Identification of the environmental impacts contributors related to the use of Additive Manufacturing technologies

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THÈSE

Pour obtenir le grade de

DOCTOR DE LA COMMUNAUTÉ UNIVERSITÉ GRENOBLE ALPES

Spécialité : **GI : Génie Industriel : Conception et Production**

Arrêté ministériel : 7 août 2006

Présentée par

Kléber da Silva Barros

Thèse dirigée par **Peggy Zwolinski**

Préparée au sein du **Laboratoire G-SCOP**
dans l'École Doctorale **IMEP-2**

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Thèse soutenue publiquement le **18 septembre 2017,**
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Abstract

Investigations focused on the environmental impacts related to Additive Manufacturing are evolving and far from being consolidated. This thesis tries to answer the following question: How to identify and control the environmental impacts associated to the use of Additive Manufacturing technologies? An approach centred on scenarios was applied. Three specific scenarios were identified and studied: 1) Personal Fabrication; 2) Business use of AM and 3) Industrial use of AM. Literature analysis and the use of the Life Cycle Assessment-LCA approach provided accurate data to identify the different hotspots of environmental impacts in each scenario.

In the Personal Fabrication case, the study highlights the importance of placing a greater focus on the Human aspects. The way people use the technology often generates more impacts than the technology itself. In the 'Business' scenario the findings show that the energy consumed in Production phase is the most representative phase in terms of environmental impacts. Results from the 'Industrial' scenario using EBM technology suggests that the energy consumption of the Printing Process, the powder manufacturing, as well as the Post-treatment process are the main sources of the environmental impacts.

The results of the three studies were analysed and gathered in such a way to design a systemic framework of impacts in the case of AM use. Four group of impacts drivers are recognised: The product and the Printing Process (Technical aspects) and the User's level of experience in CAD and Printing (Human Aspects). For each group, several impact contributors are identified (product height, CAD use time, etc.). From this framework, an adapted LCA model was designed and a software concept was created to estimate the environmental impacts related to use of AM technologies.

Résumé

La prise en compte des impacts environnementaux liés à la Fabrication Additive (FA) est un sujet encore en développement et loin d'être consolidé. Cette thèse tente de répondre à la question suivante: Comment identifier et maîtriser les impacts environnementaux liés à la mise en usage des technologies de Fabrication Additive ?

Une approche centrée sur l'analyse de scénarios d'usages a été appliquée. Trois scénarios ont été identifiés et étudiés: 1) La Fabrication Personnelle; 2) l'Utilisation commerciale de la FA et 3) l'Utilisation Industrielle de la FA. L'analyse de la littérature et l'application de la méthode d'Analyse du Cycle de Vie – ACV ont fourni les données nécessaires afin d'identifier les différents *hotspots* environnementaux dans chaque scénario.

Pour le cas de la « Fabrication Personnelle », l'étude souligne l'importance de mettre en évidence les aspects humains. La façon dont les gens utilisent la technologie génère bien souvent plus d'impact que la technologie elle-même. Pour le cas du scénario «Utilisation Commerciale», c'est la phase de production qui génère le plus d'impacts environnementaux, en raison de la consommation d'énergie du processus d'impression. Les résultats du scénario « Utilisation Industriel», avec l'utilisation de la technologie EBM, indiquent que la consommation d'énergie du processus d'impression, la fabrication de poudre, ainsi que les processus de Finition sont les principales sources d'impacts.

Les résultats des trois études ont été analysés et rassemblés de manière à concevoir un cadre systémique montrant les contributeurs aux impacts dans le cas de la mise en usage de technologies de FA. Quatre groupes de contributeurs ont ainsi été identifiés en lien avec: le produit, le processus d'impression (aspects techniques), et le niveau d'expérience de l'utilisateur en matière de CAO et d'impression (aspects humains). Pour chaque groupe, plusieurs contributeurs ont été associés (consommation d'énergie, masse du produit, temps d'usage de la CAO,…). A partir de ce cadre, nous avons pu construire un modèle simplifié pour l'ACV adapté au cas de la mise en usage de la FA. Il a donné lieu à l'élaboration d'un démonstrateur pour estimer les impacts environnementaux liés à la mise en usage de la fabrication additive.

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thank you!

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Part I

Problem, State of the art and Approaches

‘Bien poser un problème, c’est déjà à moitié le résoudre’.

(Hélène Teulon)

1 Introduction

1.1 Context and Problematic

Human evolution is strictly related to 'tools evolution'. According to (Diez, 2012), history shows that tools have been used for over 2.6 million years; they are extensions of our physical capabilities and at the same time are the interface with our natural environment and habitat. The development of tools shows improved human capabilities regarding the relationship with the environment in general.

(Gershenfeld, 2007) says that *'the world of tomorrow can be glimpsed in the tools available today'*. (Diez, 2012) states that '*a shell used to produce a specific sound for long range communication between Aborigines in Oceania is not that different from a wifi enabled device that allows New Yorkers to create blogs'*. Both authors are speaking about the same thing, the undeniable relation between human development and physical products.

Looking back through history, the first and most important event that changed the way we relate to products today was the Industrial Revolution in the XIX century. Between 1760 and 1860, technological progress, education, and an increasing capital stock transformed England into the workshop of the world. The country was considered the birthplace of a consumer revolution that made more and more consumer goods available to ordinary people every passing year (Nardinelli, 2008).

The consequences of this revolution, positive or negative have been numerous and still visible today. According to (Kazazian, 2005), the industrial revolution generated a great necessity of manpower which emptied the countryside of cities and started a significant process of degradation of nature. However, it also caused a formidable dynamic of capitalism, progress and the renovation of goods.

In the 50's, the movement 'American way of life' has changed the way how people all over the world relate to products. This lifestyle started during the post-war decade (1950 - 1960) when American soldiers who liberated the 'hurt Europe' returned to their country with a dream of happiness related to material goods. During 20 years (1954 – 1974) the 'American way of life' changed the occidental lifestyle which experienced a prodigious progress. In France for instance, in this period the percentage increased dramatically. Fridge-possessing home passed from 9% to 88%; washing-machine from 9% to 71% and televisions from 1% to 82% (Kazazian, 2005).

Over the past 30 years, the way in which people consume products has changed. Nowadays, people are looking for customised products, in other words, products specifically adapted to their particular needs and pleasure.

In this context, from the 80's and early 90's a type of manufacturing starts to present a considerable development, the concept of Additive Manufacturing (AM), a type of manufacturing that produces physical objects from digital information layer-by-layer using different materials (Wohlers & Gornet, 2014). Nowadays this new manufacturing process is called by many authors as 'The New Industrial Revolution' and it is one of the 'Industry 4.0'[1] foundations.

The Additive Manufacturing (AM) is opposed to subtractive manufacturing processes. It supports a wide range of applications including parts manufacturing, transportation, art, architecture, education, hobbies, space exploration, military, medical, dental and aerospace industries. (Gibson, Rosen, & Stucker, 2015).

As all disruptive technology, AM is breaking many manufacturing paradigms. It presents some advantages such as the possibility to manufacture more efficient designs (lighter, stronger, less assembly required) and customised product with complete flexibility in design and construction. Furthermore, in an economic context, according to (Thompson, 2016), '*AM has experienced double-digit growth in the past 27 years, taking it from a promising set of uncommercialized technologies in the early 1980s to*

[1] A new digital industrial technology powered by advanced connected systems. Industry 4.0 will make possible to gather and analyse data across machines, enabling faster, more flexible, and more efficient processes to produce higher-quality goods at reduced costs. This in turn will increase manufacturing productivity, shift economics, foster industrial growth, and modify the profile of the workforce ultimately changing the competitiveness of companies and regions.(Rüßmann et al., 2015)

a market that was worth over $4 billion in 2014. The AM market is expected to grow to more than $21 billion by 2020.'

Nevertheless, not only advantages are announced. Many authors have listed some current and upcoming challenges in technical, social and environmental aspects for AM. Regarding the environmental dimension, a couple of thesis and papers are found in the literature with different viewpoints, considering different technologies and sources of the impacts.

For many authors, AM is recognised as more environmentally respectful regarding a classic manufacturing process. According to (Berman, 2012; Koff & Gustafson, 2012), AM:

- Provides an efficient use of raw materials (less waste) and use of biodegradable plastic (PLA);
- Allows creating on demand (batches of one);
- Individuals become manufacturers, then the lines (transport chain, for instance) between manufacturer and customer will blur;
- There is no need for costly tools, moulds, or punches;
- There are no scrap, milling or sanding requirements;
- 3d-printing technologies does not use fluids and chemicals like injection processes;

For others, this is debatable. (Decker, 2014) states: *'when billions of people are just a click away from getting factories to work for them, whether in the cloud or on their desktops, this does not bode well for sustainability; we will create even more stuff, and each product will cost much more energy than if produced with conventional methods.'*

Indeed, the problematic concerning the dichotomy between Classic and Printed manufacturing concerning the environmental advantages seems to be just starting. The problem of this research emerges from this context.

It can be noted that Classic industrial manufacturing (focused in mass production), although being one of the biggest contributors to the environmental impacts, aims optimising time, costs, use of material and service. In this context, considering the production volume, the impacts per product are minimised. This type of manufacturing works to satisfy the collective acting.

Making an analogy with the human behavior, it is possible to affirm that the collective acting (e.g. car sharing; cohouse; large packing, etc.) is the current and most efficient way to reduce the environmental impacts associated to goods' consumption. (Fig. 1)

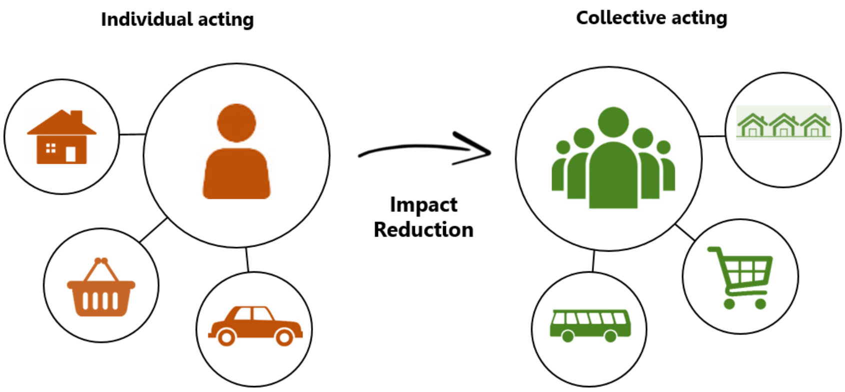


Figure 1 - Transition from individual to collective acting

On the other hand, Additive Manufacturing evokes a return to the individualization and custom product. It stimulates the individual acting and works to satisfy single production and individual desires. (Fig. 2)

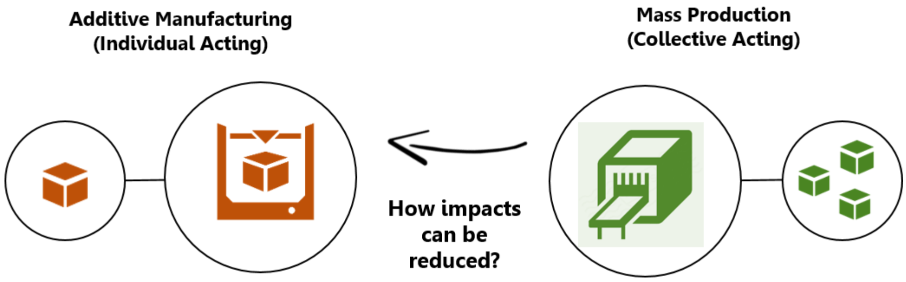


Figure 2 – Transition from collective to individual production

This research goes into the crux of this problem to try to find accurate answers that may qualify and situate Additive Manufacturing about its environmental impacts even being a single production. Hence, in this viewpoint the main question of this research is:

How to identify and control the environmental impacts associated to the use of Additive Manufacturing technologies?

From this main question, further sub-questions emerge, such as:

- Where do the environmental impacts of Additive Manufacturing come from?

- Which elements are the main contributors to the environmental impacts in AM?
- Is it possible to determine if AM is better than traditional manufacturing in an environmental perspective?

Answers to these questions will provide support to reach the fixed objectives for this work and will bring an important contribution to the AM researchers and professional communities.

1.2 Motivations

(Ford & Despeisse, 2015) state that *'the current lack of understanding about how AM-based production systems and value chains will affect overall resource consumption indicates that greater studies are required if we want to gain a more informed view of the sustainability impacts of AM implementation'*.

The main motivation of this research lies in the fact that AM has been influencing our manufacturing methods and may 'shake up' the traditional manufacturing in the medium/long term future. Allied to that, its environmental impacts are a matter still little explored. Thinking about the environmental concerns from now is a necessity. Each day more and more people are equipping themselves with digital and manufacturing equipment to produce their products, and we do not know the consequences that this will have on our planet and society.

Sustaining efforts to employ research in this domain seems necessary and urgent.

1.3 Summary of contributions

In this work, the Life Cycle Assessment – LCA method as well as an approach centred on scenarios are chosen to investigate and find out clues and evidence about how environmental impacts are addressed in the field of Additive Manufacturing.

This research will provide three important contributions to the AM research and technical community.

The first one is to classify AM in different activities and investigate their impacts separately using dedicated scenarios. This allows to present more precise results on AM environmental impacts and to avoid generic conclusions, already found in literature and sometimes ambivalent.

The second contribution is the proposition of a framework that will provide guidelines to help AM users understanding where the impacts lie in each type of AM use and thus, driving their decision for a more environmentally friendly way to use Additive Manufacturing.

Finally, the third contribution of this research is the proposition of a tool (software concept) to roughly estimate the environmental impacts in relation to AM processes. It is based on the five main life cycle phases, and it suggests in each phase, critical points to be considered in order to reach a more reliable result when the environmental impacts of AM are being assessed.

These contributions will add new standpoints into the field of environmental impacts in AM, a subject fairly investigated but still not consolidated.

1.4 Organization of the Thesis

Chapter 2 presents the state of the art in the field of Additive Manufacturing. It clarifies the principles, technologies and challenges. Then, it presents an analysis about how the environmental impacts have been studied over the years in the AM research field. Finally, a study to determine AM user's profiles is presented.

Chapter 3 presents the thesis arguments, hypothesis and the approach defined for this research. Also, it presents the method chosen to measure the environmental impacts associated to AM: The Life Cycle Assessment – LCA. The third section presents the research structure highlighting the three AM domains that will drive the research investigations.

Chapters 4 to 7 (Part II) describe the experiments carried out in the three AM scenarios investigated and the analysis, discussions and contributions of this research. For each scenario, a literary review is presented as well as the LCA's results and the discussions and analysis aiming to identify the impacts contributors in each domain. Chapter 7 is dedicated to present the main 'products' of this thesis.

Finally, Chapters 8 and 9 (Part III) outlines the concluding clarifications of this research. It presents the hypothesis validations, the answers for the research questions, the limitations found during the work, the papers published during the three years of research and the promising prospects for future studies. To close, an extended abstract in the French language is presented in Chapter 9.

2

Additive Manufacturing

This chapter describes the literary context within which the research for this thesis was conducted. It presents the general concept and applications of Additive Manufacturing as well as revisions about how AM environmental impacts have been studied over the years. Additionally, studies about AM user's profiles have been realized using literature context and a specific survey carried out with 112 users around the world.

2.1 Principle

Additive Manufacturing (AM) is the formalised term for what used to be called Rapid Prototyping and what is popularly called 3d-Printing. (Gibson et al., 2015). The term rapid prototyping (RP) is used in a variety of industries to describe a process to quickly create a system or a part representation before its final commercialization. In recent years the evolution of technologies used for AM has made it possible to shift the manufacturing processes from the stage of the prototype to the stage of production. (Gibson et al., 2015).

AM is a process of joining materials to make objects from 3d data model, usually, layer by layer as opposed to subtractive manufacturing methodologies. It supports a wide range of activities including parts manufacturing, energy, transportation, art, architecture, education, hobbies, space exploration, military, medical, dental, and aerospace industries. (Thompson, 2016, p. 4).

Figure 3 (a,b,c) exemplifies some applications of AM.

a) b) c)

Figure 3 - a) Metal complex shape application | b) – Dental applications | c) Innovative products
Source: Internet

2.2 Evolution

According to (Wohlers & Gornet, 2014), Additive Manufacturing first emerged in 1987 with stereolithography (SL) from 3D Systems, a process that solidifies thin layers of ultraviolet (UV) light-sensitive liquid polymer using a laser. After 3D Systems had commercialised SL in the U.S., Japan's NTT Data CMET and Sony/D-MEC commercialised versions of stereolithography in 1988 and 1989, respectively.

The SL technology opened doors for other revolutionary technologies. In 1991, three AM technologies were commercialised, including Fused Deposition Modelling (FDM) from Stratasys, Solid Ground Curing (SGC) from Cubital, and Laminated Object Manufacturing (LOM) from Helisys. FDM extrudes thermoplastic materials in filament form to produce parts layer by layer. SGC uses a UV-sensitive liquid polymer, solidifying full layers in one pass by flooding UV light through masks created with electrostatic toner on a glass plate. LOM bonds and cuts sheets material using a digitally guided laser. (Wohlers & Gornet, 2014)

From the 90's the technology becomes less expensive. In 1996, the first 3d-printer using technology that deposits wax material layer by layer using an inkjet printing mechanism was sold. The new generation of machines, (smaller and simpler) started to be introduced in the 2000's. (Wohlers & Gornet, 2014)

According to (Le Bourhis, 2014), the appearance of the first low-cost personal machines based, in large part, on the technology of depositing melted yarns occurred in 2007. Figure 4 shows the explosion of the sales of these machines since the year 2010. In 2015 more than 278,000 desktop 3D printers (under $5,000) were sold worldwide (McCue, 2016). These numbers demonstrate the massive democratisation of the technology towards the general public.

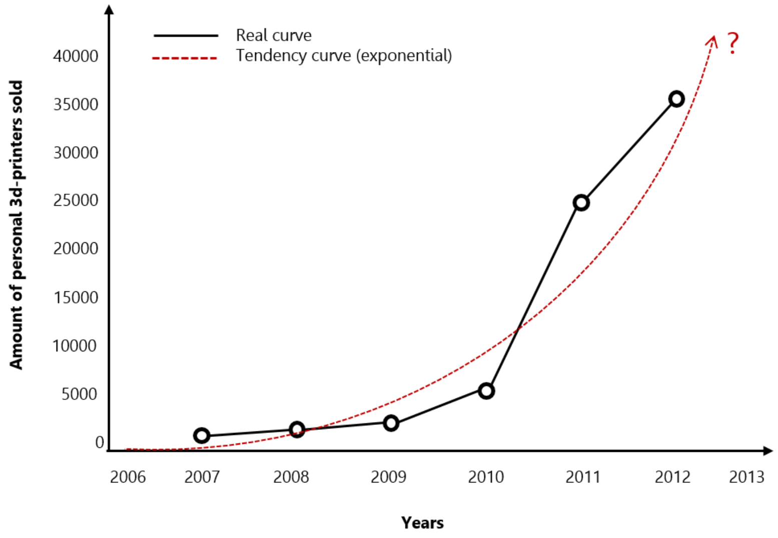


Figure 4 - Amount of personal 3d-printers sold
Source: Adapted from (Le Bourhis, 2014; Wholers, 2013)

Regarding the economic issues addressed in this market, (Thompson, 2016) declares:

> *(...) the evolution of Additive Manufacturing (AM) over the past three decades has been nothing less than extraordinary. AM has experienced double-digit growth over the past 27 years, taking it from a promising set of uncommercialized technologies in the early 1980s to a market that was worth over $4 billion in 2014. The AM market is expected to grow to more than $21 billion by 2020.*

This remarkable scenario has stimulated many authors to call AM as the 'New Industrial Revolution'. According to (Morris, 2007), '*this digital revolution can change the role of industrial design dramatically'*. To (Gershenfeld, 2007) *'AM is a coming revolution on your desktop'.*

2.3 Technologies

Additive Manufacturing is widely based on two processing: Polymer and Metal. In each one different technologies are applied to different purposes. Polymers processing are well known in all industrial sectors because they have been commonly used for prototyping. Metal processing is capable of producing fully dense and functional parts that offer complete reliability and are used in many industrial sectors such as biomedical, tooling, aerospace, automotive, etc. (Petrovic et al., 2009).

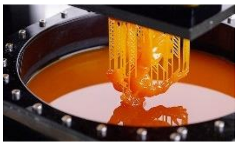
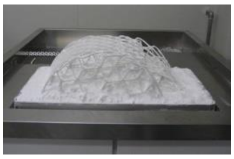
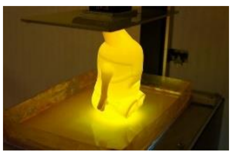
Others innovative processes such as concrete to print houses (Fig. 5-a), wood powder to print wood objects (fig. 5-b), alimentary materials to print food (Fig. 5-c) as well as paper, wax and clay are also a reality but still not widespread.

a) b) c)

Figure 5 - a) House Printing system | b) Watch wood-based printing | c) Food printing
Source: Internet

Regarding Polymers and Metal Processing, Table 1 describes the most common used technologies with their applications, description and illustrations.

Table 1 - AM technologies uses
Source: Adapted from (Petrovic et al., 2009)

	Use	Technology	Process	Product
Polymers	Prototypes, Biomedical parts, Artistic Design, Personal Fabrication	**Stereolithography (SLA)**		
		Uses a laser beam to perform the photopolymerization of material. The material that is initially in a liquid state becomes hard and consistent. SLA is capable of processing different resins that emulate the performance of the thermoplastic material.		
		Selective Laser Sintering (SLS)		
		Uses a laser beam to fuse powder and create a part layer by layer. It normally uses powdered polyamide that can sometimes be reinforced with a filler of glass fibre or aluminium.		
		Digital Light processing (DLP)		
		Uses a UV-light lamp to expose a photo-sensible resin which will solidify.		
		Fused Deposition Modelling (FDM)		
		Consists of the deposition of fused material which was previously stored in the form of a plastic thread on a roll. Materials used in FDM are usually based on polycarbonate (PC) and ABS or a mixture of these two		

Metals	Tooling; Biomedical parts, lightweight aerospace and automotive parts	**Laser-based technologies** A focused beam of laser light is used to produce fusion. There are several variants of laser technology. The parts fabricated with these metal processing technologies are prone to oxidation which can diminish their mechanical properties		
		Electron beam based technology The energy is provided by the impact of a focused beam of electrons. The electrons are emitted from a filament made of tungsten. This technological characteristic is widely used to obtain parts of high purity		

2.4 Advantages and Challenges

As all disruptive technology, AM presents advantages in comparison with others technologies but also challenges to be faced in the foreseeable future. Many authors (Berman, 2012; Muthu & Savalani, 2016; Petrovic et al., 2009) have listed different advantages and challenges, such as:

Advantages:

- It allows manufacturing more efficient designs — lighter, stronger, less assembly required;
- Product customization with complete flexibility in design & construction;
- Freedom for designers coming up with product designs that cannot be manufactured conventionally;
- It allows creating on demand;
- Time-to-market reduction due to high speed of the process;
- Material savings;
- No tools, moulds or punches are needed;
- Full-density of final parts;

Challenges:

- Remove the 'stigma' of its original name 'Rapid Prototyping';
- Validation of mechanical and thermal properties of existing materials and technologies;
- Development and characterization of new materials;
- Change in the designer's way of thinking;
- Automation design and process planning;
- Decrease the necessity of support structure;

- Availability of CAD software and data management;
- Formalise the 'open design' and the property rights;

Additionally, besides these challenges, AM must face another important pending dare: to be also efficient in terms of environmental impacts. This is an actual discussion in the scientific community, and a couple of thesis and papers focusing on it can be found with different approaches, considering different technologies and sources of impacts. Nevertheless, this is a matter still in development without a conclusion about how additive manufacturing impacts the environment and where the impacts come from. Next section will present a broad literature review about this subject.

