are similar.

	Energy use [MJ]	GWP [kgCO ₂ eq]
Scenario 1 & 2 - Recycling plastic parts and reusing the rest of the components, Transport from home to FabLab: 30 km (car), Transport from FabLab to recycling factory: 50 km (truck)	9.714	0.647
Scenario 3 - Complete recycling of the product, Transport from home to FabLab: 30 km (car), Transport from FabLab to recycling factory: 50 km (truck)	11.8	-0.65
Scenario 4 - Landfill, Transport from home to landfill: 2000 km (truck)	9.28	13.55

4.3.9. Impact assessment

The contribution of each of the life cycle phases for the 4 scenarios depicted above can be observed on Figure 4.6 in terms of Global Warming Potential (GWP) [kgCO₂eq] and on Figure 4.7 in terms of Energy use [MJ].

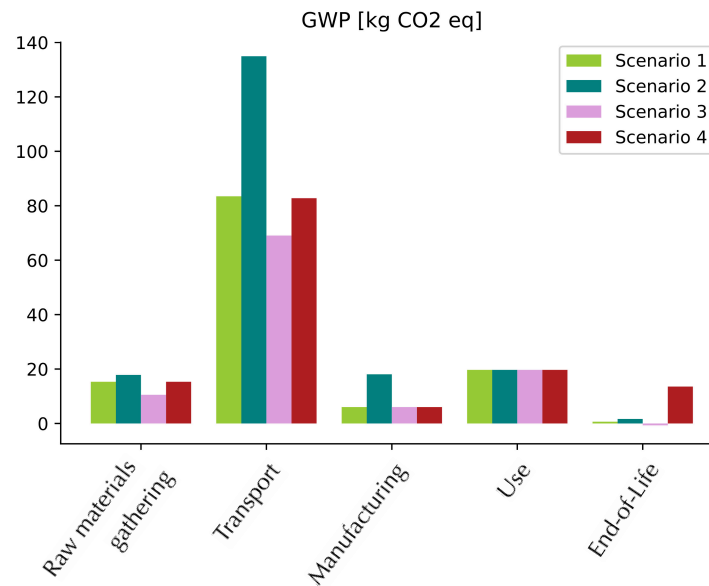


Figure 4.6: Life cycle analysis results for the four scenarios depicted in Section 4.3.3, in terms of Global Warming Potential (GWP) [kgCO₂eq].

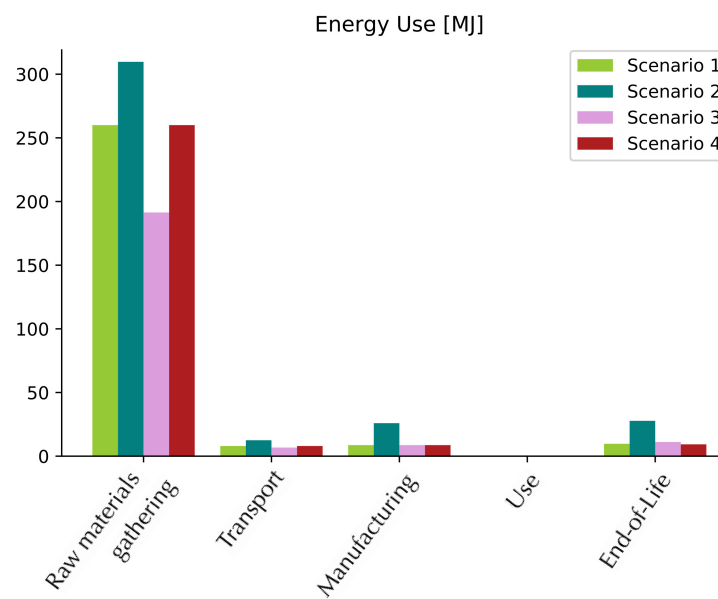


Figure 4.7: Life cycle analysis results for the four scenarios depicted in Section 4.3.3, in terms of Energy Use [MJ].