2.5 Additive Manufacturing and Environmental Impacts

In 1972, (Meadows, Meadows, Randers, & Behrens, 1972), authors of the polemical book '*The Limits to Growth*', stated:

> *If the present growth trends in world population, industrialisation, pollution, food production and resource depletion continue unchanged, the limits to growth on this planet will be reached sometime within the next one hundred years. The most probable result will be a rather sudden and uncontrollable decline in both population and industrial capacity.*

Researchers and reviewers from many countries have concluded that statements on this book associated with the concept of Sustainability emerging in the 80's, have stimulated the first steps to a new consumer behaviour. This, in turn, has also driven new manufacturing strategies of material goods.

According to (Muthu & Savalani, 2016), sustainable industrial practices can contribute to the development of more sustainable materials, products, and processes. It is critical to apply eco-design principles and develop greener products and production processes, reducing impacts associated with production and consumption.

Concerning Additive Manufacturing practices, the majority of studies highlights two main positive factors regarding environmental issues:

- AM provides an efficient use of raw materials (less waste), and some machines use biodegradable plastic;

- Individuals become manufacturers, then impacts for the transportation phase are eliminated from the life cycle.

Although these statements are true, there is not a complete accordance about the real reduction of impacts. Some authors have been studying the impacts of AM via comparative Life Cycle Analyse (LCA). In some studies, authors found that AM impacts less than Industrial Manufacturing (IM) and in others the results are opposite.

(Kreiger & Pearce, 2013) in their comparative study declare that '*the environmental impacts of polymer objects manufactured with 3D printers and using PLA (Polylactic acid) are less than a conventional manufacturing'*. They also state that *'with PLA, 3D-printing always had a better environmental performance than conventional mass-manufacturing'*, both using less energy and emitting less carbon.

In contrast to this study, (Faludi, Bayley, Bhogal, & Iribarne, 2015) state that the relative sustainability of 3d-printer vs. CNC machining depends primarily on the usage profiles, and then on the specific machines. It cannot be categorically stated that 3D printing (using ABS plastic) is more environmentally friendly than machining or vice-versa.

Other studies do not make a comparison between AM and IM. However, they present Additive Manufacturing as a positive transformation for society or sometimes as a 'green technology', two aspects refused by other authors.

According to (Olson, 2013) *'enthusiasts are quoted predicting that 3-D printing will make conventional factories and warehouses obsolete and empower people everywhere to become inventors, entrepreneurs, and manufacturers'.*

(Lipson & Kurman, 2010) declare that *'AM technologies will profoundly impact how we design, make, transport, and consume physical products'*. (Koff & Gustafson, 2012) state that *'AM is simpler, cheaper, smaller and more convenient to use than traditional manufacturing technology; provide an efficient use of raw materials and use of biodegradable plastic'.*

In an opposite perspective, (Decker, 2014) states:

> *When billions of people are just a click away from getting factories to work for them, whether in the cloud or on their desktops, this does not bode well for sustainability; we will create even more stuff, and each product will cost much more energy than if produced with conventional methods.*

(Wilson, 2013) quoting Timothy Gutowski, Professor of Mechanical Engineering at the Massachusetts Institute of Technology (MIT) says that '*there is a lack of strong evidence or research that suggests that 3D printing is going to lead to a more widespread sustainable society. In fact, in some cases, it may have the opposite effect'.*

The author completes: *'It is very easy to combine mixtures and customise 3D products, but it becomes much more difficult to break up such a product for recycling purposes; likewise, it may create another waste problem if everybody starts printing out 3D objects without thinking it through.'*

There are still others studies that present a more reflexive and less affirmative conclusion about the environmental impacts of AM. (Kohtala & Hyysalo, 2015) declare that *'Currently, no evidence-based handbooks or manuals exist for how to conduct or organise environmentally-sound maker spaces or activity'*. They say yet: *'there is a real/clear need for targeted research on the environmental impacts of AM technologies and materials'*.

In this same point of view (Ford & Despeisse, 2015) state:

> *The current lack of understanding about how AM-based production systems and value chains will affect overall resource consumption indicates that greater studies are required if we are to gain a more informed view of the sustainability impacts of AM implementation'.*

All of these conclusions about the environmental impacts of AM (based on comparisons), sometimes convergent and sometimes not, come forward the instability of the matter. It brings out an important question: Why that lack of sync and unity among the studies? On the whole, it seems that the problem lies in two main aspects: the number of different scenarios/hypothesis able to be studied and the systems differences when the comparison AM vs. IM is the goal.

About the first point, it can be noted that there is a wide number of possible scenarios that gives to authors a high level of liberty to define different study boundaries, hypothesis and negligible points. This allows different results, according to each scenario studied favouring the ambivalence of studies.

On the other hand, when we try to compare AM and Industrial Manufacturing we are comparing two different production systems with distinct functions/goals, and this seems not make sense. AM means availability, personal adaptations, small scale, that is not well supported by industrial manufacturing which is more costs/mass oriented.

Drawing on this analysis, it can be stated that independently of the results, it seems inconsequential to give conclusions about the environmental impacts associated to AM based only on a comparison with Industrial Manufacturing processes. Additionally, the way people work and manage AM technology (user profile) is a potential lever for environmental impacts increase/decrease.

Besides those comparisons, others studies found in the literature are most focused on metal-based technologies and the impacts assessment emphasis only the technical aspects such as energy consumption. This subject will be better developed in Chapter 6.

To conclude this part, an overview of sustainability-related implications of AM is presented in Table 2. According to (Salonitis, 2016), regarding the Environmental dimension, three important problems are cited: 1) Ambivalence of studies regarding environmental impacts and eco-efficiency; 2) Higher specific energy demand and 3) Product quality issues and risk of wrong parts and rework.

Problem 1 was already identified and confirmed in this literature review. Problems 2 and 3 will be observed and analysed in the practical experiments conducted in this research.

Table 2 - Implications of AM on Sustainability dimensions
Source: (Salonitis, 2016)

Sustainability Dimensions					
Economic		**Environmental**		**Social**	
Potentially higher profit due to customer-specific solutions	(+)	**Ambivalent studies in terms of E.I and eco-efficiency**	(±)	Equal possibilities for all participants in markets and societies	(+)
Profitability could be proved in selected cases	(+)			Bridge technological, educational and cultural gaps between developed and developing countries	(+)
Longer manufacturing time	(–)			User-oriented products, more customer satisfaction	(+)
Higher material utilization			(+)	Potential benefits in human/worker health	(+)
Simpler, more efficient supply chains with fewer transportation efforts			(+)	New work alternative/perspective	(+)
Less material and energy losses due to less inventory			(+)	Products Copyright	(±)
Less waste and better waste management through possibility of direct recycling			(+)	Unclear impacts on an employment situation of industry	(±)
User-oriented manufacturing, less overproduction in stocks			(+)		
No moulds, etc. necessary			(+)		
Higher specific energy demand			(–)		
Quality issues are not finally solved, thus risk of bad parts and rework			(–)		

2.6 AM users/usage profile

The additive manufacturing user's profiles are quite diversified and still little studied. Most of the studies found in the literature focus on FabLabs users profiles, in which AM is just a part of digital fabrication.

A survey conducted by the Statistical Studies of Peer Production (Moilanen & Vadén, 2012) with 358 3d-printing users showed that the average age of users is 30 years old (male) and that the number of users increases from 2005. The survey concludes that the fast evolving landscape provides a fertile ground for both social and technological improvements. This encourages new users and amplifies the production at Home, creation of Makerspaces (Fab Labs) and 3d-print service companies.

The same survey verifies that RepRap, a low-cost 3d-printer was identified as the most common printer among 20 different options. Considering the costs of domestic machines, (Campbell, Bourell, & Gibson, 2012), says that, if the manufacturing expenses can be reduced, or the number of potential users becomes larger, then machine prices can be reduced.

Concerning AM user's motivations, (Campbell et al., 2012) states four different drivers:

- User-fit requirement – a desire to customise the product to suit individuals or groups of individual's ergonomic requirements.
- Improved functionality – a desire to improve the product performance through the adoption of complex forms, both externally and internally.
- Parts consolidation – a desire to reduce the overall parts count in a product.
- Aesthetics – a desire to endow the product with specific design features that will increase its value to the customer.

These statements found in the literature give an idea about AM users profiles, but it does not present a concrete outline capable to supports this research in such a significant way. In order to fill this gap, a specific survey was conducted with AM users and people interested in the technology. This survey aims to collect information that allows determining more detailed AM user's profiles to guide this research.

2.7 Survey about AM users

The survey was composed of 16 questions (single and multiple choices) and hosted online with an internet-based distribution. Invitations to participate were placed on specific *facebook's* communities and sent by e-mails to FabLabs in different countries. During 20 days (February 2016) 112 persons from 26 countries (5 continents) answered it. Table 3 shows the classification by countries and the number of answerers. (Survey model in Annex 1).

Table 3 - Countries and number of answerers

	Countries	**# Answerers**
1.	Brazil	28
2.	USA	27
3.	France	18
4.	England	8
5.	Netherland	4
6.	Australia	2
7.	Belgium	2
8.	Finland	2
9.	Italy	2
10.	Malaysia	2
11.	Sweden	2
12.	Austria	1
13.	Canada	1
14.	Denmark	1
15.	Egypt	1
16.	Estonia	1
17.	Germany	1
18.	Israel	1
19.	Macedonia	1
20.	New Zeeland	1
21.	Norway	1
22.	Philippines	1
23.	Poland	1
24.	Portugal	1
25.	Romania	1
26.	Scotland	1
TOTAL		**112**

The age of the participants varied between 15 and 71 years old, being 26% between15 and 25 y/o, 28% 26-35 y/o, 21% 36-45 y/o, 19% 46-55 y/o and 6% between 56 and 71 y/o. It can be observed that people between 15 and 35 years old represent 54% of the participants.

The first question asked to the participants was: Which 3d printing user profile suits you best? The answer options were defined based on previous studies and analysis about the possible user's types.

As it can be observed in figure 6, the profile 'Non-professional user (Recreational interest)' represents about 31% of the answers, i.e., the majority of respondents. 'Potential users' represent 22.7% of respondents, an important and unexpected result. 'Non-professional users with business interest' characterises 21.8% of the responses and 12.7% declare themselves as 'Expert users'.

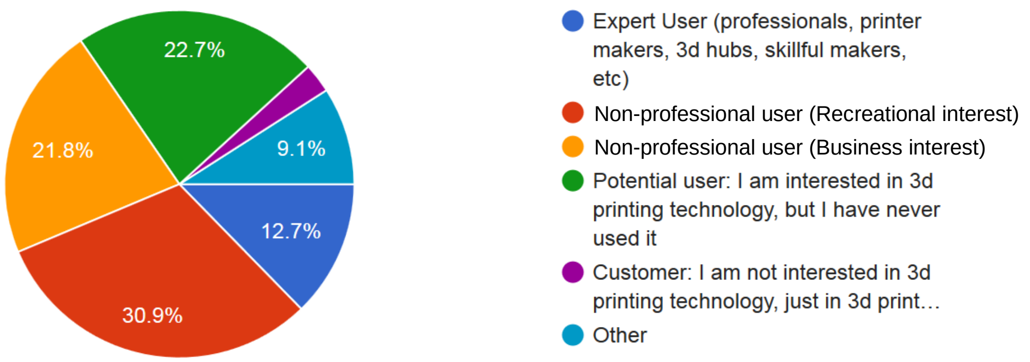


Figure 6- 3d Printing user profile

The second question asked to the participants was: Which are/were your motivations to use/start using 3d printing technology and printed products? Figure 7 presents the results.

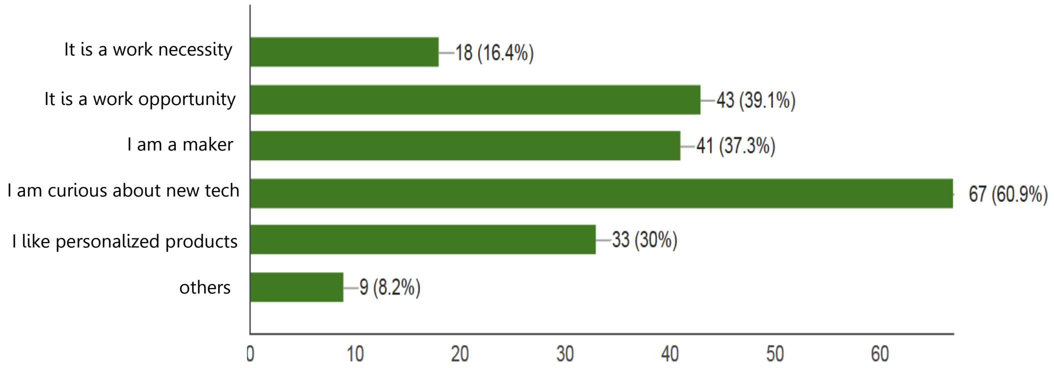


Figure 7 - Motivations to use 3d-printing technology

About 61% of the respondents have answered that the curiosity about new technologies was the motive to start using 3d printing. The work opportunity comes in the second position. This results may indicate that 3d-printing represents for most of the participants a way to be connected with the innovation and this might become a work opportunity.

This scenario gives to the 3d-printing technology an important role in the social changes regarding the fact that curious users may become experts who will develop the technology and create new markets.

When people were questioned about their level of expertise in Computer Aided Design – CAD, it was observed that 68% of them have knowledge of the subject. 37% have an intermediary level of knowledge/practice and 31% are beginner users. (Figure 8).

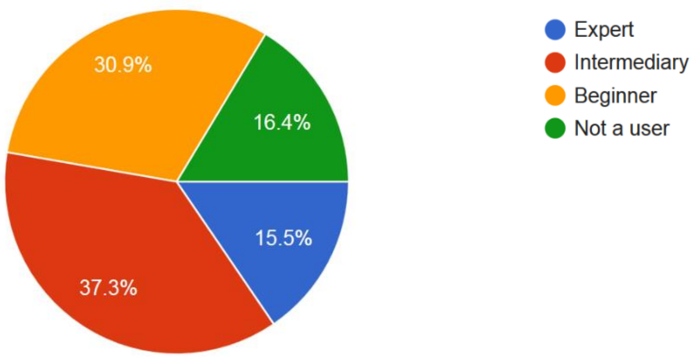


Figure 8 – Level of expertise in CAD

Still concerning the CAD expertise, it was verified that the majority of persons prefer to make their design at home (63.6%) and 14.5% prefer to download a free file on the Internet (Figure 9). This data may indicate that the majority of people that start with 3d-printer technology already have some knowledge in CAD systems.

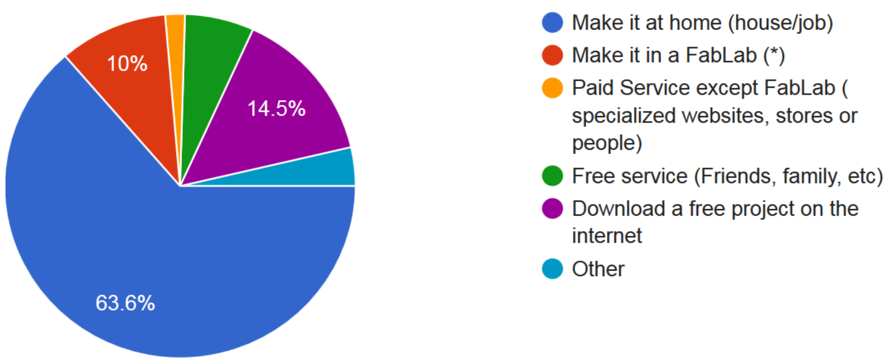


Figure 9 - Preferences to make a new product design using CAD

Likewise the CAD expertise, the Printing expertise is another very important element. Figure 10 shows that 60% of the survey participants print frequently. The second position (16.4%) represents the participants who have never printed before but are interested in starting printing. This upward number of interested users brings up the necessity to create usage rules and methods to guide them in a more efficient and environmentally way of use.

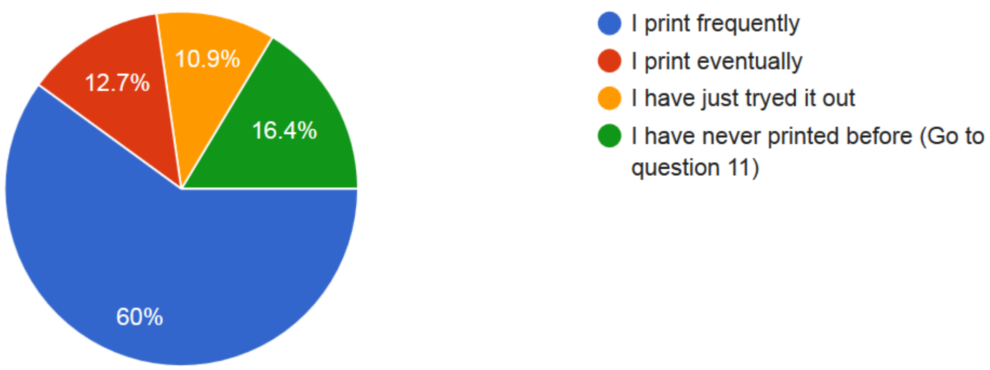


Figure 10 - Frequency of printing

Figure 11 shows the answers for the following question: If you have already printed a product, where have you done it? As it can be observed, 61.3% of the persons answered 'at home'. This result may demonstrate that each day more people are equipping themselves with 3d-printers and that this market has an increasing tendency. Among the 112 participants, 85 have already printed at least once. They have cited 58 different models of printers, and the three most used are: RepRap (19 users), Ultimaker2 and Maker Bot2 (9 users each one).

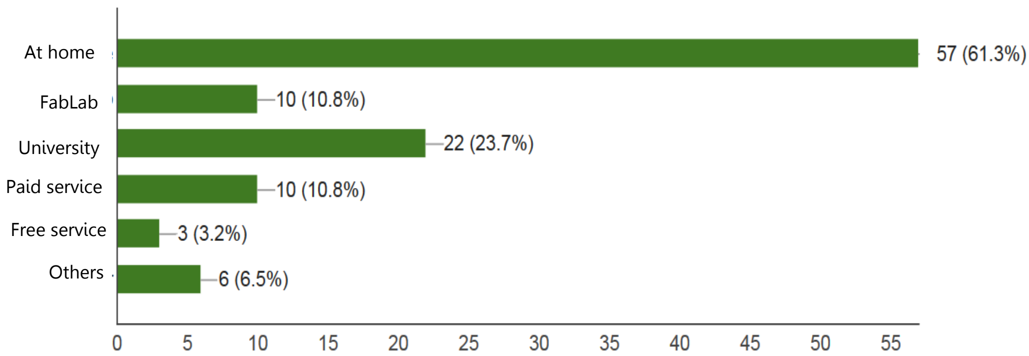


Figure 11 – Printing places

When people were questioned about the types of products they prefer to print or would be interested in printing, the majority of answers (65.5%) cites 'Prototypes: products and architecture' and the second option is 'Spare parts for replacement' with 62% of answers (Figure 12).

This result indicates that, in many cases, 3d-priting technology might be used to improve and/or give a 'second life' to products, which may suggest a positive and promising scenario to 3d-printing regarding environmental issues.

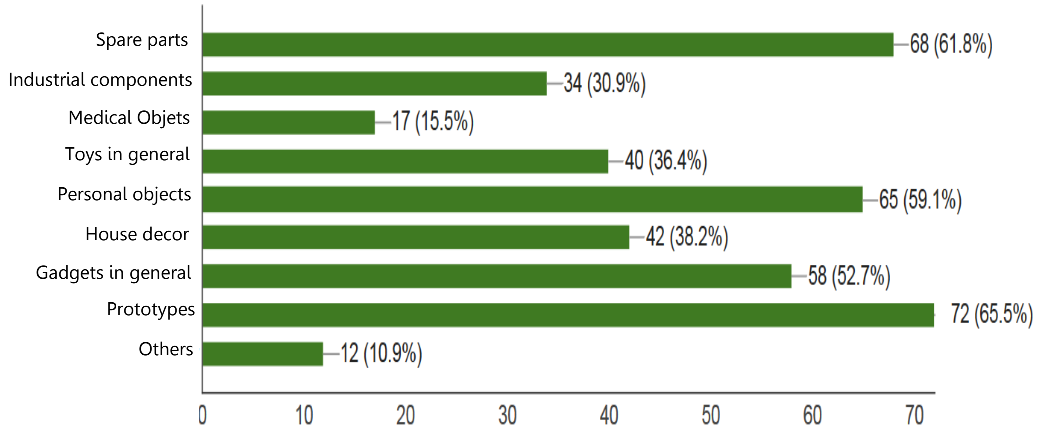


Figure 12 – Type of most printed products

Concerning the environmental topic, figure 13 shows the results obtained from the following question: In a linear scale below (1-6), choose the value that better represents your feelings about environmental impacts of 3d printing technologies.

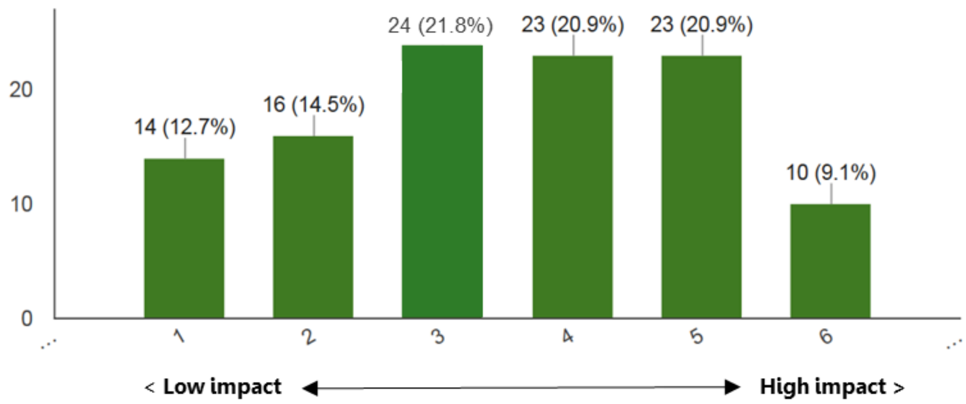


Figure 13 - Environmental impacts

49% of participants have chosen the values 1, 2 and 3, and 51% have chosen values 4, 5 and 6. This data constitutes a real balance among answers which highlights that the environmental impacts of a printed product are still little known by most of the users. Additionally, as 77% of the participants of this survey have printed at least once, so these results are surely based on their use/user experiences of waste generation and energy consumption.