The first observation that stands out is the importance of the two first phases compared to the rest. This is representative of the hand blender use reality as it can go months unused depending on users' habits. Therefore, its environmental effects are mainly due to material extraction and transport of these. Raw materials gathering is the predominant driver for Energy use by far. The low-tech version of the product is the least impacting, as expected since critical parts were reused and therefore no data was associated to them. For all scenarios, the transport phase is predominant when looking at GWP. This highlights the need for local materials if the goal is to minimize environmental impacts. Manufacturing within a FabLab environment proves to have reasonable energy consumption and CO₂-equivalents effect. The use is completely marginal on energetic aspects but still generates some CO₂-equivalents given the non-carbon-neutrality of the Belgian electricity mix. Considering the EoL, landfill is clearly the worst disposal option for GWP. The EoL value on GWP for the third scenario, implying complete recycling of the product is negative. This means that there is a positive effect from precious metals recycling but a slightly higher energy use during this phase compared to the reference scenario.

4.3.10. Discussion

The goal of this LCA was to provide an overview on the proportion of each life cycle stage environmental impacts of the product and to give matter to compare scenarios. Two impact categories were chosen but if one wishes to envisage the bigger picture of these impacts, more impact categories should be taken into account (water usage, particulate matter or human toxicity are good examples, among others). This limit was decided since these two categories are quite famous and representative indicators, also they are the most spread over the literature and other ones were tricky to get. Therefore, for a sake of accuracy, insights were assumed to be sufficient compared to the initial with these two categories.

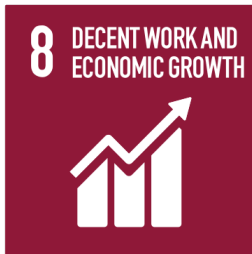
Eventually, as to have a more holistic view, results should be compared to the LCA of a similar product on the market. Unfortunately, no literature providing the necessary data was found and after many contacts with brands on the market, either these results were confidential or just not carried out. Performing the LCA of the market case in itself was also an option but given the amount of incertitude on materials provenance, manufacturing processes and transportation modes, it was concluded that these results would not be representative.

4.4. Contributing to the SDG's

In September 2015, the United Nations and all member states adopted the ambitious 2030 Agenda for Sustainable Development and identified 17 Sustainable Development Goals (SDGs) and 169 targets for ending poverty, protecting the planet, and ensuring prosperity for all over a 15-year span. As [18] rightfully explains, increasing levels of e-waste, improper and unsafe treatment, and disposal through incineration or in landfills pose significant challenges to the environment, human health, and to the achievement of the SDGs.

Product design and e-waste are closely related to many SDG's. In general, e-waste management through a new electronics economy as developed in this project can improve; health and well-being (SDG 3), inclusive and sustainable economic growth - decent work (SDG 8), sustainable cities and communities (SDG11) sustainable consumption and production patterns (SDG 12).

More particularly ²,



Target 8.2 : Achieve higher levels of economic productivity through diversification, technological upgrading and innovation, including a focus on high-value added and labour-intensive sectors.

Indicator 8.2.1 : Annual growth rate of real GDP per employed person.

Target 8.3 : Promote development-oriented policies that support productive activities, decent job creation, entrepreneurship, creativity and innovation, and encourage the formalization and growth of micro- small- and medium-sized enterprises, including through access to financial services.

Indicator 8.3.1 : Proportion of informal employment in non-agriculture employment, by sex.

Target 8.4 : Improve progressively, through 2030, global resource efficiency in consumption and production and endeavour to decouple economic growth from environmental degradation, in accordance with the 10-Year Framework of Programmes on Sustainable Consumption and Production, with developed countries taking the lead.

Indicator 8.4.1 : Material footprint, material footprint per capita, and material footprint per GDP.

Indicator 8.4.2 : Domestic material consumption, domestic material consumption per capita, and domestic material consumption per GDP.

Target 9.b : Support domestic technology development, research and innovation in developing countries, including by ensuring a conducive policy environment for, inter alia, industrial diversification and value addition to commodities.

Indicator 9.b.1 : Proportion of medium and high-tech industry value added in total value added.



²All the targets cited under come from the official final list of proposed Sustainable Development goal indicators [33]

Target 11.6 : By 2030, reduce the adverse per capita environmental impact of cities, including by paying special attention to air quality and municipal and other waste management.



Indicator 11.6.1 : Proportion of urban solid waste regularly collected and with adequate final discharge out of total urban solid waste generated, by cities.

Indicator 11.6.2 : Annual mean levels of fine particulate matter (e.g. PM2.5 and PM10) in cities (population weighted).

Target 12.2 : By 2030, achieve the sustainable management and efficient use of natural resources.

Indicator 12.2.1 : Material footprint, material footprint per capita, and material footprint per GDP.