To conclude, this survey has questioned the participants if they have a 3d-printer at home or if they would like to have one. As shown in figure 14, almost 50% of them already have one, and almost 30% would like to have one. Among the respondents that already have a printer, once again the Rep Rap model is the most common, representing 26 % of the answers.

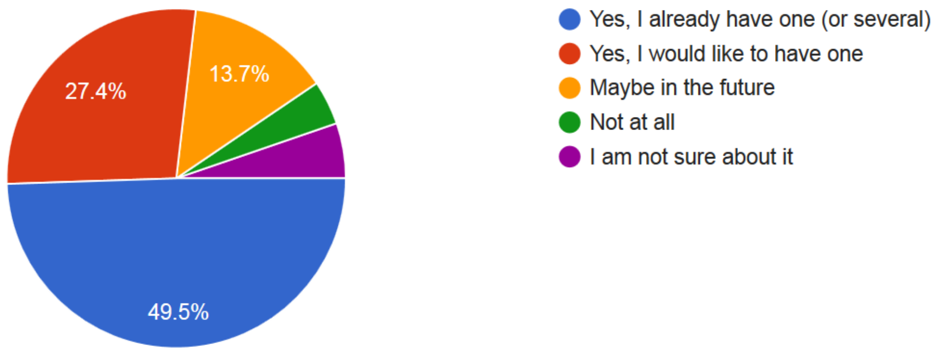


Figure 14 – People who have or would like to have a 3d-printer

To close, all of these answers were gathered and organised in such a way to compose the infographic in Figure 15. This infographic illustrates the general survey results and will guide the studies of the different users' profiles presented in the next section.

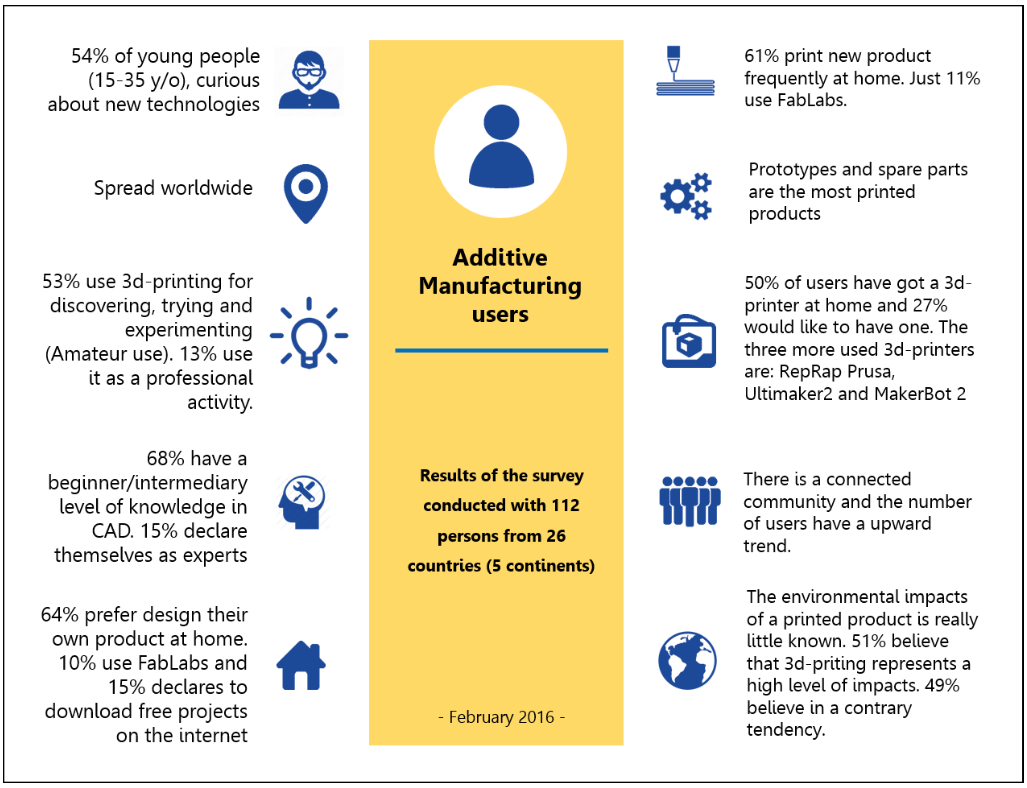


Figure 15 – Survey results

2.7.1 AM user's profiles

In order to identify the different AM users' profiles, the method of Cluster Analysis was applied. According to (Kaufman & Rousseeuw, 1990), Cluster Analysis is 'the art' of finding groups in data. The objective is to form groups in such a way that objects in the same group are similar to each other, whereas objects in different groups are as dissimilar as possible.

The most common way to present the cluster analysis results is by means of a Dendrogram[2], a type of graphic where the individuals are presented and clustered according to the distance of their responses. The maximum distance depends on the number of cluster wanted in the analysis. When the distance of two individuals is '0', this means that both have given exactly the same answers for all questions.

Using the statistic software Statgraphics, the answers of the 112 participants were carefully analysed and separated into four clusters. The number of clusters was determined according to the answers for the question 1 in which four user's profiles were identified. The goal of this cluster analysis is to found out the similarities of answers in order to know the characteristics of each profile.

Figures 16 to 19 present the four dendrograms representing the four clusters. They show the individuals and the distance among them according to their answer. It can be observed that the maximum distance identified was '70'. However, the largest part of the respondents present distance between '0' and '10' in the four clusters. We have assumed that these distance range is enough to validate the characteristic of the group.

The first group gathers 34 persons who consider themselves as 'Non-professional user with recreational interest'. The similarity of their answers determines the following profile: young (15- 25 y/o) and adults (up to 36 y/o). They print multi-products, frequently at home. They have a beginner level of expertise in CAD and a slight tendency to consider that 3d-printing generates low Environmental Impacts (E.I). The Dendrogram in figure 16 illustrates the cluster. 28/34 respondents have maximum distance up to 10.

[2] Dendrogram is a tree diagram frequently used to illustrate the arrangement of the clusters produced by hierarchical clustering. (Wikipedia, 2016)

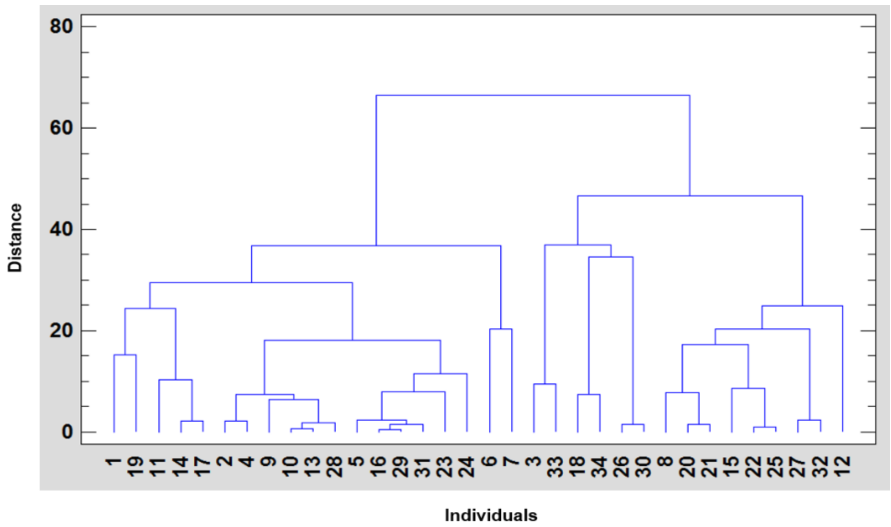


Figure 16 - Cluster 1 (Hobbyists users)

The second cluster represents 28 persons. They are adults (26-35 y/o), not users of 3d-printing, but 'Potential users' and interested in printed products. The majority has never used CAD system and never printed. Others are beginners in CAD and just tried out to print. They consider that 3d-printing generates low/medium E.I. 22/28 individuals have maximum distance up to 10. (Fig. 17)

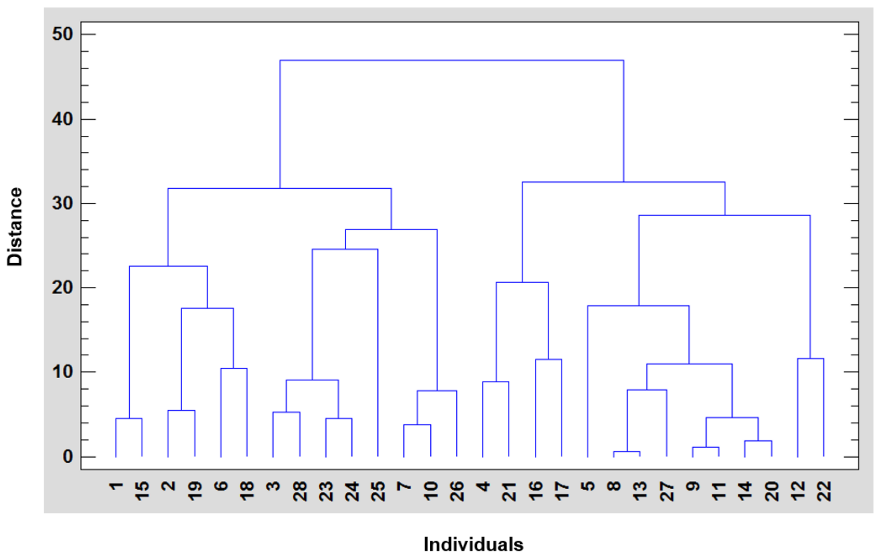


Figure 17 - Cluster 2 (Potential users)

'Non-professional user with business interest' represent the third group. 20/26 individuals have maximum distance up to 10. They are 26 persons, adults aged between 26-35 y/o, printing multi-products, frequently at home and institutions. They have an intermediary level of expertise in CAD and consider that 3d-printing generates considerable/high E.I. (Fig. 18).

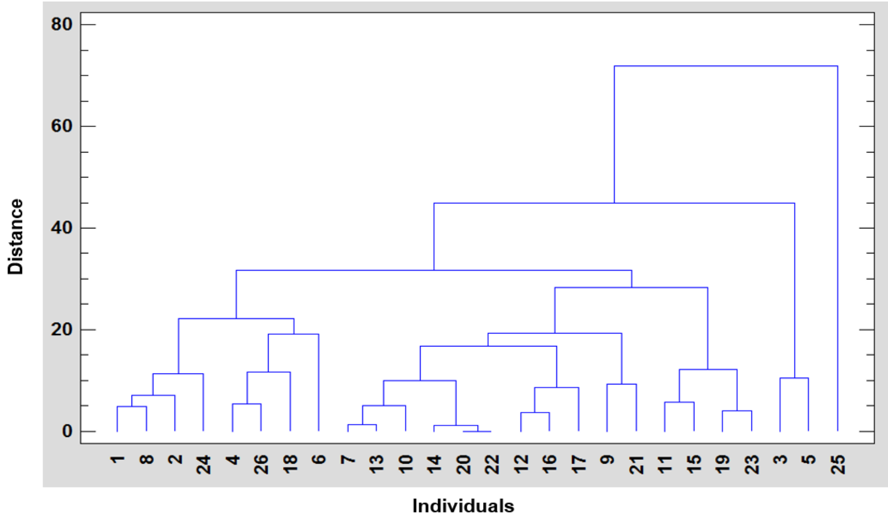


Figure 18 - Cluster 3 (Visionary users)

The last group represents the 'Professional users' (24 persons). They are aged between 26-35 and 46-55 y/o, 3d-printing experts, printing multi-products. They have an intermediary level of expertise in CAD and consider that 3d-printing generates medium/considerable E.I. 20/24 individuals have maximum distance up to 10. (Figure 19).

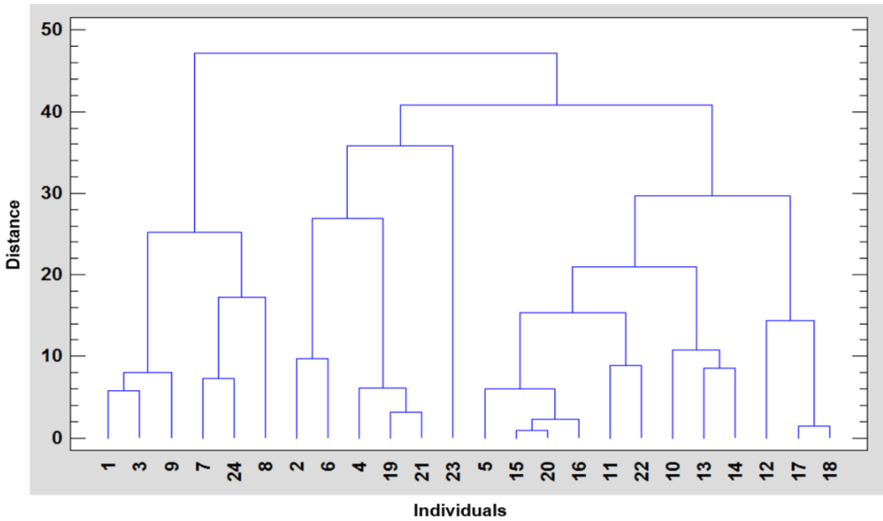


Figure 19 - Cluster 4 (Professional users)

Considering that in the four clusters the majority of respondents have distance up to '10' with maximum distance '70', it possible to define, therefore, four different respondents' profiles according to each cluster:

Profile 1) - *Hobbyists users*, from cluster 1;

Profile 2) - *Potential Users*, from cluster 2;

Profile 3) - *Visionary Users*, from cluster 3; and,

Profile 4) - *Professional Users*, from cluster 4;

Figure 20 illustrates and characterizes these profiles.

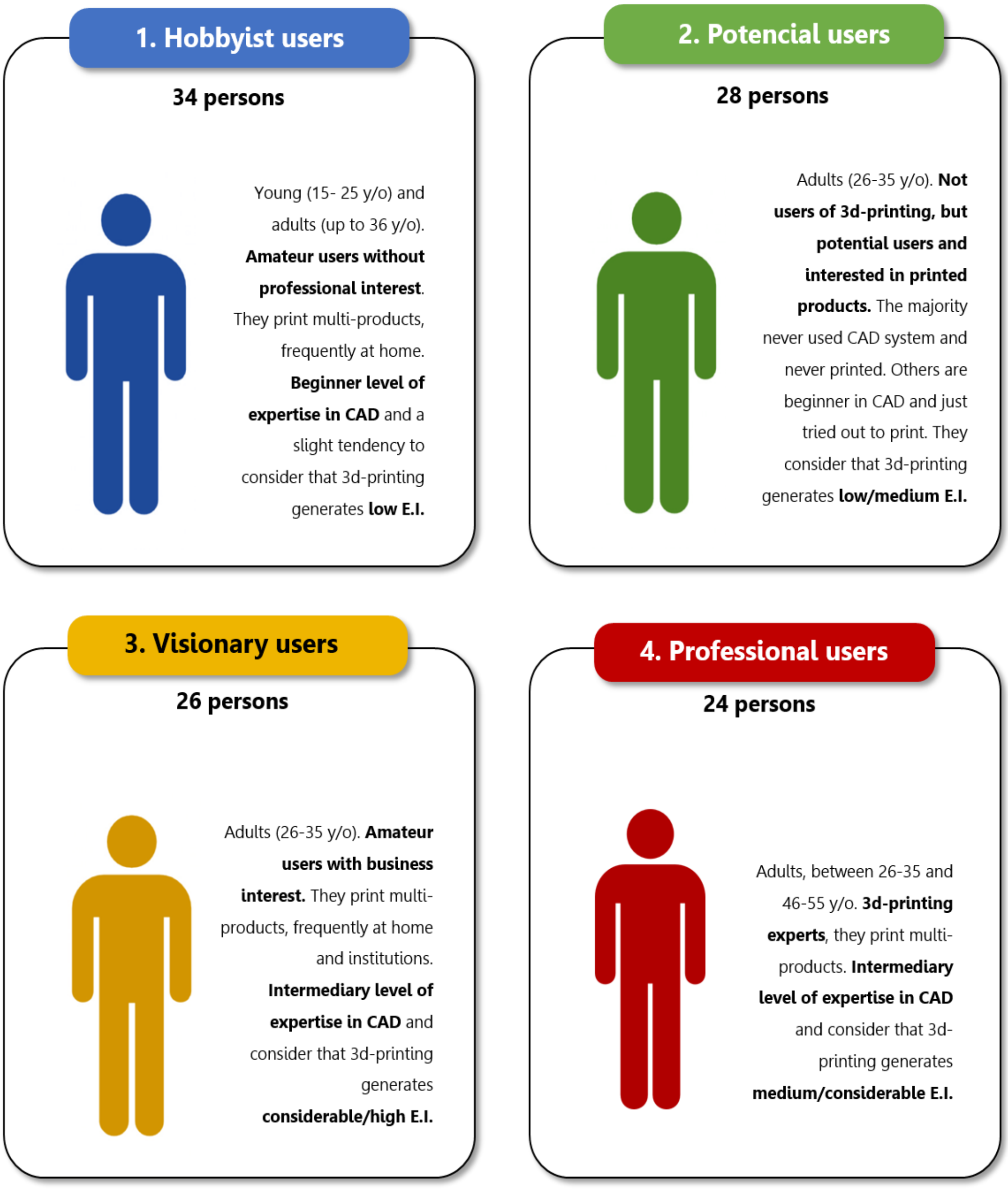


Figure 20 - Users profiles identified through our survey

So, the Cluster Analysis have shown that Additive Manufacturing is a large field of research and work that gathers and attracts a vast number of people with different profiles. These people have particular objectives, knowledge, experience and practice. AM technologies seem to correspond all these individuals' challenges and criteria.

This study strongly suggests that investigations realized in AM field must consider these different profiles. As long as the objective of this research is to assess the environmental impacts associated to AM, the planed LCA's should be performed in an adapted and specific way according to the profiles particularities. Doing this, more reliable and coherent results are assured.

2.8 Conclusions

The first section of this chapter has presented the literature context studied and analysed in this research. It was presented the principle, evolution, advantages and challenges of Additive Manufacturing technology.

A particular emphases on the studies of its environmental impacts was done. In most of the cases these studies compare AM and a Classic manufacturing via LCA. Analysis have demonstrated that there are a lack of consensus among similar investigations. The findings are sometimes convergent and sometimes divergent. Also, the impacts assessment are mostly focused only in the technical aspects.

The second part was dedicated to the study of the AM user's profiles. For this, a survey internet-based was applied with 112 users from different countries. Using cluster analysis, four profiles were identified: Hobbyists users, Potential Users, Visionary Users and Professional Users. This study has strongly suggested that investigations carried out in AM field must consider the difference of user's profiles.

Next Chapter describes how the literature analysis and the survey findings were used to define the statements, hypothesis and approaches of this research.

3

Thesis Statements, Hypothesis and Research Approach

This chapter is composed of 2 sections. The first one presents the thesis statements and the hypothesis defined for the study and section 2 presents the method and the research approach. The second section reports firstly the way used to calculate the AM environmental impacts with Life Cycle Assessment – LCA and then, it presents the research approach focusing on three AM domains to be investigated in different use scenarios.

3.1 Thesis Statements and Hypothesis

Chapter 2 reviewed the literary context of AM and the different studies regarding its environmental impacts. Additionally, AM user's profiles were identified using a literary base and a specific survey.

From these previous analysis and considering the research question, it was possible to summarise three general statements and four hypothesis:

1. *Statement A* - AM is a worldwide disruptive technology with a growth potential that can transform the way manufacturers, and people relate to products. It gathers a vast number of different technologies and uses.

   ✓ *Hyp.1 – To separate the AM field in specific usage scenarios is the more reliable way to investigate the environmental impacts associated to it. The impacts seem to be different according to the use and technology.*

2. *Statement B* – Some authors have been using the LCA method to study and analyze the environmental impacts of AM, but there is no consensus among those studies.

- ✓ *Hyp.2* **–** *LCA is the most appropriate method to investigate the E.I associated to AM. However, the studies need to be well structured and consider the specificities of the technology.*

- ✓ *Hyp.3 – Comparing AM to Industrial Manufacturing without taking into account the specificities and functions of each system do not make sense.*

3. *Statement C* - There are an upward number of interested users with different profiles. This brings up the necessity to create usage rules and methods to guide them in a more efficient and environmentally way of use.

   - ✓ *Hyp.4 – Besides the Technical aspects, the Human aspects (User experience, for instance) might actively contribute to the generation of the impacts.*

These arguments and hypothesis yield to realise that there is a gap in the research field of AM regarding the understanding of the environmental impacts associated with it. The validation of these hypothesis will allow to contribute to fill this gap and improve AM towards a more environmentally way of use. For this, a specific research approach was designed.

3.2 Research Approach

This research will apply a 'multi-activity' approach based on the thesis objectives, the statements and hypothesis.

The environmental impacts will be assessed by adopting the LCA method. This method will be used in different scenarios of Additive Manufacturing regarding their specificities. According to (Lorent, Mandil, Svecova, Thivel, & Zwolinski, 2015) the way the LCA methodology is applied influences significantly the final results.

Also, on site observations and practical activities, interviews with AM users and literature review will complete the approach.

3.2.1 Life Cycle Assessment (LCA)

This research will use the method of Life Cycle Assessment – LCA to identify and assess the environmental impacts associated to AM. (Wilson, 2013) declares that '*to look for evidence of environmental benefits of Additive Manufacturing, sustainability professionals have to seek proof using ISO 14001.'*

ISO 14001 describes the standardisation of Life Cycle Assessment, a scientific approach to a growing number of modern environmental policies and business decision supporting the context of sustainable consumption and production (European Commission, 2010). It is receiving more and more attention in the industry and authorities as one important tool for, e.g., Integrated Product Policy (IPP), Technology Assessment or Design for Environment (DfE). (Frischknecht & Rebitzer, 2005).

According to (ISO 14040, 2006), LCA allows assessing the environmental aspects and potential impacts associated with a product, process and organisations, by:

1. Defining the scope of the study with objectives and system limits;
2. Compiling an inventory of relevant inputs and outputs of a product system;
3. Evaluating the potential environmental impacts associated with those inputs and outputs and;
4. Interpreting the results of the inventory analysis and impact assessment phases connected with the objectives of the study. (Fig. 21).

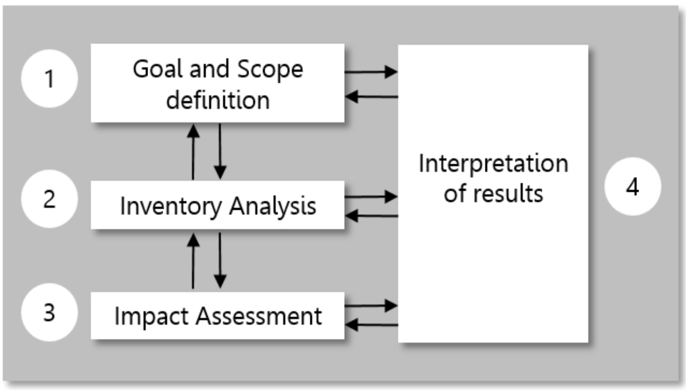


Figure 21 - LCA Framework
Source: (ISO 14040, 2006)

In this study, the experiments will examine the environmental impacts of specific printed products by considering the major stages of the product's life cycle (Raw material acquisition, Production, Distribution, Usage and Waste management/End of life). All of them will be examined according to pre-determined system boundaries and a specific Functional Unit.