Indicator 12.2.1 : Domestic material consumption, domestic material consumption per capita, and domestic material consumption per GDP.

Target 12.4 : By 2020, achieve the environmentally sound management of chemicals and all wastes throughout their life cycle, in accordance with agreed international frameworks, and significantly reduce their release to air, water and soil in order to minimize their adverse impacts on human health and the environment.

Indicator 12.4.1 : Number of parties to international multilateral environmental agreements on hazardous waste, and other chemicals that meet their commitments and obligations in transmitting information as required by each relevant agreement.

Indicator 12.4.2 : Hazardous waste generated per capita and proportion of hazardous waste treated, by type of treatment.

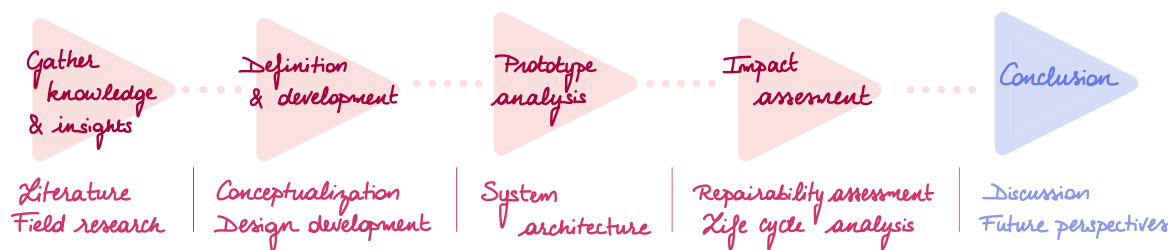
Target 12.5 : By 2030, substantially reduce waste generation through prevention, reduction, recycling and reuse.

Indicator 12.5.1 : National recycling rate, tons of material recycle.



5

Discussion and conclusion



5.1. Discussion

In this work, a few hypothesis and assumptions were made. Even if their veracity was meant to be maximized, they certainly need to be nuanced nevertheless.

To begin with, the scope of the research was limited by the assumption that the necessary business model for the value recovery processes was in place. Unfortunately, even if the collect of failed and broken 3D printed part is usually always done in FabLabs, their recycling is another challenge. Also, it was assumed that there is an existing market demanding for reused and long-life products. Without this, the research would not make sense but given how the regulations and mentalities are evolving, it seems fair to say that this assumption was legit as the economy markets are driven by customer demands and international standards. It is obvious that the required business model must be established in conjunction with design strategies to specify distribution, logistics, and management of the second-hand products, for example, in order for the process to be economically effective.

The user interaction with the redesigned object was limited to the framework of the local FabLab. The research focused on product-level requirements and economics but a user experience gathering feedback from repairers and citizens would for sure be enlightening, and even induce a second iteration. The initial intention of the project was to include this thematic as well, but given its social facet, the experiment was concluded out of the scope of the study. Interactions with the Social Media Lab took place to evaluate the possibilities of such experiment but the tools were not the best adapted for physical objects as it was more oriented towards IT. Nevertheless, user interaction was kept in mind

during the redesign, while interacting with communities present at the Repair Studio.

Legal aspects were not included in the study, however, they are an important component in the battle for Right to Repair. Determining who will be responsible in the case of an accident and to what extent a guaranty on the product will apply, are questions needed to be further investigated would the project be carried out. However, since this new business model can be realized independently of the industry, legal initiatives could be taken on a local scale, allowing end-users to take control over them.

Although they are necessary, repair and open-source manufacturing do not close the loop on their own. Besides technological issues, problems related to social systems may interfere with the demand and the collection of goods and restrain the market. Additionally, economic agents' choices, including those of producers and consumers, may have an impact on the expenses and advantages of the recovery process [10].