3.2.1.1 System Boundaries and Functional Unit

Several factors determine the system boundaries, including the intended application of the study, the assumptions made, cut-off criteria, data and cost constraints, and the intended audience.

The selection of inputs and outputs, the level of aggregation within a data category, and the modelling of the system shall be consistent with the goal of the study. The criteria used in establishing the system boundaries shall be identified and justified in the scope of the study. (ISO 14040, 2006).

Regarding the LCA's scope and the study field investigated in this research (Additive Manufacturing), the boundaries will be defined according to the data availability and pertinence. It will be prioritized primary data and the negligible points will be defined and justified considering the importance of the data in relation to the impacts.

Beyond the system limits, another important step in a LCA (when the objective is to compare two or more systems) is to define a Functional Unit (FU).

A LCA does not compare products/services itself, but the function delivered. The FU represents the common level of performance to be achieved by all the compared systems. Then, it is a service unit, not an amount of products. The primary purpose of an FU is to provide a reference to which the inputs and outputs are related. This reference is necessary to ensure the comparison of LCA results. (ISO 14040, 2006; Teulon, 2015)

Thereby, the FU's defined for the LCA's performed in this research will consider the particularities and functions of AM technology. The goal is to be the most realistic and reasonable as possible. Studies concluded by (Lorent et al., 2015) showed that the lack of consensus among FU in the same science field may jeopardize the LCA results.

3.2.1.2 LCA software and impact calculation method

Some software and databases have been developed to support the LCA procedures. Among them, the most cited in the literature are Simapro, KCL-ECO, LCAIT, GaBi and PEMS.

LCA's carried out in this research will use the SIMAPRO 8, a professional tool to collect sustainability data and to analyse and monitor the sustainability performance of products and services. (Goedkoop, Oele, Leijting, Ponsioen, & Meijer, 2013).

Simapro contains some impact assessment methods, which are used to calculate different environmental impacts. Each method is chosen according to the scope of the study. Considering the nature of the LCA's conducted in this research, the method IMPACT 2002+ (Version Q2.21-2012) is used in all studies. This choice was done considering that 'Non-renewable energy consumption' is an important criteria we want to focus on and that this criteria was improved in the last version of the software.

The IMPACT 2002+ calculation method proposes an approach via 15 midpoint categories and 4 endpoints categories as illustrated in figure 22. The LCA results of this research will not consist of an exhaustive list of impact analysis. It will be centred in specific midpoints impacts categories determined according to the pertinence and relevance for each LCA conducted.

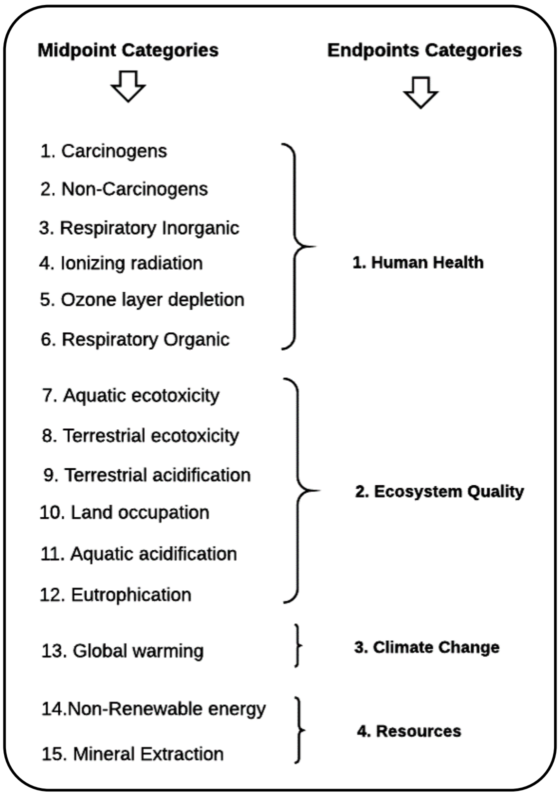


Figure 22 - Impacts categories of the IMPAC 2002+ method

3.2.2 Research Structure

Based on the survey results showed previously in which four AM user's profiles were identified and referring to the Statement B and Hypothesis 2, the investigation of this research will be done separately per scenarios.

The first scenario will be called 'Personal Fabrication'. It is a type of AM usage in which experimenting and pleasure are the mainstream. It was defined by the user profile 'Hobbyist users'.

The second one, entitled 'Business Use' was recognised by the group of users called 'Visionary users'. It represents a type of AM use in which economic interest is the main drive to manufacture a final product.

The third AM scenario to be investigated is 'Industrial Use'. It comes from the user profile 'Professional users', and its main characteristic is related to the production of series of printed parts, in general using metal as material. (Fig. 23).

'Potential users', the fourth profile identified in the survey will not be a direct focus in this study because they are not users (yet).

This division and the names given to classify the scenarios reflects the users profiles identified in the previous survey (Chapter 2) by means of cluster analysis. It constitutes a realistic and coherent framework to guide the investigation on this research. Nonetheless, it does not purport to be a closed and invariable distribution. Variations and exceptions are possible.

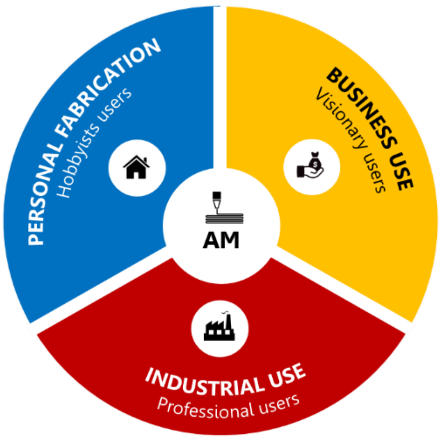


Figure 23 - Three AM domains focus of this research

The three scenarios will be studied separately considering their particularities. This division allows identifying specific key nodes and providing more realistic results. Also, it avoids general conclusions already found in the literature and sometimes doubtful.

The first scenario (Personal Fabrication) will be investigated by means of observations and interviews with users and managers in different FabLabs and maker spaces. The goal is to observe and analyzing the work dynamic around the 3d-printers.

Supplementing the study, a LCA will be performed to analyse the environmental impacts of a part printed using a RepRap 3d-printer. The lifecycle of this printed part will be compared to a lifecycle of a same product made by classic manufacturing. This experiment will provide condition to validate the hypothesis 2 and 3.

At the end, sensibility analyses will be carry out in order to define the hotspot of impacts in this scenario and investigating the impacts of the Human aspects in this type of AM domain.

The second scenario (Business use) will be studied in partnership with a start-up that uses 3d-printing technology to print and sell custom products. Meetings, interviews and internet searches will provide the necessary data to perform the projected LCA.

In this study, a comparative LCA will be performed to compare the life cycle of two products. One made by a classic production and the other one printed in a high performance 3d-printer. The goal is to identify the main sources of impacts in this specific AM use and also validate the defined FU. The particularity of this study is that both systems compared (classic and printing) have the same production scale, functions and target customers.

The third scenario is dedicated to investigate the environmental impacts of AM in an industrial context. For this, a broad literature review will be presented firstly. Researches focusing on the environmental impacts of AM are still poor, but a large majority of them is based on the industrial use.

A third LCA will be carried out with a different perspective. The goal is to compare the impacts of the three different processes that make up this type of production: the CAD Process, the Printing Process and the Finishing Process. It is expected to show where the impacts come from in this type of AM use.

Thereby, the results of these three different investigations will be interpreted and analysed according to their specificities and considering the Technical and the Human aspects. Also, it will be compared to some literature results.

Based on these results, a framework to help users to understand the environmental impacts associated to AM will be proposed. Additionally, a concept of LCA tool to roughly calculate the environmental impacts related to AM processes will be presented based on the 3 AM studies and considering the main research question: *How to identify and control the environmental impacts associated to the use of Additive Manufacturing technologies?* Figure 24 illustrates the research structure.

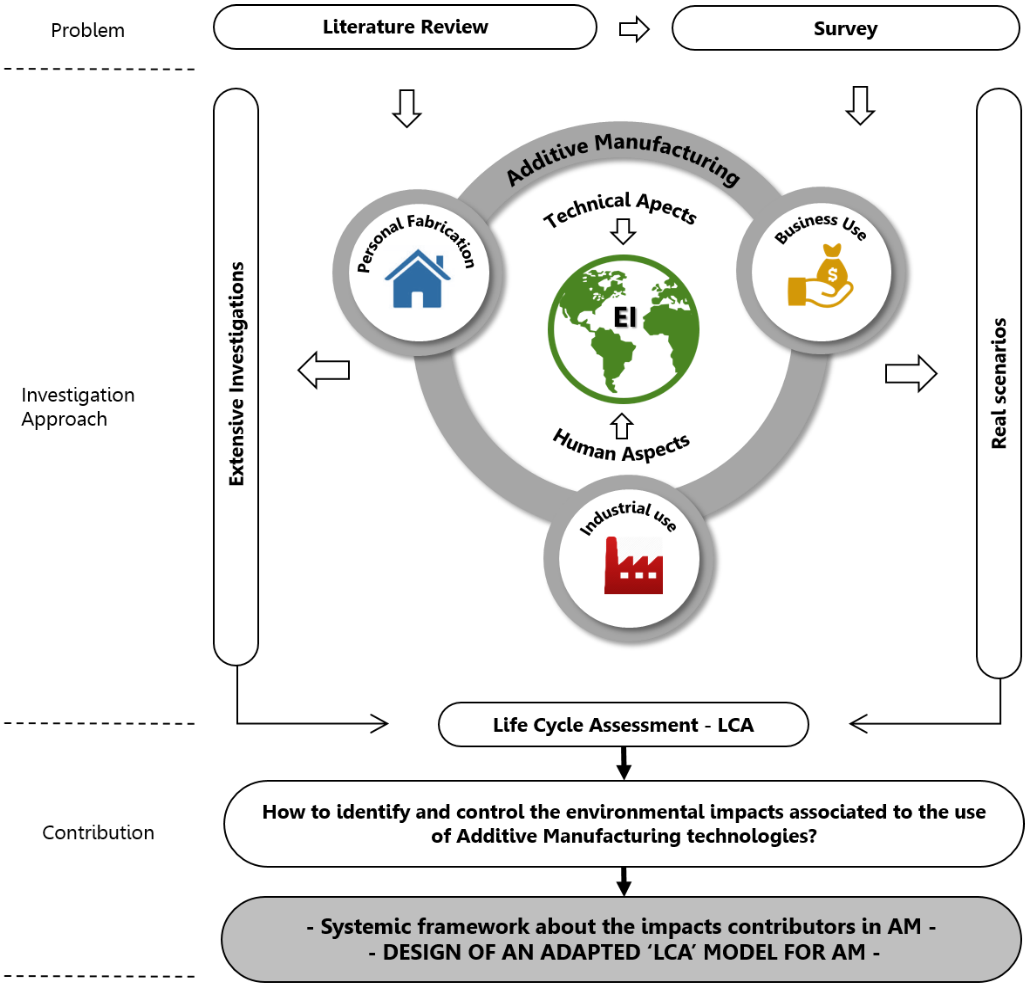
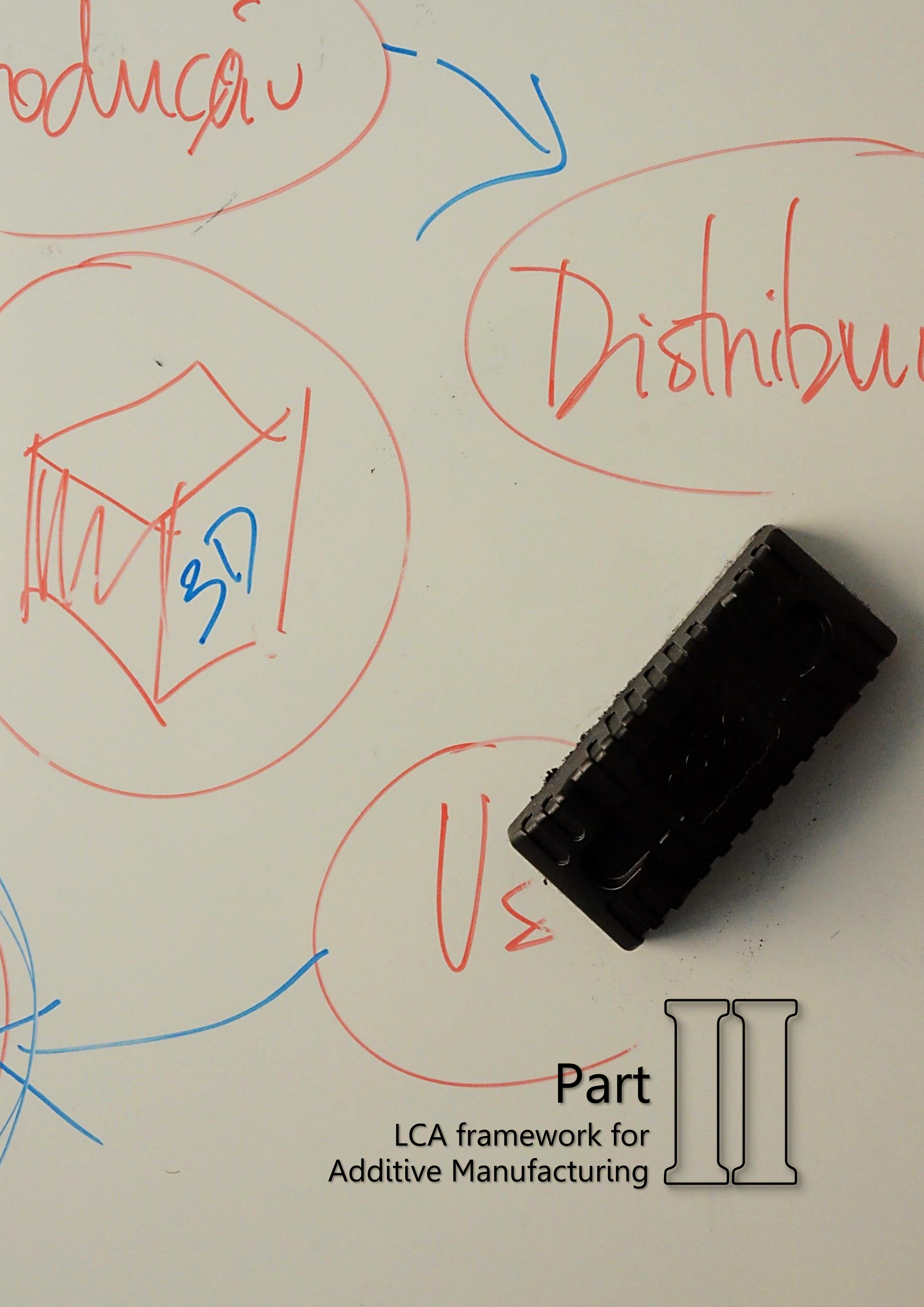


Figure 24 - Research structure

Next Part (Chapters 4 to 6) presents the 3 scenarios studied with their experiments, analysis and conclusions. The final contribution for this research is presented in the chapter 7.



Part II

LCA framework for Additive Manufacturing

‘Personne n'est un artiste à moins
qu'il ne porte son œuvre dans sa tête
avant de le peindre et soit sûr de sa
méthode et de sa composition.’

(Claude Monet)

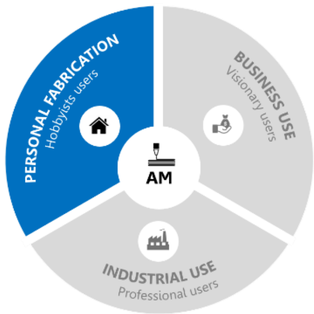
4

Scenario 1: Personal Fabrication

This chapter characterizes the AM domain called Personal Fabrication. It presents the main features of this type of use and two practical experiments carried out on it. Experiment 1 refers to the observation and interaction with users in three makerspaces in Europe. Experiment 2 shows the results of a product LCA manufactured using Personal Fabrication model. The results and conclusions of these activities are presented in the last section.

4.1 Characterization

(...) today anyone with an invention or good design can upload files to a service to have that product made, in small batches or large, or make it themselves with increasingly powerful digital desktop fabrication such as 3d-printers (Anderson, 2012).



This statement characterises how noteworthy is AM today and its entrance into the people real life. Using domestic 3d-printers, anyone may create and manufacture a product at home or in specifics maker spaces. This is Personal Fabrication (PF). This type of AM recreational use is becoming very common and represents an important part of its use. In general, people who use AM as a leisure activity are more interested in learning, sharing and having fun.

According to (Morel & Roux, 2016, p. 86),

L'usager, dans le modèle de fabrication personnelle, quitte son statut ancestral d'individu-objet de choix faits pour lui, en dehors de lui ; il cherche à s'émanciper de ce système sans liberté pour tenter de constituer sa vie quotidienne selon ses propres volontés et ses propres désirs. (Original text without translating).

The growing interest in this new type of manufacturing (mainly among young people) associated with easy access technologies have expanded the production at home and the number/types of spaces dedicated to the individual fabrication (maker spaces).

One of the reasons for the growing of home production comes from the availability of machines designed to simple and small use, such as RepRap, MakerBot, Ultimaker, Zortrax, Mcor Arke and others.

A RepRap (Fig. 25) takes the form of a free desktop 3D printer capable of printing plastic objects. Since many parts of it are made from plastic and RepRap prints those parts, it self-replicates by making a kit of itself (RepRap, 2015). The survey conducted in this research has identified that the RepRap is currently the most common 3D printer used by the PF users.

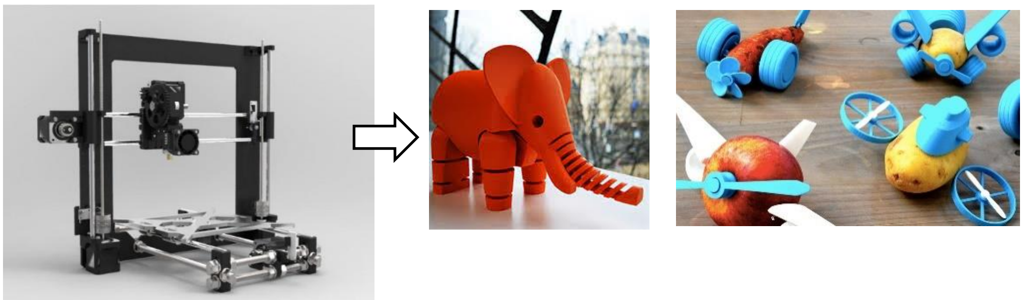


Figure 25 - Rep Rap and some printed products
Source: Internet

Concerning the maker spaces, FabLabs are widely the most frequented spot by recreational 3d-priting users. A FabLab is a short term for 'Fabrication Laboratory', a name given by Dr Neil Gershenfeld, a professor at MIT (Massachusetts Institute of Technology) to denominate globally, a space to make, test and use inventions.

The idea of a FabLab was designed to attend student's needs who desired simply making things without worry about publishing a paper, filing a patent or marketing a product. According to him, the student's inspirations was not professional, it was personal; '*Their motivation was their pleasure in making and using their inventions'* (Gershenfeld 2012).

From this idea, the first official FabLab was implanted into the Center for Bits and Atoms (CBA), a Research Center linked to MIT that develops studies focused in the digital revolution and in particular, digital manufacturing. After this, since 2002 a growing number of Fab Labs has started to be built all over the world. (Eychenne & Neves, 2013; Gershenfeld, 2007)

According to the Fab Foundation (2015), nowadays it is possible to find FabLabs in more than 30 countries around the world, being more numerous in Western Europe countries. As we can see in Figure 26, in this region, there are about 272 Fab Labs, and the six most populous countries of this area (Germany, France, United Kingdom, Italy, Spain and Netherland) gather 183 FabLabs being 51 in France.

Figure 26 - Fab Lab around the world
Source: fabfoundation.com

Fab Foundation (2015) describes a Fab Lab as '*a technical prototyping platform for innovation and invention, providing stimulus for local entrepreneurship'*. It is also a platform for learning and innovation: *a place to play, to create, to learn, to mentor, and to invent'.* (Fig. 27 a-b)

a) b)

Figure 27 - a) FabLab Grenoble | b) FabLab Paris
Source: Internet

Eychenne & Neves (2013, p. 9), describe a Fab Lab as *(...) a physical objects rapid prototyping platform that intends to entrepreneurs who want to go faster from concept phase to prototype.*

Figure 28 shows that a Fab Lab is composed of distinct small 'cells' arranged together in the same place to confer it the basic work dynamic: the coworking[3]. In this context, Personal Fabrication provides new manufacturing possibilities.

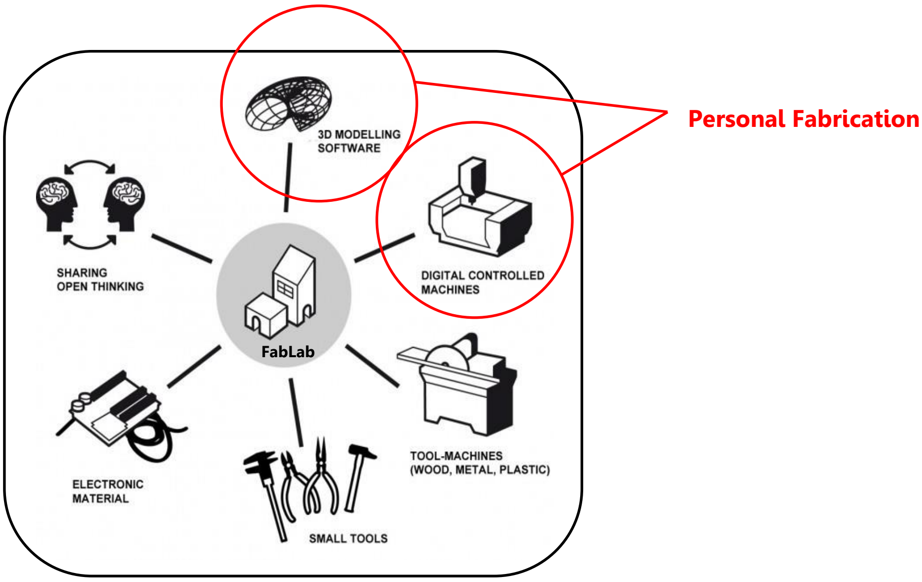
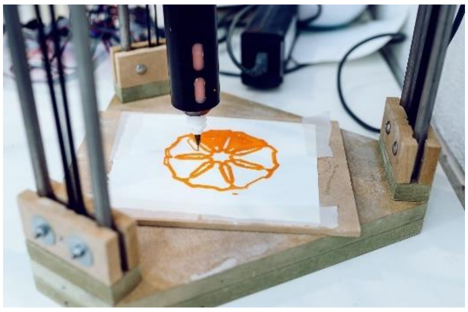


Figure 28 - Fab Lab work structure
Source: Internet

Figure 29 (a,b) shows some exemples of parts printed in FabLabs.

a)



b)

Figure 29 – Printed parts made in FabLabs
Source: Internet

[3] Style of work that involves a shared working environment. Is also the social gathering of a group of people who are still working independently, but wants share values. (Wikipedia, 2015)

So, Personal Fabrication can be characterized according to the following aspects:

- User experience is the key node of this manufacturing;
- Challenge and pleasure are the main motivation elements;
- Designers and makers are in general the same person;
- Co-working is a constant;
- Use the philosophy of 'open design', co-creating, information sharing;
- In most of the cases, time is not a constraint and getting money is not a motivation;
- General audience: curious people with different level of expertise both in CAD (Computer Aided Design) and 3d-printing;
- In FabLabs or at home, helping each other increases the expertise level;

4.2 Experiment 1: On site observations and interaction with users

In order to observe how people works, how environmental issues are addressed and what are the main characteristics of personal fabrication, observations and interactions were made in four maker spaces: FabLab London, Barcelona and Grenoble and the LOG (*Laboratoire Ouvert de Grenoble*) in Grenoble. In these places, it was possible to interact with users and to observe the dynamic of work around 3d-printers machines.

The FabLab London was visited in 20/Feb/2015 in the 'free open day'. Observations, interactions and an interview with the manager Mr Ande Gregson were carried out. The FabLab is well organised, and workshops are offered continuously to stimulate new users. During the visit, 3d-printers were being used by teenagers to make personal parts (Figure 30 a-c).

Figure 30 a,b,c – FabLab London

In the FabLab Grenoble, visits were done to observe the use and to measure the energy consumption of 3d-printers. Regarding the use, similarly to London, the primary usage of 3d-printers is for personal fabrication. The audience is in general young students interested in new technologies.

The energy consumed by the printers was measured using a professional equipment (CA 8335 - Power and Quality Analyser Chauvin Arnoux), and two personal 3d-printers were measured: Ultimaker 2 and Zortrax. (Fig. 31 a-b).

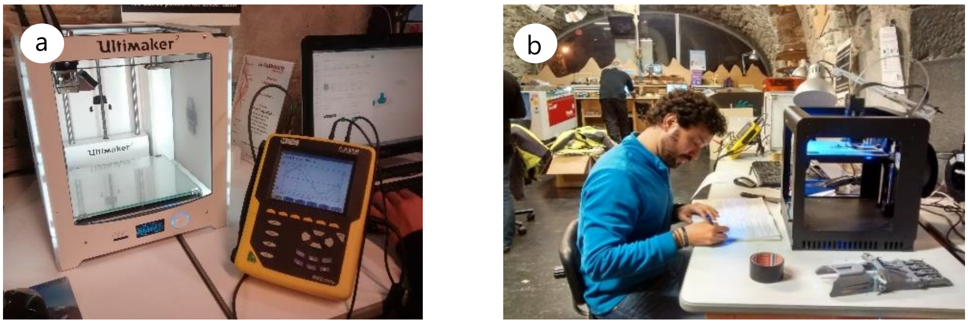


Figure 31 - a) Energy measure equipment | b) Measure process

Results of this activity showed that the printing quality (Normal or HD) does not determine the level of energy consumption. The printing duration determines it. Many factors can affect this duration such as the product size, weight and geometry/ complexity as well the user level of expertise. Table 4 illustrates the results of energy measures. The 3d-printer Ultimaker 2 consumes slightly less energy.

Table 4 - Energy consumption of two 3d-printers

3d-Printer	**Ultimaker 2**	**Zortrax**
Material	PLA	ABS
Energy Consumption (Heating time=3 min)	25,7 wh	28,9 wh
Printing time measured (less heating time)	60 min	60 min
1 HOUR OF PRINTING (Normal)	**98 wh**	**137,5 wh**
1 HOUR OF PRINTING (HD)	**99 wh**	**141,5 wh**

Finished visit at the LOG (*Laboratoire Ouvert de Grenoble*) shown the same reality of FabLabs: a place where makers and hackers meet to do experiments, to share information and to have fun. A sixteen years old young maker, when asked about his interest in using 3d-printers, answered: *I'm building my 3d-printer because I love new technologies and I have a dream to print my drone in the future".*

Another activity observed in that place was the spare parts printing to repair damaged products. It was noted that users are embedded of challenges, and their goal/pleasure is more than fixing a product. To design and print a new useful part to prove to themselves their capacities/advances in the technology is their motivation.

Figures 32 and 33 illustrate two examples of spare parts printing. The first one shows to the manufacturing of supports for a broken chair and the second one a cover for a pen-drive.

Figure 32 - Chair supports

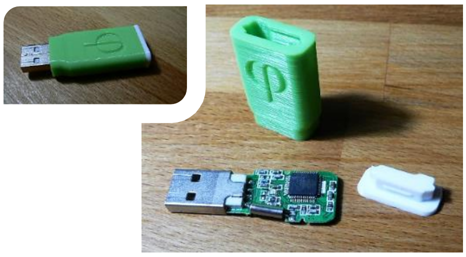


Figure 33 – Pen-drive cover

During the visit realised at FabLab Barcelona in May/2016 (Fig. 34 a,b) it was observed a wide number of prototypes made by design and architecture students. It is an academic FabLab, and Personal Fabrication is presented as a manufacturing alternative for the students.

Figure 34 a,b - FabLab Barcelona

Regarding the environmental issues, none of the four maker spaces visited has a clear politic of environmental impact reduction. Saving energy and avoiding/reusing waste, for instance, are not mentioned for any user. In an interview, Ande Gregson, manager of FabLab London, declares:

The waste comes mainly from printing fails. If fails stop, waste stop. (...) The software is becoming better to help people design things more efficiently, and so decreasing fails and wastes. When people learn more about 3d printers, the waste can become small as well. (...)

4.3 Practical Experiment: Comparative LCA

As already mentioned, Personal Fabrication is characterised by an experimental AM use in which users are more interested in learning, sharing and having fun. In this perspective, this experiment carried out in June/July 2015 intended to analyse the life cycle of a product printed by a Personal Fabrication user. The experiment was performed by using LCA to compare two similar products (two mugs), one made in the industry (Thailand) and the other one printed at Gi-Nova laboratory, in Grenoble-Fr.

4.3.1 Materials and Methods

The LCA was realised using the software SIMAPRO 8. Primary data were collected employing the following instruments and materials:

1. Mirospark (Gut Environmental Technologies): Used to detect plastic type.
2. CA 8335 - Power and Quality Analyser (Chauvin Arnoux): Used to measure energy consumption during the printing process.
3. Kern KB Balance: Used to measure the weight of materials.
4. Prusa i3: 3d-Printer RepRap used to print the product.
5. PLA filament 1,75mm and 3mm: Plastic used to print.
6. Software SolidWork: Used to design the printed mug

The experiment was divided into three stages: firstly, the life cycle analysis of a mug made in the industry. Secondly, the LCA of a printed mug and finally the comparative analysis using the method of calculation 'Impact 2002+'. (Simapro Database)

To compare both products, the following Functional Unit (FU) was defined: 'Serving 250ml of cold water, 4 times per day, during 3 years'.

The experiment was designed just to provide conditions to carry out the analysis, but PLA is not indicated to make a product that will have contact with foodstuffs. According to (Pinshape, 2015), there are four reasons for this: 1) bacteria build up in the product because of surface roughness; 2) presence of chemicals in the filament to colour it; 3) release of toxic particles in the printing process and 4) some brass nozzles contain lead. To validate this study, a sensitive analysis related to the material was also conducted using a nylon to contact with food or beverages and results differences were not significant.

Part of this experiment was adapted to an academic project for four bachelor students from PAGORA School (International School of Paper, Printed-communication and Biomaterial). From September 2015 to January 2016 the students were engaged and the results were also used in their graduation work.

4.3.2 Life cycle of a mug made in industry (IM)

The life cycle of a mug made in the industry (Fig. 35) considers 3 phases: Production, Distribution and End of Life.


Figure 35 - Mug made in industry

The Production phase considers material (Polyamide PA6), the Injection Process and the energy consumed in this process.

The Distribution phase was entirely considered (Thailand to France), and transport mileage was estimated using specialised websites.

The Usage phase was not considered because water consumption and soap for the cleaning are supposed to be the same for the two different mugs.

Finally, the End of Life phase was designed regarding the fact that Polyamide is not recycled in Grenoble-Fr. Therefore, people will discard the mug to municipal waste.

Figure 36 illustrates the whole life cycle of a mug made in the industry. Table 5 shows the life cycle inventory (LCI) used to perform the study.

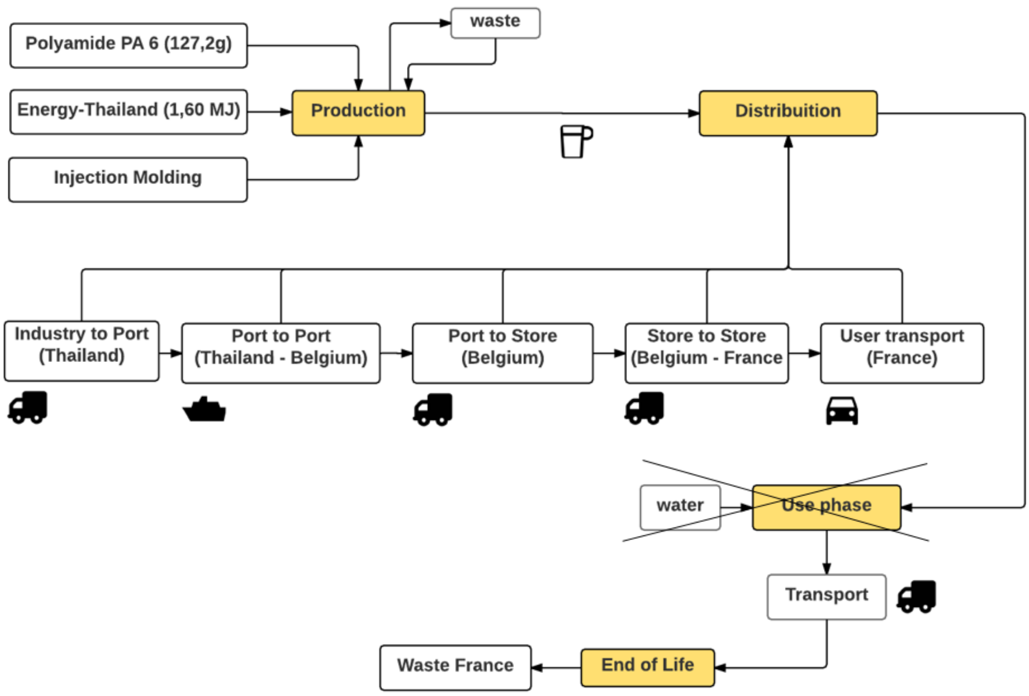


Figure 36 – Life cycle of a Mug made in Industry

Table 5 – Life cycle Inventory (LCI) used to model the mug life cycle (made in industry)

	Item	**Characteristic**	**Quantity**	**Source**
Production	Material: PA6x	Polyamide	127,2 g	Primary data: Equipment: Mirospark
	Injection Process	All-electric machine (Lowest average specific energy consumption)	127,2 g	(Thiriez & Gutowski, 2006) Database Simapro
	Energy (Thailand)	75% Natural Gas	Energy machine consumption: 12,6 MJ/Kg P/ 1 mug: 0,0127 x 12,6 = 0,160 MJ	(Thiriez & Gutowski, 2006) (Commerce & Energy, 2013)
Distribution	Transport	1. Industry to Port: Truck (95% of transportation in Thailand. Truck-load limit is 25T)	26,6 km	www.google.fr/maps (2015) (World Bank Country Development, 2009)
		2. Port to Port: Ship (Thailand – Belgium)	16.892 km	www.searates.com (2015)
		3. Port to Store: Truck (Belgium)	43,2 km	www.google.fr/maps (2015)
		4. Store to Store: Truck (Belgium – France)	881 km	www.google.fr/maps (2015)
		5. Store to User: Car (France)	3,3 km	www.google.fr/maps (2015)
End of Life	Municipal Waste			Database Simapro

4.3.3 Impacts of the mug made in industry

Considering the midpoint impact categories and analysing by Normalisation[4] the graphic in figure 37 shows that, "Respiratory Inorganics', 'Global Warming' and Non-renewable energy' are widely the most important categories to be observed regarding the industrial manufacturing of a plastic mug.

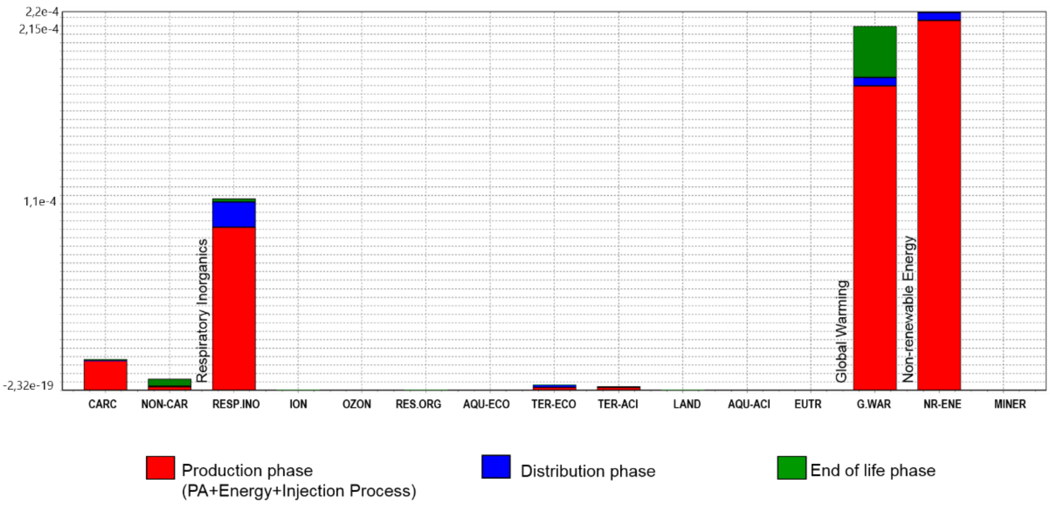


Figure 37 - Impact analyses per phase (IM)

[4] Normalisation is used to simplify the interpretation of the results. It shows to what extent an impact category indicator result has a relatively high or a relatively low value compared to a reference. (Goedkoop et al., 2013)

Certainly these impacts are linked to the type of material (Plastic) and the energy mix of the country where the product is made. (Thailand).

Analysing the three impacts per percentage, it can be seen in figure 38 that 88% of the impacts come from the Production phase (material + energy + injection process). In detail, the material (Polyamide) is responsible for 63%, energy 15% and 10% comes from Injection process.

The transport impacts allocated to 1 mug made in Thailand and bought in France represents 5% of the impacts, and the End of Life phase represents about 6%.

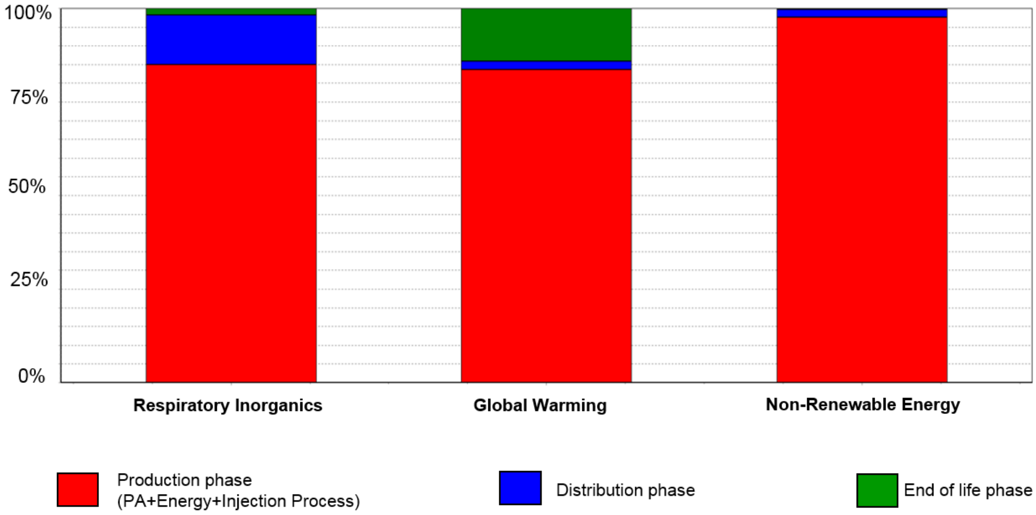


Figure 38 - Percentage of impacts per phase (Mug Industrial manufacturing)

Globally, this brief analysis allowed to see that, for this type of manufacturing, Production phase is widely the most harmful item to the environment, mainly in the Non-Renewable Energy category. Moreover, the Distribution phase does not represent a significant part of impact as expected and broadcasted in several LCA's.

4.3.4 Life cycle of a mug made by 3d-printing (Personal Fabrication)

The mug manufactured to perform this LCA has the same shape of the mug made in the industry. The product was designed and printed by a Personal Fabrication user.

Figure 39-a shows the mug design made using the software Solidworks taking as reference the industrial mug. Figure 39-b shows the printing process using a RepRap 3D-printer and figure 39-c shows the final printed mug.

a) b) c)

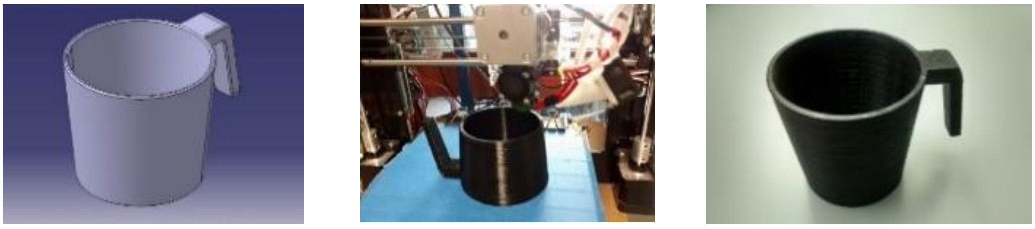


Figure 39 - (a) Mug Design | (b) Mug printing process | (c) Mug printed

To carry out the mug LCA in a proper way, a process called '3d-printing' was created and inserted into the SIMAPRO database. This process did not exist in the current database.

The printing process was made from the results of a 3d-printer (RepRap Prusa i3) LCA carried out considering all machine components with its respective materials, transport and end of life phases. The estimated machine lifespan is 2000h of use (8h/week – 5 years).

The energy consumed for the estimated lifespan (214,4 kwh) was calculated from measures carried out with tree similar 3d-printers (RepRap Prusa i3, Utimaker2 and Zortrax).

The 3d-printing process was used in the mug life cycle through allocation rule. This means that, for one printed mug (94,4g of plastic), it was used 0,24% of the printing process. Nowadays, this process is available into Simapro database (G-scop) to be used by other researchers (Fig. 40). Figure 41 shows the details of this Process with all components considered.

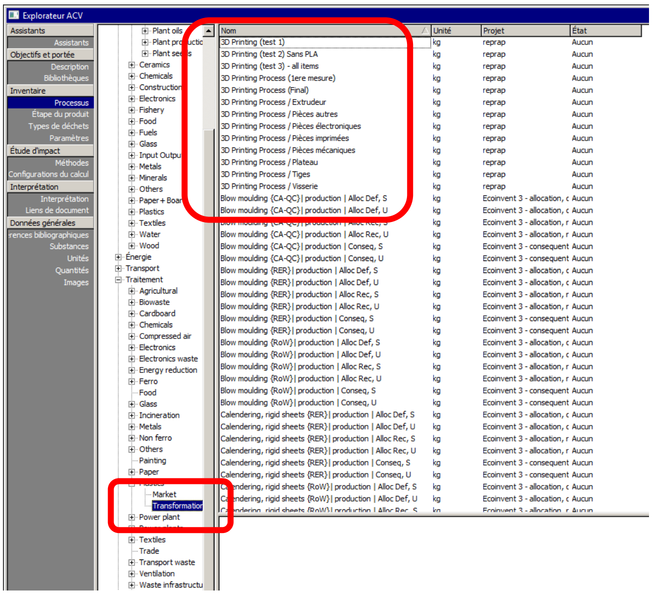


Figure 40 - '3d-Printing Process' inserted in the SIMAPRO database

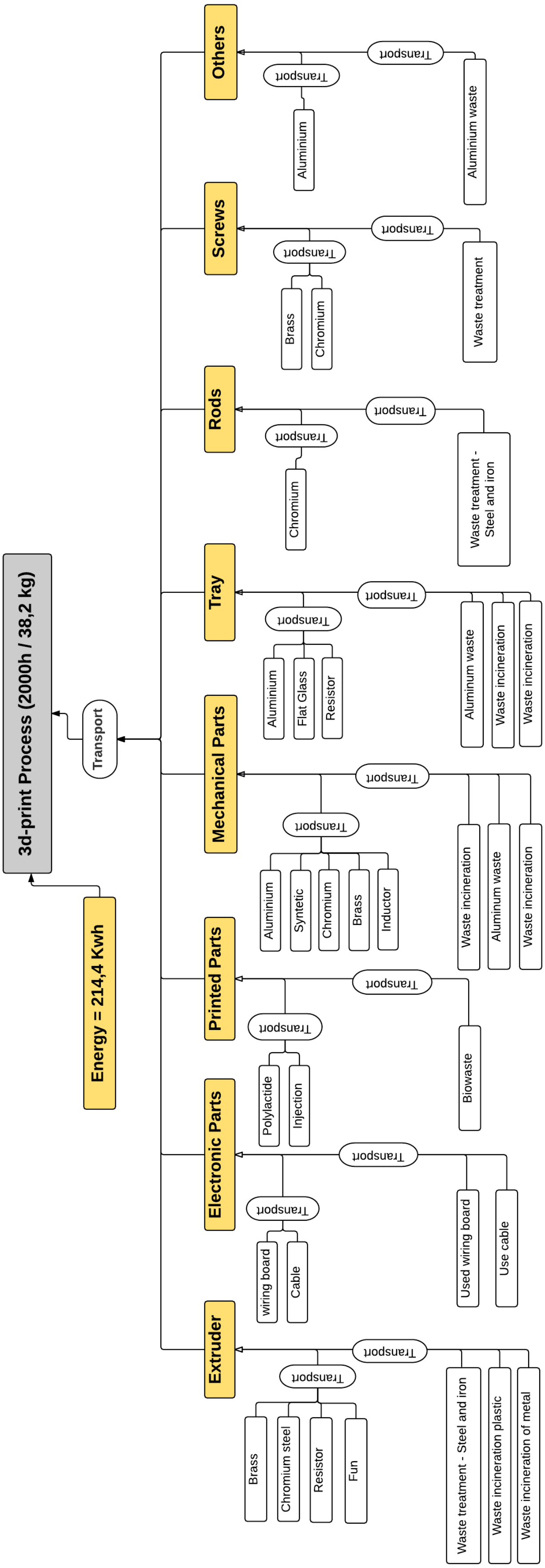


Figure 41 - LCA of a RepRap

Once the printing process was done and inserted into Simapro database, the whole life cycle of the printed mug consists of the Material (PLA Filament+Bobbin+transports), 3d-printing process (machine + energy consumption) and computer use (Design and Printing).