5.2. Conclusion and perspectives

The ever increasing amount of e-waste (53.6 Mt generated in the world in 2019 and 74 Mt are expected by 2030) has drastic social and environmental consequences (soils pollution, precious materials extraction, open-air landfills, greenhouse gas emissions,...). The linear economy in which we live in today can't be compatible with these new emerging challenges. This project aims at investigating one of the many ways to solution the e-waste problem. The research objective was to propose an alternative electronics economy, by enhancing repair tendencies of household appliances thanks to distributed design and local manufacturing processes within a FabLab. As a proof of concept, a hand blender underwent a redesign phase. To gather complete knowledge of the specifications and composition of this kind of object, a case study of a traditional hand blender was done in Chapter 2. After its disassembly and functional analysis, target components and critical steps were identified thanks to the HotSpot mapping method. The Fab Lab prototype was then presented and broken down to its components in Chapter 3. A reparability and reproducibility grid was constructed in Chapter 4 to evaluate the prototype's reparability and reproducibility but also serve as guidance for designers, repairers and users. Documentation, disassembly, availability of spare, cost considerations and FabLab environment were at the heart of the grading system. Life cycle analysis considerations were also evaluated under different scenarios and it could be concluded that raw materials gathering and transport are the most impacting phases on the life cycle of the product. Use of local materials could significantly reduce Global Warming Potential and electronics components should be employed responsively given their high embedded energy use from production. Recycling the whole product (plastics and WEEE separately) proved to be the preferred EoL scenario.

Even if this new paradigm may sound disruptive, it does not aim at staying marginal. Its compatibility with classical bigger manufacturing units can potentially make its proofs as the design can be widely reproduced at bigger scales. Creation in a Fab Lab will prove the reproducibility and easiness of repair and once accomplished, the design plans and guidelines can be communicated to production lines with bigger capabilities of production. Repair and refurbishing lines could also be opened to support a great amount of products once they'll be on the market. The perspective of answering the market demand makes sense in this case, solving the limited production capabilities of local hubs of production. The local activities in FabLabs would still remain but industry could support scale production, therefore making economies of one and economies of scale interact and complete each other to offer multiple products' life cycles.

This case study showed that appliances can be replicated in a FabLab with the help of a few standard components. However, these local and highly customizable manufacturing processes come with a downside. The prototype analysis allowed to underline high printing times and a similar price to the original product if all spare parts were to be bought new or manufactured. The differentiation however, resides in product longevity and the promise of long term support and accessible repair. By applying the design to bigger scale manufacturing processes, manufacturing cost and time could be optimised.

To complete the bigger picture, an online platform should allow users to easily download files and g-codes for the production of spare parts along with assembly and repair guides. One could think to add a QR code to the appliances giving direct access to the related platform. This platform would be destined to the user, repairers and FabLab communities to provide all the necessary files and manufacturing guidance. Not only giving information about making the object, the platform could also locate the user (if he allows) in order to put them in contact with their local communities and FabLab. Additionally to the making information, a self-assembly and self-repair guide could guide the user through each step of the way.

When looking at the EoL scenarios of FabLab made objects, disposal might be tricky. One could imagine putting a special take-back program for these kind of appliances and even creating a local hub for plastic recycling and components reuse, in parallel of the classical activities. This could potentially push people to repair their objects since they would in any case, find a solution by coming to the FabLab, might it be repair, replacement or disposal.

It is important to recall that the very goal was to produce a hands-on proof-of-concept, that would be easily repairable. The promise was achieved, after applying design guidelines from the literature and field experience. The principles developed during this research apply to all small household appliances and hopefully many more case studies will add to picture. Putting both the end-user and the repairer as the consumers, on the same level, was an important statement, differing from many industry cases but evaluated as one solution to close the loop of valuable materials.

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AppendixA

Producing an object through 3D printing

Describing a 3D object

Long gone is the time where engineers used to draw 2D projections using pen and paper to describe a piece. Nowadays, a computer with a CAD software, a slicer software and a 3D printer would be all you need to design your own spare part and produce it.

Computer aided design softwares

Before the design of new pieces, a big question arose. Which software would be the most appropriate one, given that the goal is to reach as many people, even the ones with low design experience ? The first level one would be ThinkerCAD, an online CAD package for children and hobbyist who don't have professional CAD skills. It allows to draw basic shapes but the cons arise quickly when designing more complex parts. The best combination between user-friendliness and complexity was found when overlooking Fusion 360, which was used exclusively for the rest of the project. Other CAD softwares like Solidworks or OpenCAD were brought to the table but their high learning curve or pricey tags were a turn down.

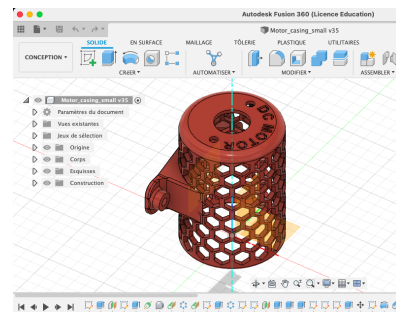


Figure A.1: A spare part modelled with Fusion 360.

Slicing

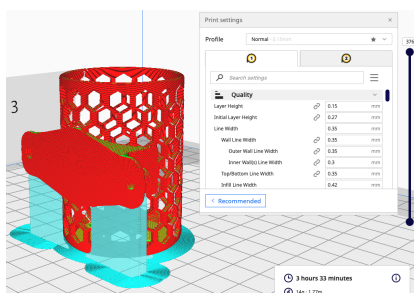


Figure A.2: A spare part sliced with the associated setting in Cura.

Having the CAD model of the spare is not yet enough to get the final object in your hands. In order for the printer to understand how to deposit layers to form the object it needs to read g-code. To convert the model to this programming language enabling computer numerical control, a slicer software does the job. Not only does the model itself need to be uploaded by the user but also printing parameter such as layer height, speed, temperatures and support structure settings.

AppendixB

3D printing exploration

Different the get-to-know phase of the manufacturing processes in a FabLab, a few 3D printer were tested. The Ultimaker 3 is a high quality printer and is the machine that produced all final spare parts of the project. It assured great printing quality and a 'plug and play' environment. The price range starts at 500 euros and with it comes dual extrusion and a precise output.

The Creality Ender 3 is also present in the FabLab and is actually the most common 3D printer for makers with a small budget, and therefore representative of the 'at home' conditions. As the debuting price is at 200 euros, the results can't be the same as the previous one but the functionality of the spare parts is conserved. This proved to be a very capable printer with a similar amount of experienced failed prints compared to the Ultimaker but showing less precision for detailed components (like textual indications). Still, for the spare parts of this project, it showed good performance with a bit of tweaking, proving that 3D printers owners could produce the spare parts of their own products at home.

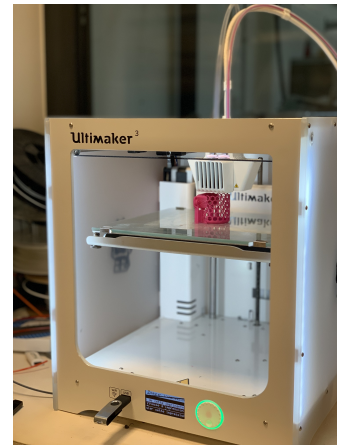


Figure B.1: The Ultimaker under use at the MakiLab.