The Distribution phase does not exist given that the mug was printed on site, the Use phase is not considered, and the same hypothesis for the mug made in the industry is used for the End of Life. Figure 42 illustrates the life cycle of the printed mug and Table 6 show the life cycle inventory.

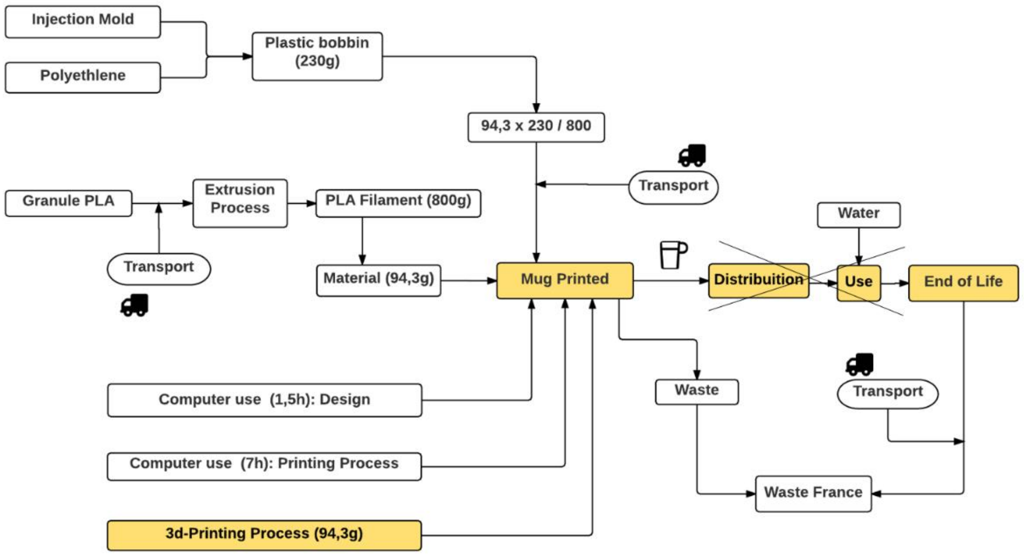


Figure 42 – Life cycle of a printed mug

Table 6 - Data used (LCI) for modelling the life cycle of a printed mug

	Item	Use	Quantity	Source
Material	PLA (Polylactide)	Printing Mug	94,3g	Primary Data
	PE Polyethylene	Manufacturing Bobbin	94,3g x 230g/800g	
	Transport 1	Transport PLA	Lorry - 930km	
	Transport 2	Transport Bobbin	Lorry - 700km	
Production	Extrusion Process (PLA)	Transform granule to filament	94,3g	Simapro Database
	Injection Process (PE)	Transform plastic to bobbin	94,3g x 230g/800g	Simapro Database
	3d Printing Process	LCA of 3d-printer (RepRap)	Lifespan: - 2000 h - 38,2 kg - 214,4 kw	Primary Data
	Computer Use	Design + Printing Process	8,5h	Primary Data
End of Life	Municipal waste France		94,3g	Simapro Database
	Transport		20km	

4.3.5 Impacts of the printed mug

Analysing the impacts delivered by the printed mug, it can be noted that, similarly to the industrial mug, "Respiratory Inorganics', 'Global Warming' and Non-renewable energy' are the most affected impact categories. (Fig. 43)

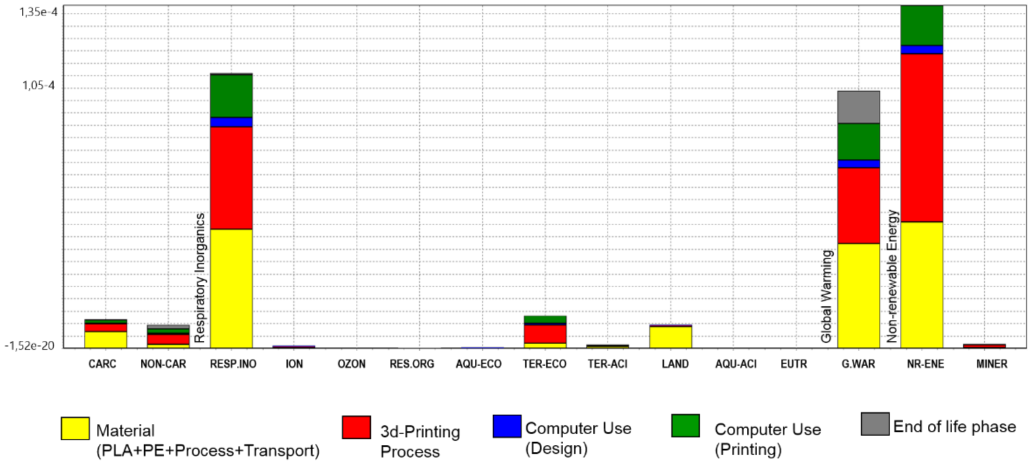


Figure 43 – life cycle of a printed mug – Impacts per phase

In these three categories, the Material (PLA + PE + Transport + Process) represents 40% of impacts, the 3d-printing process (machine manufacturing + energy consumption) is responsible for 38% of impacts. Computer use (Product Design + use during printing process) for 16% and the End of life phase represents 12%, concentrated in Global Warming category.

Regarding only the Production phase (3d-printing + computer use), it represents 54% of the impacts. These impacts are provoked by energy consumption directly linked with computer use time and printing duration.

4.3.6 Comparison (IM vs. PF)

Considering the product type, function and lifespan, the following Functional Unit is used to compare both systems:

→ Serving 200ml of cold drink, four times a day, during 12 months.

For this, 1 unit of each product is used as comparison base.

The graphic in figure 44 shows that, comparing the same three midpoint impact categories, the mug made in industry impacts more than the printed one in Global Warming and Non-renewable energy categories in about 55%. The category Respiratory Inorganic is not considered given that the gap is less than 10%.

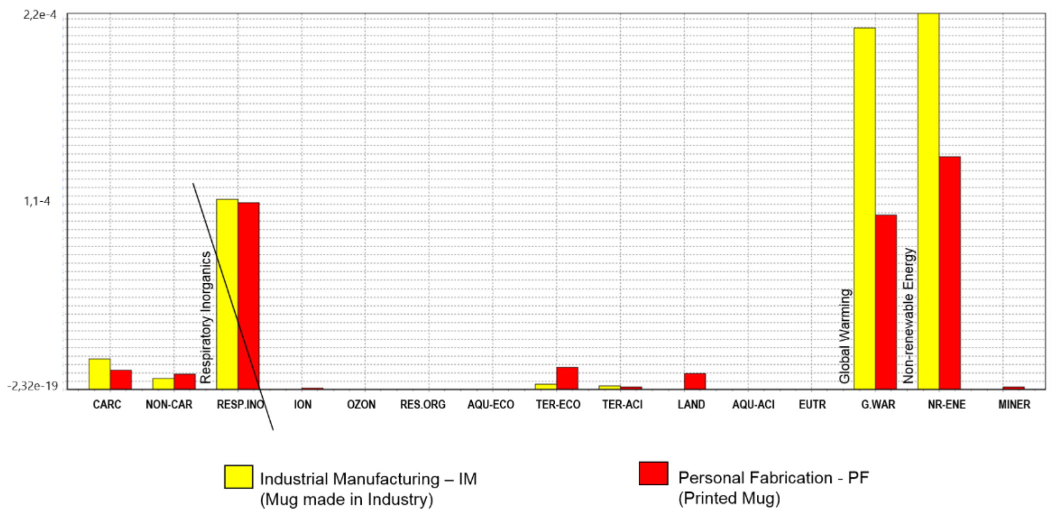


Figure 44 – Industrial mug vs. Printed Mug (normalization)

Merely looking at this comparison, we could conclude that a printed product using PLA can deliver 65% less environmental impacts than a mug made in the industry by the injection process. However, this conclusion would be certainly doubtful and incomplete.

When 13 impacts categories are analysed (Fig. 45), it can be noted that Personal Fabrication overcomes Industrial Manufacturing in 8 with a representative difference in 'Land Occupation', 'Eutrophisation' and 'Mineral Resources' categories. This could suggest that a printed mug generate bigger environmental impacts than one made in Industry.

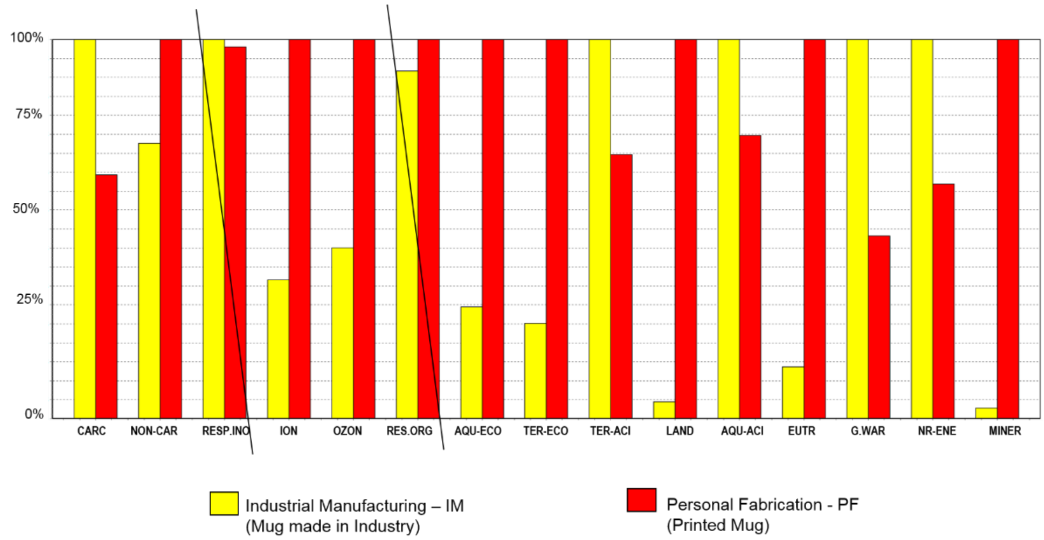


Figure 45 – Industrial mug vs. Printed mug (percentage)

These two different results for the same comparative study prove the fragility of this type of comparison and ratify the analysis presented in the literature review.

Actually, the results are extremely depending on the study hypothesis and scope defined. Additionally, this comparison, like others found in the literature, does not consider the differences of the two systems (function, objective, production volume, product design, etc.) and others aspects such us the user experience affecting the printing duration, for example.

This analysis validates the hypothesis 2 and 3 and brings up the necessity of further analysis in order to investigate the importance of the user's experience in the impact generation. In Personal Fabrication scenario, as already described, the user is more interested in experimenting and exploring. These characteristics must be taken into account.

4.3.7 Sensibility analysis (User's experience)

According to (Morel & Roux, 2016), the user, in the Personal Fabrication leaves his ancestral status of 'specimen-object' to try to constitute his quotidian life according to his own ways and desires.

The same authors say that taking into account that 'innovation' is a phenomenon strictly linked with the productive process, Personal Fabrication becomes a fertile ground for the development of a new user profile: the 'creator-inventor-innovator user'. A profile composed of persons interested in designing/manufacturing their objects by nonindustrial ways.

This statement is validated by the experiments conducted in this research. The first experiment (observation on site) shows that in FabLabs, the user experience is the key node of this type of manufacturing. Challenge and pleasure are the primary motivation for work and people are interested in trying, innovating and make true their ideas independently of the environmental costs. In this perspective, (Kohtala, 2016) confirms:

> *Fab Labs and maker spaces are contexts rife with paradox and complexity concerning the appropriate use of materials and energy. Little empirical research on material peer production currently exists, and the environmental impacts, and benefits, of digital fabrication, are largely unknown.*

The second experiment (comparative LCA) shows that comparing industrial and printing manufacturing is not enough to have an accurate conclusion about how impactful is PF related with industrial production and which are the main source of impacts. This simple comparison discards the user profile and considers only the technical aspects (product and printing process).

In order to verify and measure the impacts related to the user experience in Personal Fabrication, a sensibility analysis focused on Human Aspects seems indispensable. In this perspective, (Teulon, 2015, p. 264) states that, in some LCA results interpretation, a sensibility analysis can be necessary to verify the strength of the results and the possible variation and validation of new hypothesis.

Whereas this comparative analysis aims to identify how the user's experience affect the impacts, it will be observed the global variation on the 15 midpoint impacts categories. For this, three different hypothesis are considered and analysed:

I. Comparison between the life cycle of a mug made in the industry and that one made by a Beginner user (someone who is starting to use CAD and 3d printers).
II. Comparison between a beginner and an expert user in managing CAD software;
III. Comparison between a beginner and an expert user in managing 3d-printers machines.

The first hypothesis was the real situation. In this fabrication, the mug was designed by a Beginner user. 12h of CAD process, 22 h of Printing process were necessary, and 211,4 g of waste were generated because of errors and parameters adjustments. Figure 46 illustrates the amount of waste produced.

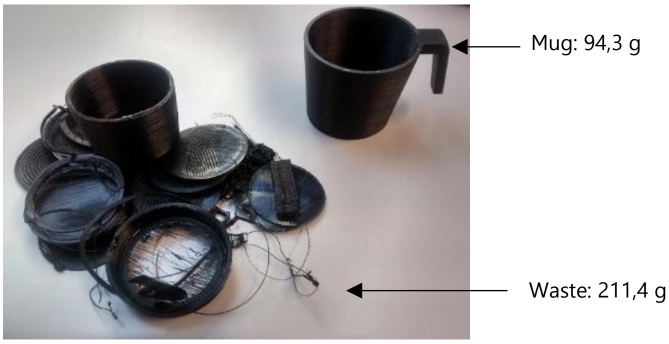


Figure 46 - Mug and waste (beginner user)

The first graphic in figure 47 shows that Personal Fabrication can be widely more harmful to the environment when managed by beginner users. PF overcomes IM in the 15 impacts categories, including Global Warm and Non-Renewable energy categories (a), an unexpected and surprising result.

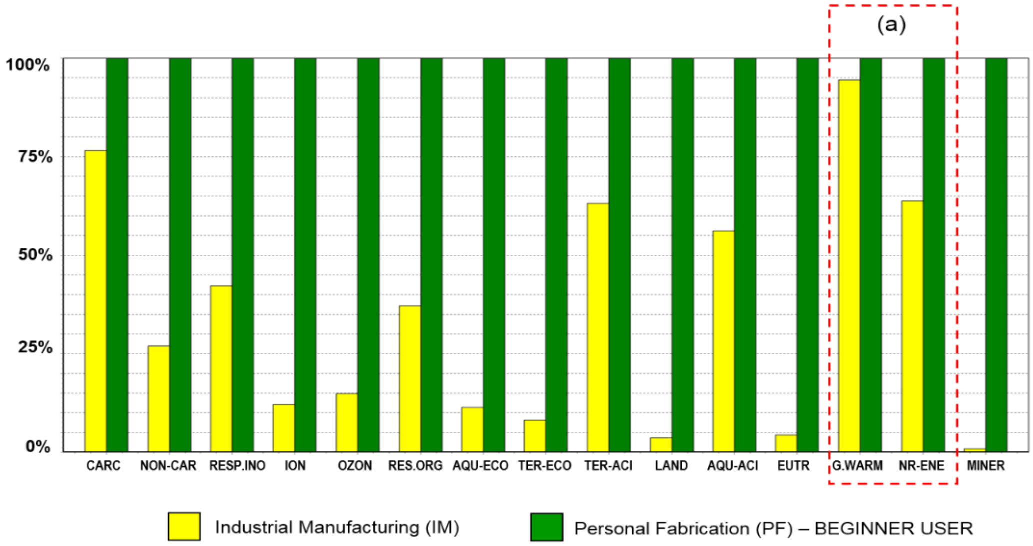


Figure 47 - IM vs. AM (Beginner user)

According to the IPCC (Intergovernmental Panel on Climate Change, 2013), the sectors of Industry and Energy will be the primary agents of the Global Warming over the next 50 to 100 years. Therefore, realising that Personal Fabrication, a small and individual manufacturing system, may overcome Industrial Manufacturing even in Global Warming and Non-renewable energy categories because of a non-expert use, reinforce the importance of considering the use/user profile in the environmental assessment of printed products.

To identify the importance of the computer use time regarding the whole environmental impacts, a second hypothesis was carried out considering two different CAD users level, one expert and one beginner.

The graphic in figure 48 shows that a CAD beginner user (12h of computer use to design a mug) generates about 21% more impacts than a CAD Expert user (1,5h of computer use). Also, for a beginner user, the CAD process represents about 18% of global impacts while for an expert user, this process represents about 3,5%.

In this second hypothesis, an unexpected result concerns the verification of how computer use time brings impacts to a printed product in PF scenario. In general, LCA of Additive manufacturing found in the literature are just focused on 3d-printers machines and their energy consumption. This result shows that the product design, as well as the user's CAD expertise level (affecting the computer use time), can make a real difference in the global impacts and must always be considered in any LCA.

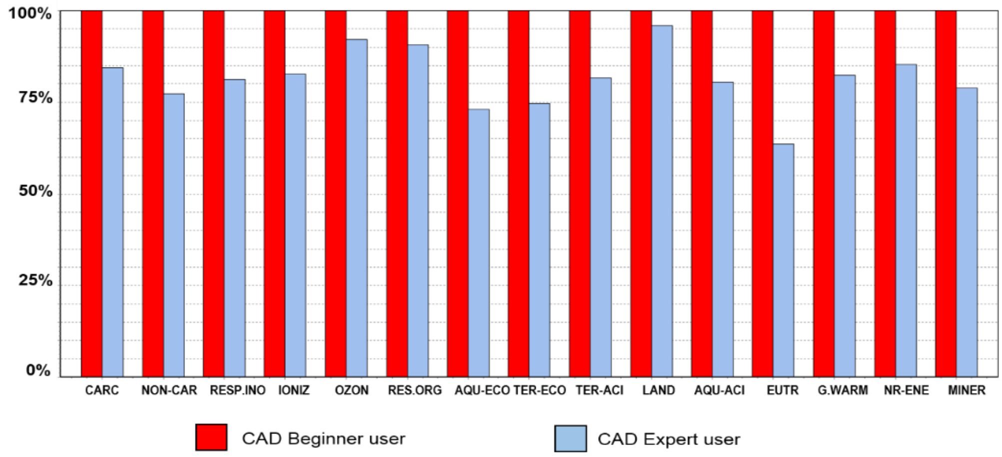


Figure 48 - CAD beginner vs. CAD expert

The last hypothesis of this sensibility analysis was performed to identify the importance of the printing duration regarding the whole environmental impacts. As demonstrated in figure 49, globally, in the 15 impacts categories, the printing beginner user (22h of printing, 211,4g of waste to print one mug) generates about 40% more impacts than a printing expert (7h of printing, 20g of waste).

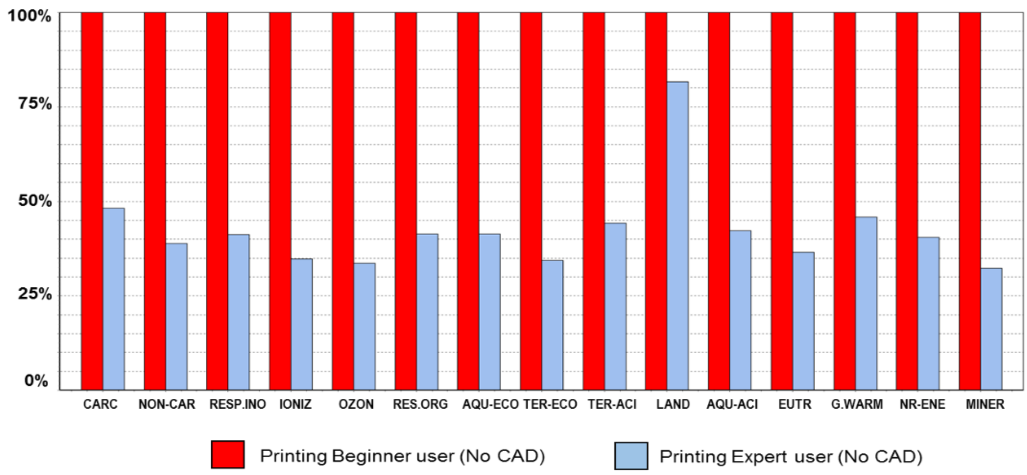


Figure 49 - Printing expertise analysis

This hypothesis showed a result considered predictable. However, it proved that, in Personal Fabrication, the way how people use the machine seems to be more important than the machine itself regarding environmental impacts. The use/user profile has a direct relation to the computer use time and the printing time and both, in turn, have a significant participation in the whole impacts.

Finally, this sensibility analysis yields to conclude that there is a direct relation between the user expertise evolution and the waste generation and energy spent during his activity. When the novice user becomes an expert, the environmental impacts of his activity is reduced, in both aspects, CAD and Printing as illustrated in in figure 50.

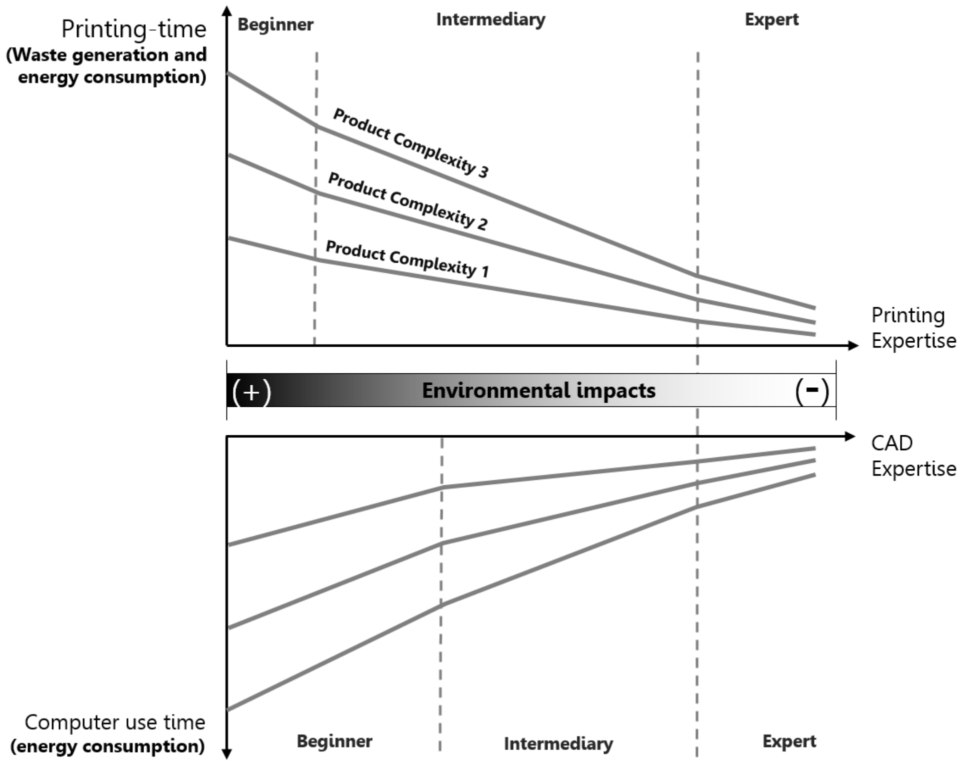


Figure 50 - Evolution (expertise level vs impact generation)

All studies conducted in this scenario yields to conclude that, in Personal Fabrication, the Human Aspects is more representative than the Technical aspects in terms of environmental impacts. Variations in CAD and Printing duration due to the user's level of expertise influence a lot the impacts.