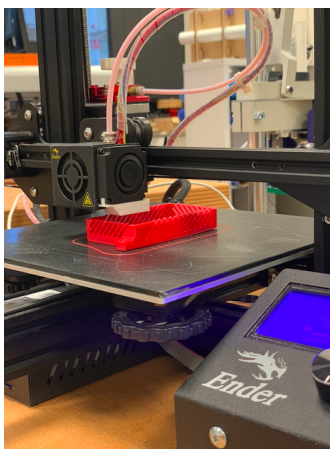
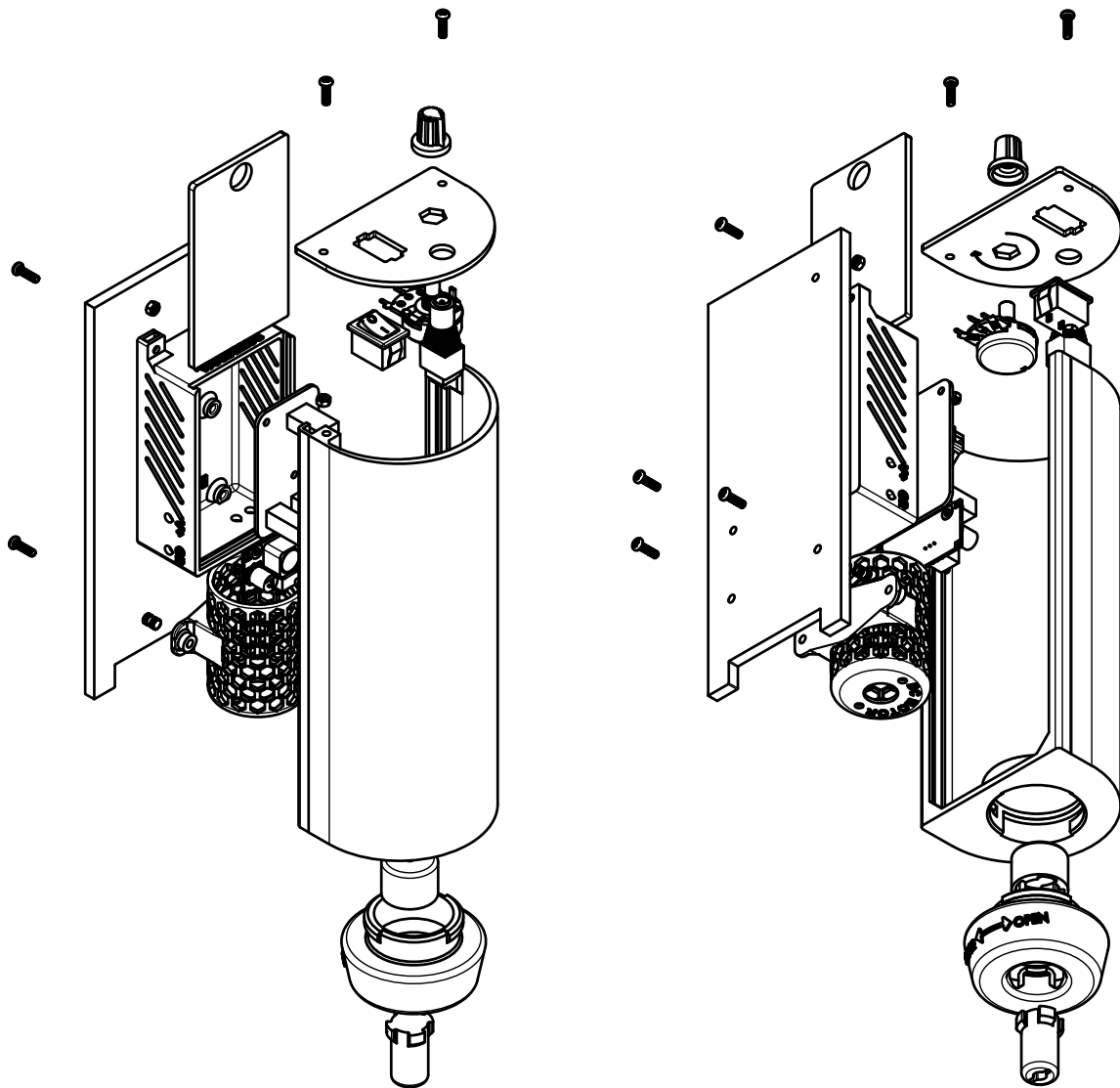


Figure B.2: The Ender 3 under use at the MakiLab.

Resin printers were not covered during the project given their likeliness to be avoided by less experienced people due to the difficulty added by toxic fluxes handling and settings. Also, FDM production quality, mechanical resistance and level of details has proven to be sufficient for the application.

AppendixC

Exploded view of the prototype



AppendixD

Circuit schematics of the PCB

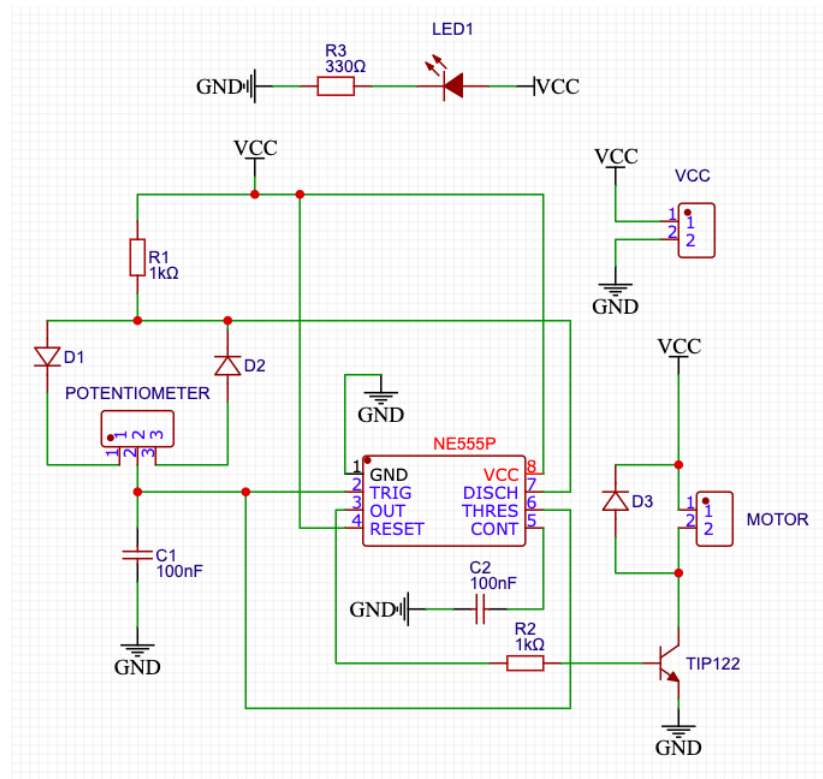


Figure D.1: Wiring schematics of the PWM motor control PCB.