Regarding the Technical aspects, in PF, the product printed using PLA (a biodegradable plastic) and the machine itself (RepRap in the majority of cases), does not represent a significant impact level when compared with other phases.

On the other hand, the level of experience in CAD (software managing; the number of attempts and the time spent to design a part) and the level of expertise in the printing process (3d-printer managing; printing duration and the number of attempts) directly affects the energy consumption and material waste. (Fig. 51).

In summary, the way how people use the machine and how they conduct the printing process is the crux of the matter regarding impacts generation in Personal Fabrication.

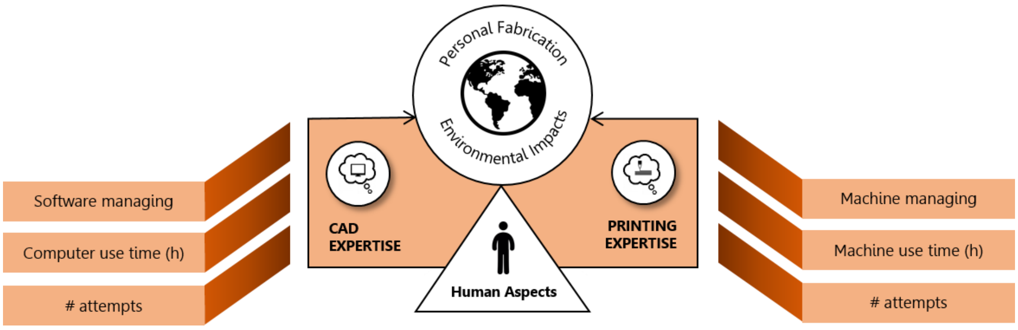


Figure 51 - Impact contributors in PF

4.4 Conclusions

Observations and interaction with Personal Fabrication users in maker spaces (FabLabs and other laboratories) showed that the majority of makers and hackers gathered in these spaces are more interested in making experiments, sharing information and exploring.

Regarding the environmental issues, it was noted that none maker spaces have a clear politic of impact reduction. Energy consumption and waste generations, for instance, are not mentioned for any user. Regarding 3d-printers, the waste generated (plastic) could be recyclable, however, in these spaces no activity is developed in that direction.

The LCA conducted in this scenario validated the hypothesis 2 and 3 of this research. It revealed that the comparison made between Personal Fabrication and Industrial Manufacturing without considering the systems differences (function, objective, production volume, product design, etc.) does not provide significant results to make an accurate conclusion about the environmental impacts related to AM (Personal Fabrication scenario).

Deeper analysis focused on the user's experience proved that the Human Aspects (level of expertise in CAD and Printing) can be very representative in terms of impacts generation. In Personal Fabrication, the way how people use the machine seems to be more important than the machine itself. (Barros & Zwolinski, 2016)

So, this study brings to light the necessity of novices users to be assisted by experts users in their activities in FabLabs, institutions, etc.. This, in turn, enhances the social character of 3d-printing technology and makerspaces.

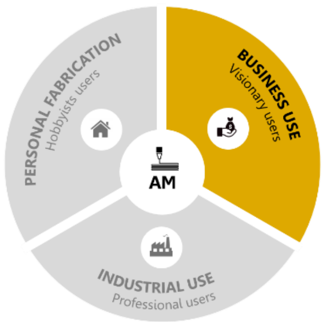
Next chapter describes the experiments conducted in the scenario 'Business use'.

5 Scenario 2: Business Use

This chapter describes the experiment carried out to identify how environmental issues are addressed by 3d-printing technology on the AM domain entitled 'Business Use'. The scenario was supported by a case study realized in an enterprise that uses 3d-printing technology to print orthopedic insoles. The life cycle of the printed product was compared with the one based on a classic manufacturing, both in the same scale production (tailored fabrication). The name/location of the company will be hidden as a matter of confidentiality.

5.1 Characterization

(...) a new generation of designers and manufacturing entrepreneurs should be created; to do this, the first step would be to change school curriculum and introduce design classes where students would learn to use 3D-CAD tools and 3D Printers naturally, as they learn about power-point in their computers class (Anderson, 2012)



Seeing a new product being made in few hours or minutes exactly as it was designed may be a dream to many entrepreneurs, designers, engineers or makers. Nowadays, a view of an industrial manufacturing as an enormous building with big machines, many people working and a large production can be replaced for another manufacturing environment, smaller, collaborative, with few or just one machine (3d-printer). This is the 'Business use' of 3d-printing technology.

In this type of use, the users go beyond a simple activity for fun; they are interested in making business and getting money with their 3d production. Anderson (2012, p. 55), in his book *'Makers, the new industrial revolution'* supports that 'it is time to return making things and get your hands dirty again'.

According to the author:

The use of Additive Manufacturing is currently a market trend and an opportunity for many entrepreneurs. First investigations about this use showed that there are numerous ways to launch out into this business and the first one is becoming a '3d-hub'.

'Hub' is a term used to denominate someone who has a 3d printer and provide a print service from his house. The system is simple: the consumer uploads his 3d design, chooses a print location (Hub house) near from his house using a 'hub location map' (figure 52) and then picks his product up. Besides a print service, this network has created a new marketing model of local economy and is spread around the world.

Figure 52 - 3d-hubs map location
Source: 3dhubs.com

A second way to use AM as a Business comes from the association of advances in 3d-printing technologies and internet facilities. It emerges to attend a new 'makers consumption demand' who want to print their creations without needing to have a 3d-printer at home. This market niche has pushed many enterprises to offer 3d-print service on-line, even because 3D printers technologies have created a new generation of DIY[5] manufacturers who are using 3D printing services online to create custom products that address unmet needs (Koff & Gustafson, 2012).

[5] DIY = 'Do It Yourself' is the method of building, modifying, or repairing things without the direct aid of experts or professionals. (Wikipedia, 2017)

3d-printing service companies can offer a 'Design service', a 'Manufacturing service' or both. This means that users may afford to download a new design on the website and then print it at home or in a Fab Lab; they may pay just for manufacturing a product designed at home or pay for both, design and manufacturing. This scenario reflects the statement of (Koff & Gustafson, 2012) when they say that

> *(...) a secondary promise of 3-D printing lies in the separation of product design from product manufacturing. As 3-D printing evolves, consumers will be able to purchase designs online and then build products at home.*

Some 3d-printing service companies can be found on the internet today. In general, they have a similar way of work and the client needs are the priority of their service. According to (Moilanen & Vadén, 2012) the firm Shapeways is the most used by makers, following by Ponoko and i.Materilase. These three companies lead the market; nevertheless, others are in constant growth such as 3D Creation Lab, 3dprintuk, 3DProParts, Cubify Cloud Print, Impression-3D, Kraftwurx.com, Sculpteo, Solid Concepts, Fabbaloo and Kazzata.

Figure 53 presents the Shapeways service process, an intuitive and simple model where users are autonomous to make their choices without a person to support. In 8 steps any customer can get his product printed at home.

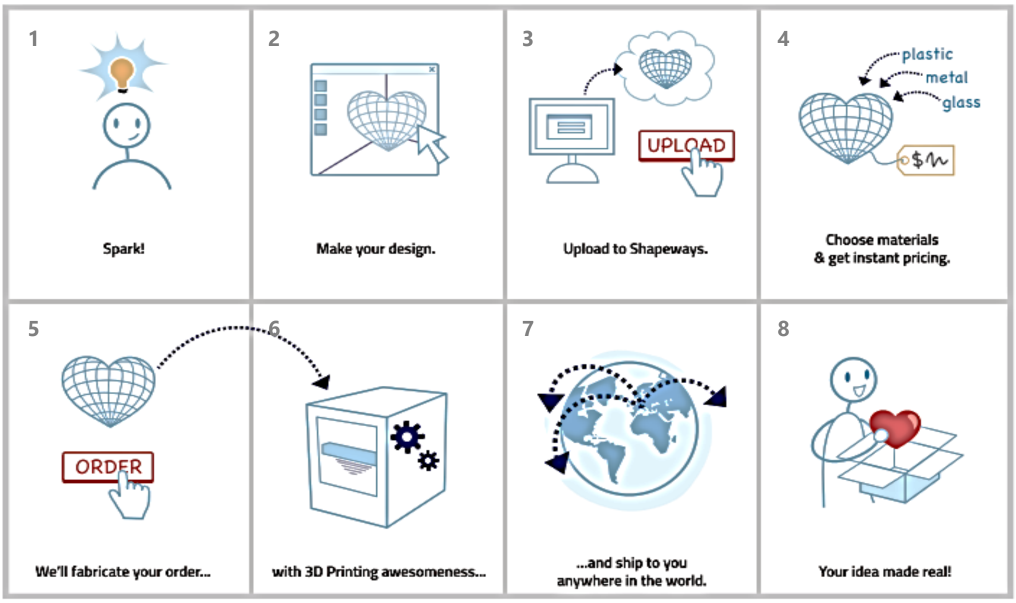


Figure 53 - Shapeways service system
Source: shapeways.com

In order to experiment this type of service, a simulation was done in the Scupteo website. Figure 54 shows that printing a mug in red plastic with the deliverance in Grenoble-FR, would cost € 95.57 (delivery costs included). This price is obviously overestimated in comparison with an industrial product, but this seems to be the 'price of personalization'. Investigating the reasons of this cost should be certainly an interesting task, but it is out of the scope of this research.

Figure 54 - Simulation of Mug printing on the Scupteo website

To design a custom product many software are available nowadays to professional or amateur user such as Catia, SolidWorks, Creo, 3DTin, SketchUp, Blender. Additionally, there are the 123D Catch and 123D Make, new tools unveiled by Autodesk in 2011 that are intended to give to almost any user the ability to create digital 3D models and schematics. This tool allows people to create 3D models with a few swipes on their iPad or by uploading photos of an object from multiple angles (Terdiman, 2011; Koff & Gustafson, 2012).

Finally, another particular way to use AM as Business concerns companies (start-ups in the majority of cases) that were created to manufacture and deliver a final printed product adapted and personalised to customer needs/desire. In general, these companies have been using 3d-printing technology for innovating and creating a new design of products sometimes already made by others companies using traditional methods.

An example of this trade is the American start-up "Protos". This company is specialised in printing glasses designed using an advanced software which allows to select and alter the shape of each pair of glasses to fit the unique client features. It uses hypoallergenic plastics with innovative designs that are impossible to replicate with traditional manufacturing methods. (Figure 55).

Figure 55 - Printed Glasses by Protos
Source: protoseyewear.com

Using 3d-printing technology to offer a service or a final product can be a new business opportunity and this, in turn, will provoke professional and social changes. The following characteristics related to the use of AM as new Business, have been identified:

- Focused on innovation and creating a new market;
- Designer and manufacturer sometimes are the same, but the client is different;
- Do not follow open design rules;
- Time and profit are constraints.
- Main users: designers, engineers, architects and entrepreneurs in general, with a high level of expertise in CAD and Printing.
- Machines are bigger and more efficient.

5.2 Comparative LCA: Orthotic Insoles

This experiment was conducted in an enterprise that prints orthotic insoles in small/custom scale. The goal, just as the first scenario is to identify where the AM environmental impacts come from in this type of use. This will be possible comparing two different life cycles of two similar insoles: one made by a classic manufacturing (handmade) and the other one made by 3d-printing technology.

The particularity of this comparison is that both systems (Classic and Printed) have the same scale production (tailored product), same function, objectives and target audience. This gives more reliability and coherence for the study.

<u>5.2.1 Materials and Methods</u>

The company studied in this scenario was identified in a report released on a specialised website in Additive Manufacturing. The first contact was made by email followed by a visit on site. During the first visit, the study objectives, as well as the confidentiality issues, were clarified.

The partnership was confirmed mainly because the company wanted to know about its environmental impacts and how to use the results to define its position in light with the concurrence.

Data were collected by means of meetings and personal interviews carried out from February to July 2016 with the company manager and the chiropodist responsible for validating the insoles. Additionally, internet searches completed the information.

The method of assessment employed was Life Cycle Assessment (LCA) by using the software SIMAPRO 8 and the method of impact's calculation IMPACT 2002+. The database prioritised was Eco invent 3.

Also, this study yielded a master internship for an Industrial Engineering student who was engaged in it during the whole period of investigation together with this PhD researcher. The results were presented by the student as his final work and assessed successfully for the jury.

5.2.2 Orthotic Insole

An orthotic insole is a moulded piece of rubber, plastic, or other material to be inserted into the shoe (Fig. 56). A wide range of orthotics insoles is available for different foot problems. They have been advocated and successfully used for many years for patients with diabetes, adjustment of flat feet, compensation for osteoarthritic knees and treatment or prevention of rheumatoid foot disease. (William H. Blahd, 2014).

Figure 56 - Orthotic Insole
Source: Internet

5.2.3 Life cycle of a Classic orthotic insole (Handmade)

A 'classic orthotic insole' is made by using different machines, materials, hand tools and manual activities. These insoles are made by the Chiropodist using a multi-layer system (layers of material overlapped on each other) completely adapted to client's need. Different densities in the same insole are reached using small layers of specifics materials added on it according to the patient feet necessity.

The life cycle of a classic orthotic insole considers five main phases: Materials, Production, Distribution, Usage and End of Life.

Regarding *Material*, it consists of an Ethylene-vinyl acetate (EVA) cover, three layers of EVA foam with different densities (made in Indonesia), Resin polyester and Neoprene glue (made in France).

Regarding the *Production* phase, different machines are used to manufacture the insole. Figure 57 illustrates the manufacturing process and Table 7 shows the details of each machine with power and energy necessary to manufacture one insole.

Figure 57 - Classic Insole manufacturing
Source: Internet

Table 7 - Machines and energy consumption for a pair of insoles

Machine	Function(s)	Power (W)	Usage for a pair of insole (Minutes)	Energy used for one insole (Wh)
Grinding machine	Mill & shape	600	30	150
Vacuum machine	Eliminate foam's dirt	2800	30	700
Fume hood	Eliminate Neoprene vapour	160	40	54
Oven	Soften the foams	1000	40	334
Chamber Vacuum Sealer	Imprint the foams, give shape	250	5	12
Total Energy Used				**1.250**

In the *Production* phase the following hypothesis were considered:

- Only the total energy used is considered in the life cycle model. In consequence, there is no impact of machines manufacturing in this LCA.
- The average time of production for a pair of classic orthotic insole is 40 minutes (30' with machines and 10' manually)

- Fume hood and Oven machines keep turned on during the whole production time from 8am to 6pm (10 h/day). It was considered that each pair of insole uses each machine 40 minutes during the production phase.

The hypothesis assumed regarding the *Distribution* phase (fig. 58) considers that the product is delivered without package and the patient drives about 30km to get it, being three round trip of 10km each one:

1st. - Patient consults a Chiropodist

2nd. - Patient collect the insole

3rd. - Patient go back to verifying the insole after test/use

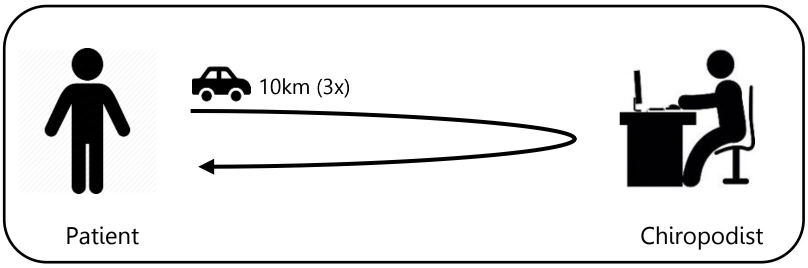


Figure 58 - Distribution phase

This Distribution hypothesis it supposed to be the worst case. In all probability, the client will use the car for others activities in the same round trip. Doing this, the impacts on the insole are minimised.

Concerning *Usage and End of Life* phases, the hypothesis considers that the patient uses the classic orthotic insole in his everyday life, precisely to go to work (5days/week-8h/day) and there is no use of water to clean it. At the end of the usage, the user simply throws the insole into a normal dustbin. The distance between the patient's place to the disposal area was considered 20km. It was verified that there is not an evident system of EVA recycling in France.

Figure 59 illustrates the whole life cycle modelled for this study with details of phases, values and sort of transport.

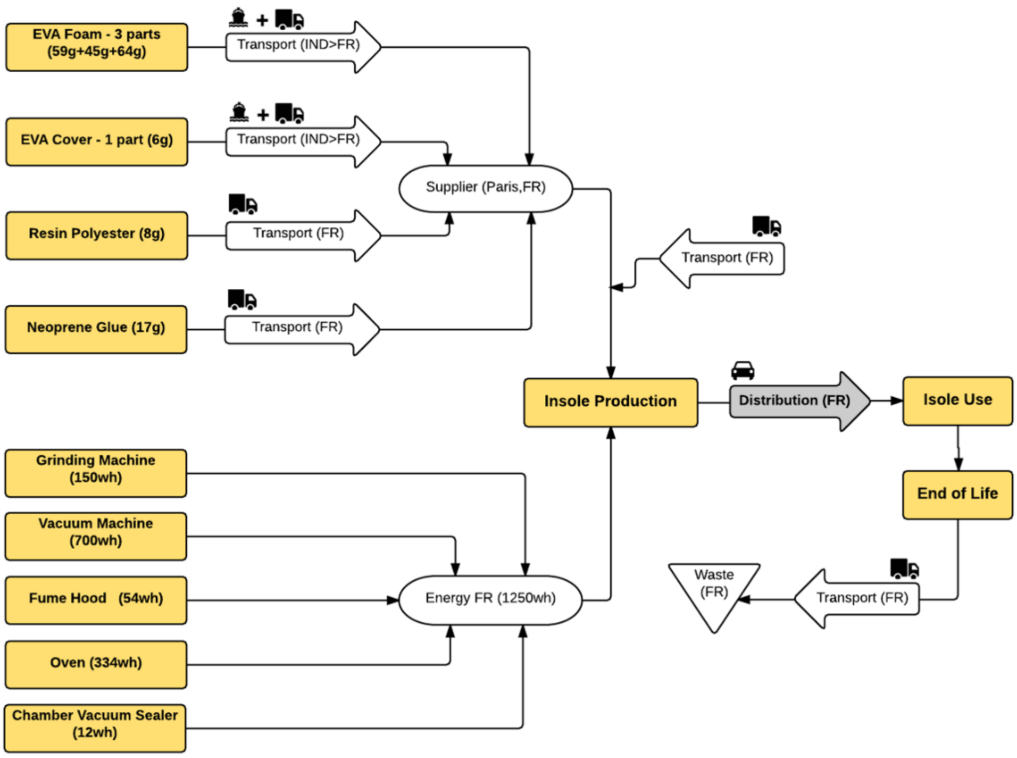


Figure 59 - Classic Insole life cycle

5.2.4 Impacts of the classic insole

The bar chart in figure 60 shows that the impact of Production, Distribution and End of life phases are most concentrated in four midpoints impacts categories: (Carcinogens, Respiratory Inorganics, Global Warming and Non-renewable energy).

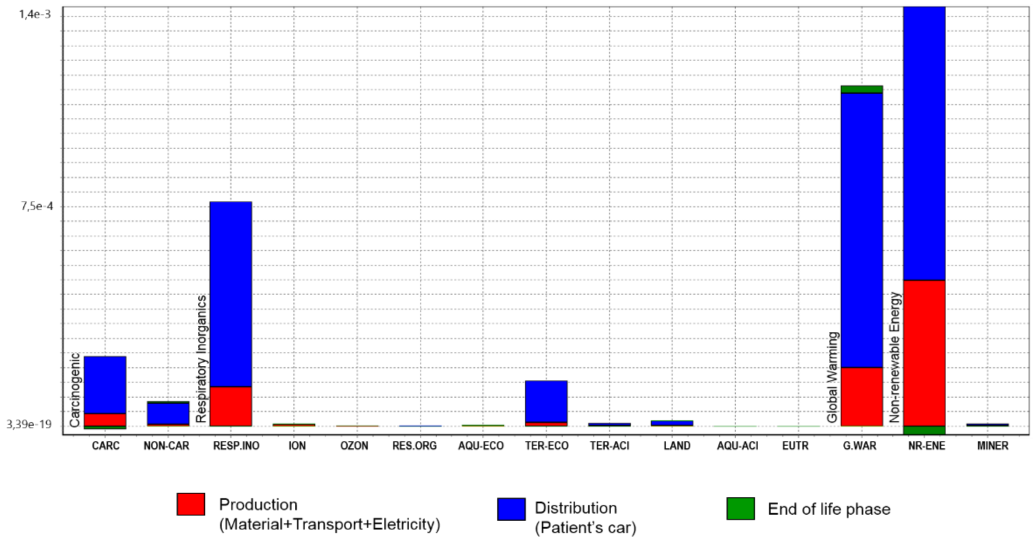


Figure 60 - Impact study - Classic Insole's life cycle

As it may be seen, the *Distribution phase* impacts the most (average 77%) followed by the *Production phase (average* 21%). There is a small impact (both positive and negative[6]) related to *End of Life* phase, which becomes no significant in relation to other phases.

Regarding the *Distribution* phase, it was observed that patient's car is the major cause of impacts. Car use gives an enormous impact on the environment especially because the patient travels about 30km specifically to get only an insole. In consequence, the total of emissions and impacts during the usage is dedicated to the distribution. As clarified previously, this is the worst hypothesis.