AppendixE

Cost considerations

Table E.1: Bill of materials and cost considerations for the FabLab prototype of the redesigned hand blender.

Component	Quantity	Unitary price	Total price [€]
3D printed PLA	206 g	0.10 €/g	20.6
Buck converter	1	1.5 €/pp	1,5 €
M3 screws	10	0.05 €/pp	0.05 €
Laser cutter use	5 min	5€/30 min	0.83 €
Acrylic spare parts	3	25€/plate (40 cm x 60cm)	3 €
DC motor	1	22€/pp	22€
PCB (all components and transport included)	1	9.7 €/pp	9.7 €
Cables	1 m	0.48 €/m	0.48 €
Potentiometer	1	1.6 €/pp	1.6 €
Rocker switch	1	0.6 €/pp	0.6 €
Female plug	1	0.4 €/pp	0.4 €
Heatset M3	6	0.08 €/pp	0.48 €
Blender's foot	1	20 €/pp	20 €
TOTAL (if all spare parts are bought/made new)			92.7 €
TOTAL (if power cord, motor and foot are upcycled)			39.7 €

AppendixF

Manufacturing technologies appropriation in FabLabs

Even if 3D printing and laser cutting were the main machines used for the making of the prototype, they certainly do not cover entirely the range of manufacturing possibilities present in FabLabs. However, their skills level requirements are not equivalent and the following picture describes how a user could use these technologies, either on their own, either with the help/supervision of an experienced person or with the help of a specialist (only by the specialist in some cases).

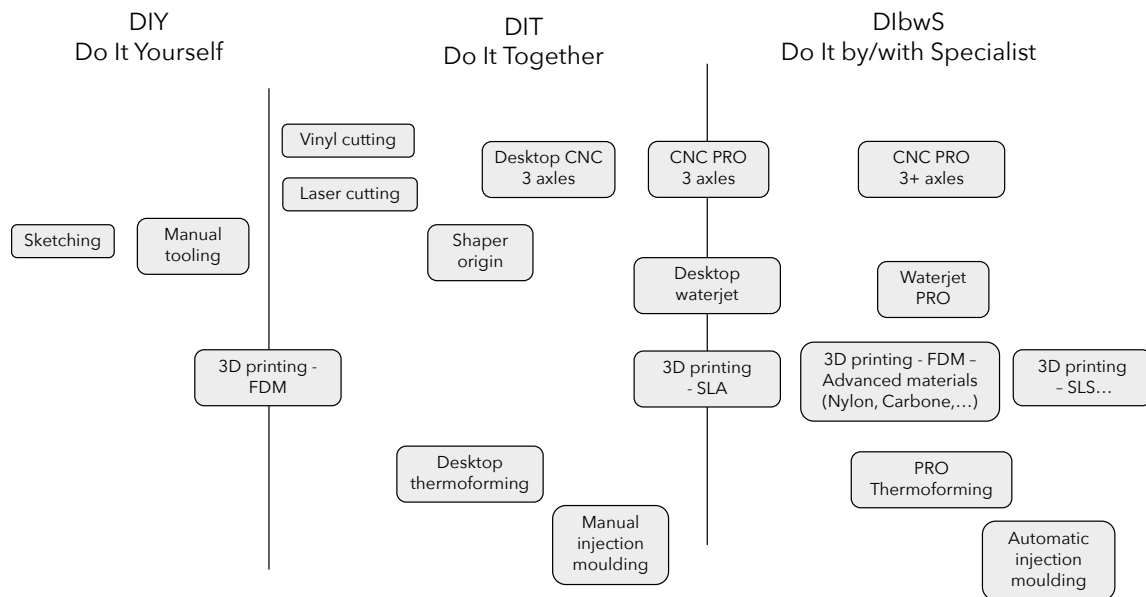


Figure F.1: Level of skills required for manufacturing machines present in a FabLab. Original figure from [66]

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