Observing the *Production* phase in details (regarding the four main midpoint categories), it can be observed that the Material responds for the most of the impacts (61,5%) and the Electrify used in France represents 18%. (Fig. 61)

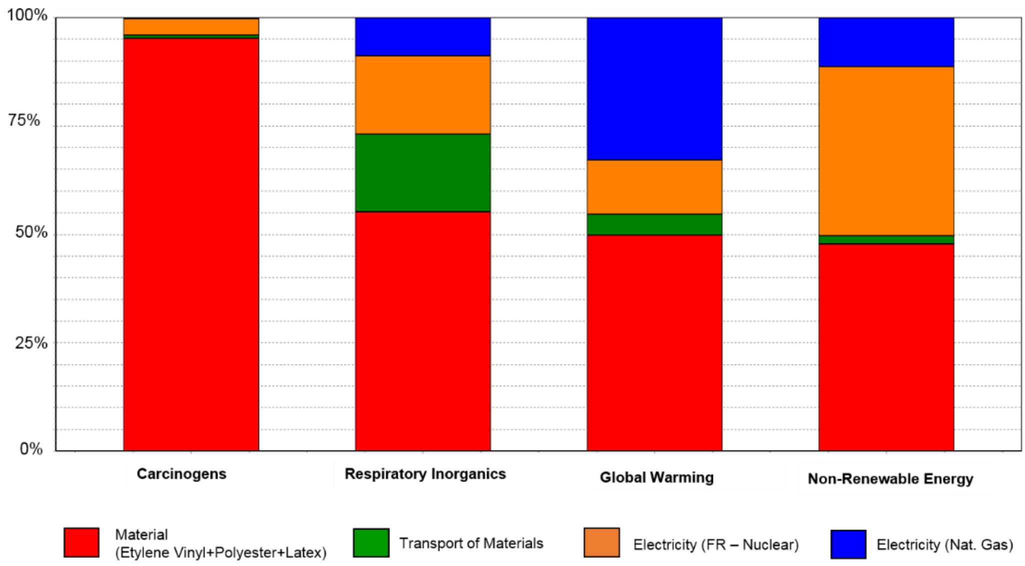


Figure 61 - Impacts in Production phase

5.2.5 Life cycle of a 3d-Printed orthotic insole

The manufacturing process of a printed insole is composed of three stages as demonstrated in figure 62: 1) Feet are scanned by the Chiropodist using a 3d-scanner and a specific software; 2) The Chiropodist design the insole using a specific software; and 3) The Company prints the insole using a specific plastic (confidential information).

[6] Positive impact (positive percentage) = Bad impact to the environment
Negative Impact (negative percentage) = Good impact for the environment

In some cases, the finishing process is made putting a thin cover of EVA on the top of the insole.

The type of plastic used to print (more resistant than EVA) gives to the 3d printing insole a bigger lifespan if compared to others similar products. Additionally, this plastic allows printing variable densities (Figure 63) in the same insole using a unique material. These are the different main elements of printed insoles compared to classic ones.

Regarding CAD process, the chiropodist designs the insole using a simplified software which does not demand a high level of expertise. The professional only chooses the insole shape, the density type and zone and then, the software calculates the best way to print.

Figure 64 illustrates the whole life cycle of a 3d-printed insole designed for this study.

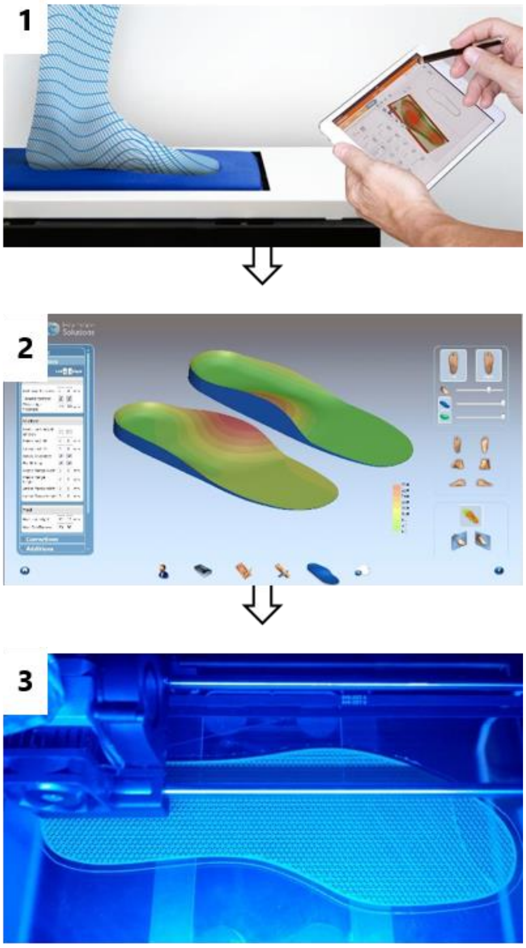


Figure 62 (1,2,3) – Printed insole manufacturing process


Figure 63 - Insole density

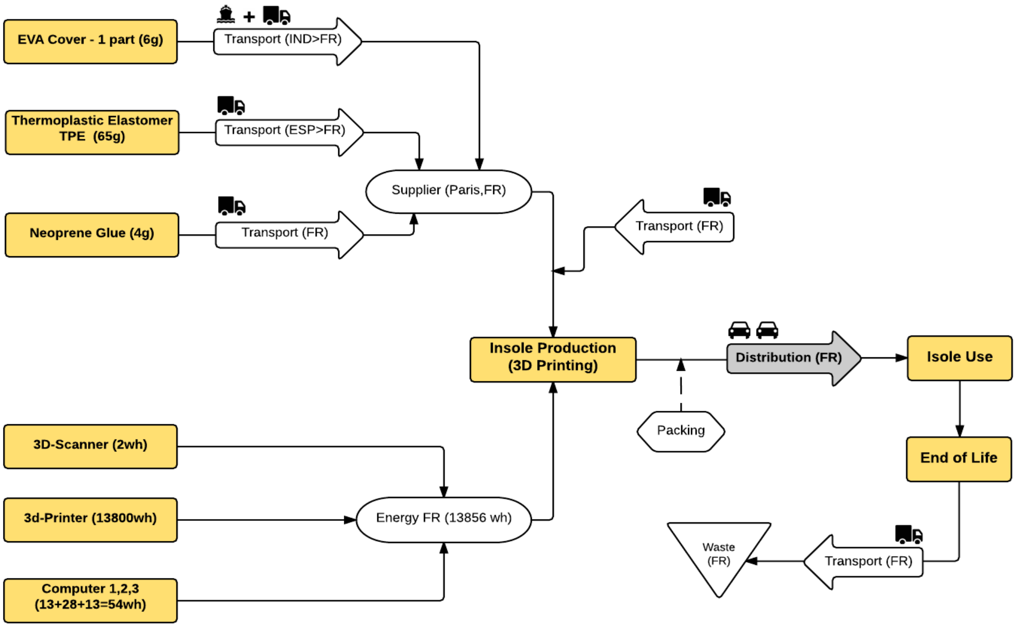


Figure 64 – Life cycle of a printed insole

The following hypothesis were considered in this life cycle:

1. The material (plastic) is fabricated in Barcelona-Spain. It is not found in the Simapro database, so, synthetic rubber replaced it. Synthetic rubber is also used to make insoles, and this will not affect the final results. A sensitivity analysis proved that both materials deliver a similar type of impacts.
2. EVA cover is fabricated in Jakarta (Indonesia) and transported to Paris via Le Havre Port, France.
3. Neoprene glue is fabricated at 10km from Paris and was replaced by latex glues in the Simapro Database without major changes in terms of impacts.

Regarding the production phase, Table 8 illustrates the machines and power consumption for each process.

Table 8 - Machines and energy used to print an insole

Machine	Use	Power (w)	Usage for 1 insole (min)	Energy for 1 insole (wh)
Computer	1. Acquisition of patient's foot data	150	11.5'	13
	2. Designing insole	150	5'	28
	3. Printing insole	150	5'	13
3d-scanner	Acquisition of patient's foot data	20	5'	2
3d-printer	Printing insole	2300	360'	13800
			Total energy used	**13.856 wh**

Concerning *Distribution* phase, figure 65 illustrates the hypothesis established for this study. Similarly to the classic insole, it was considered the worst situation:

1. Patients goes three times to Chiropodist clinic (similar to classic manufacturing)
2. Chiropodist sends the file (insole design) to the 3d-printing company by internet;
3. The insole is transported from 3D-Printing Company to the Chiropodist's place (5km) using company's car with a frequency of once per day and 60 units of insoles delivered.
4. 3d-printing company uses a paper package to transport insoles;

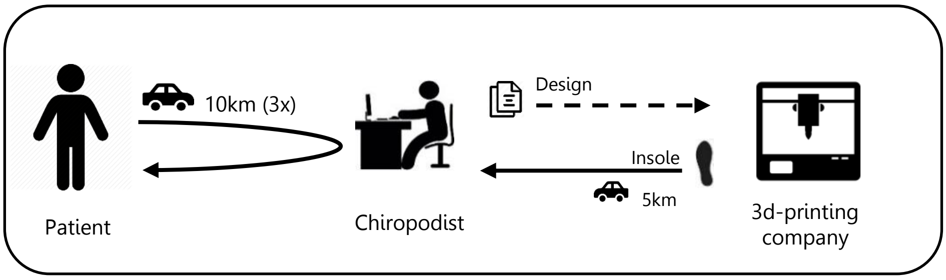


Figure 65 - Distribution of a printed insole

Usage and *End of Life* phases are exactly similar to the classic orthotic insole.

5.2.6 Impacts of the 3d-printed insole

The graphic figure 66 shows that, in average, regarding the three more representatives midpoint impacts categories, the *Distribution* phase impacts the most (56%) followed by *Production* phase (42%). *End of life* phase releases a small impact in climate change category (2%).

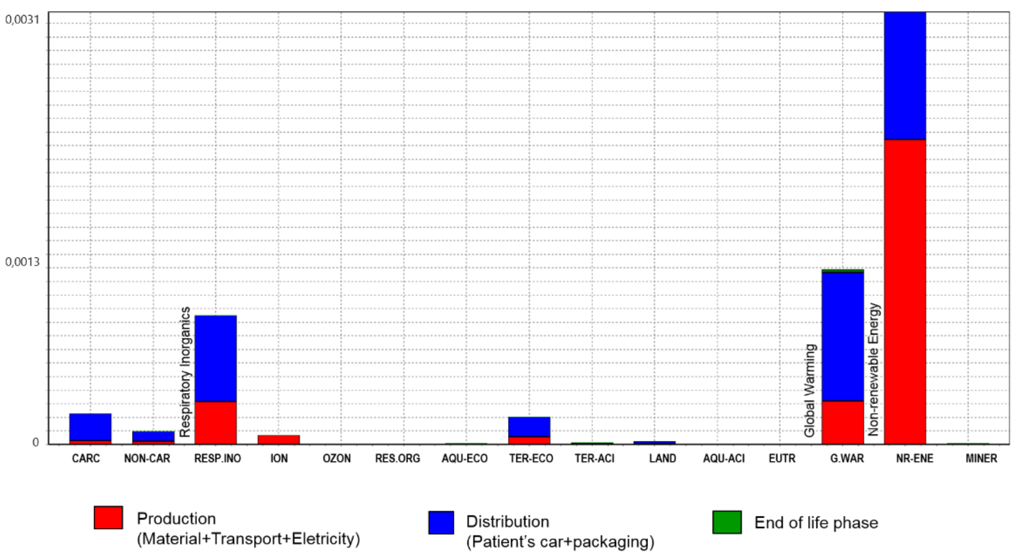


Figure 66 - Impacts per pahse of 3d-printed insole (Normalization)

Concerning *Distribution* phase, the main cause of impacts is related to the car used by the patient and 3d-printing company, similarly to the classic insole. These results can be very different if the patient uses the car for other activities in the same round trip.

When the *Production* phase is observed by percentage in the three main midpoint impacts categories, in average, Electricity represents 88% of impacts and Material 10% (Fig. 67).

This high impact of energy consumption comes from the 3d-printer machine which uses approximatively 13.800 Wh of electricity to produce just one insole. Other machines such as 3d-scanner and computers consume very small amount of energy, and it may consider it as negligible.

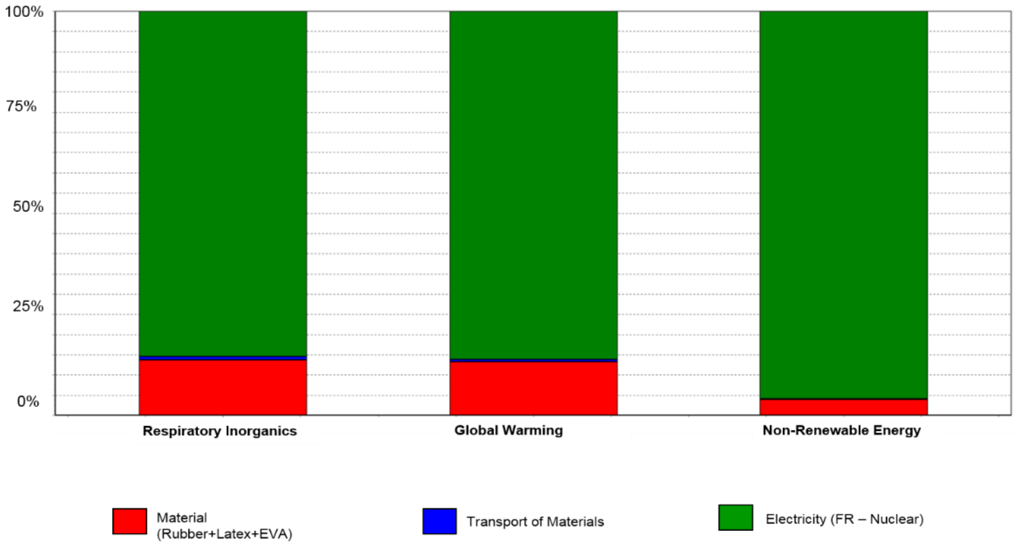


Figure 67 - Production Phase of a printed insole

5.2.7 Life cycle comparison (Classic Insole vs. 3d-Printed Insole)

The differences between both manufacturing processes make the finished products also slightly different. The main differences lie in the type of material, some physical features and the lifespan. However, both products comply the same function: providing comfort and correction to the patient's foot needs. Furthermore, both insoles are made on the same scale production level, i.e. a tailored product.

All of these characteristics make this comparison feasible and reasonable. To carry out the study, the following Functional Unit (FU) was defined:

→ Provide an 'efficient aid'[7] to patient's foot health needs for 218 working days (8hours/day) of usage during 12 months.'

Because of the type of plastic used to print (more resistant), the lifespan of a 3D-Printed Orthotic Insole is in average four months bigger than for a classic one, what means, 12 months for a 3d-printed and 8 months for the other one. Regarding this fact, to fulfil the requirement of the FU, 1 unit of 3D Printed Orthotic Insole is needed whereas 1.5 units are needed for a classic one. (Fig. 68).

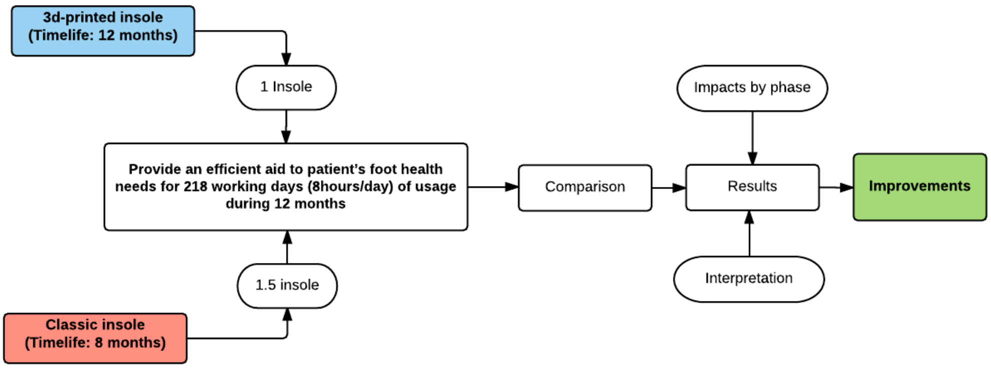


Figure 68 – Comparison structure

The first bar chart presented in figure 69 shows the comparison of both entire life cycle (Material, Production, Distribution, Usage and End of Life). Regarding the three most important midpoint categories, 3d-printed insole generates fewer impacts in Respiratory Inorganic (-18%) and Global Warming (-27%) categories but overcomes the classic insole in 34% in the Non-renewable energy category.

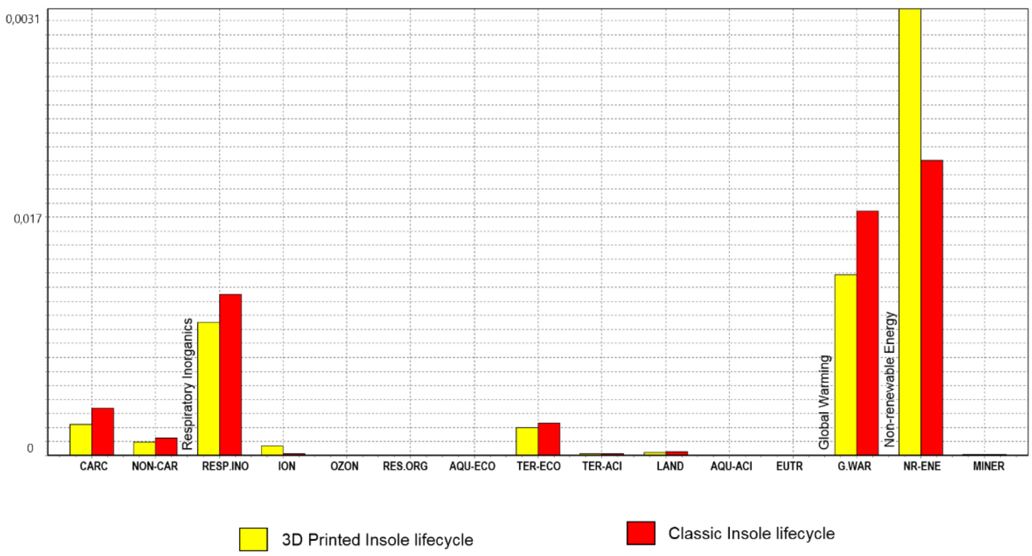
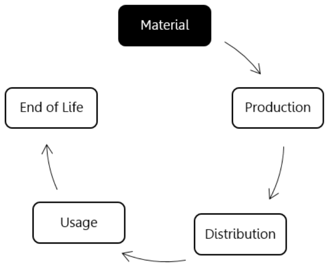


Figure 69 - Comparison (1 printed insole vs. 1, 5 classic insole)

7 Efficient aid means the insole be able to provide the same properties during the entire period of usage.

When each phase is analysed separately, the following results are observed:



Concerning *Material* phase, the impacts from the 3d-printed insole are considerably less than from a classic insole. Nearly 68% in the three impacts categories. (Fig. 70).

This is an expected result given the fact that the production of a 3d-printed insole consumes fewer types and quantities of materials. Furthermore, in this comparison, to satisfy the FU, 1 unit of 3d-printed insole was compared to 1.5 unit of a classic one.

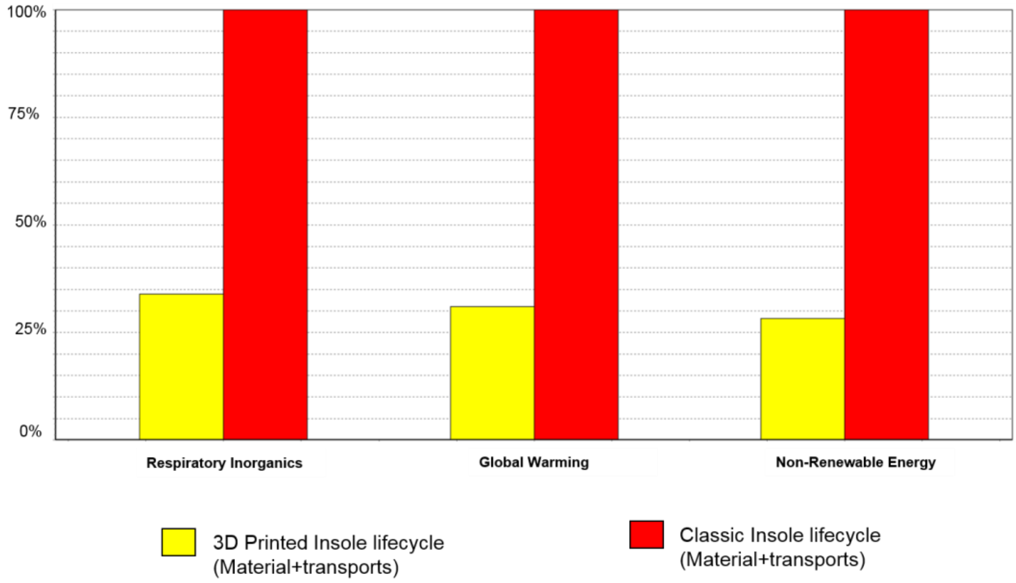
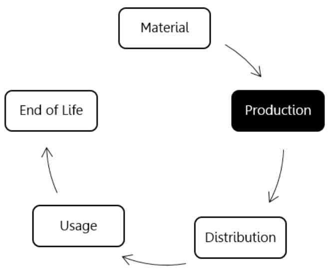


Figure 70 - Comparison (Material phase)

In the *Production* phase (material + transportation + energy), of a 3D-Printed orthotic insole, the impacts on the environment are higher in two impacts categories: Respiratory Inorganic (+35%), and Non-renewable Energy (+65%). In the Global Warming, the difference is less than 10%, therefore, not considered. (Fig.71)



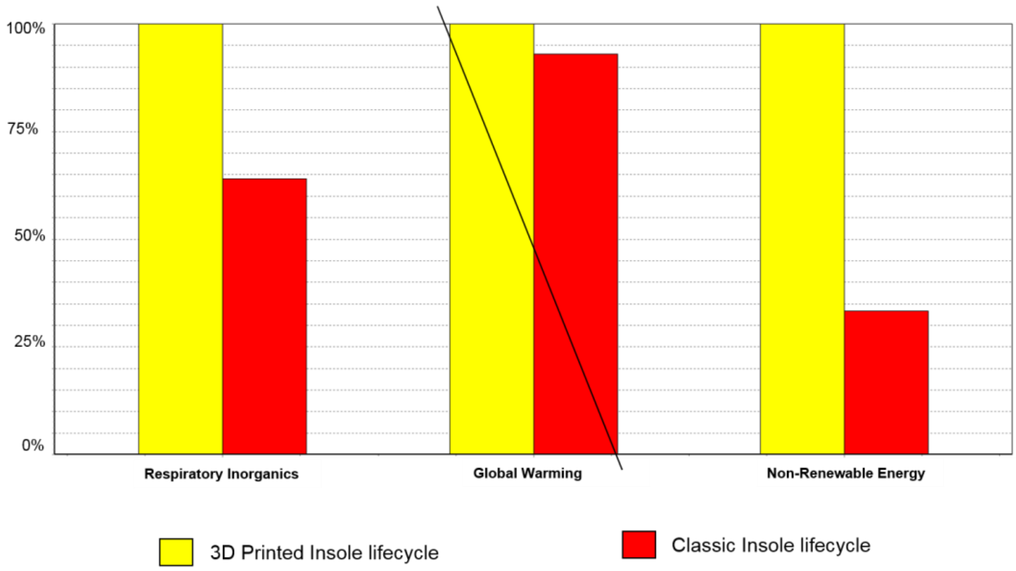


Figure 71 - Comparison (Production phase)

To further delve into this analysis, figure 72 shows that in the 15 impacts categories, the *Production* phase of the 3d-printing insole overcomes the Classic manufacturing in 10. Those results, as already seen previously, comes from the electricity used during the 3d-printing process.

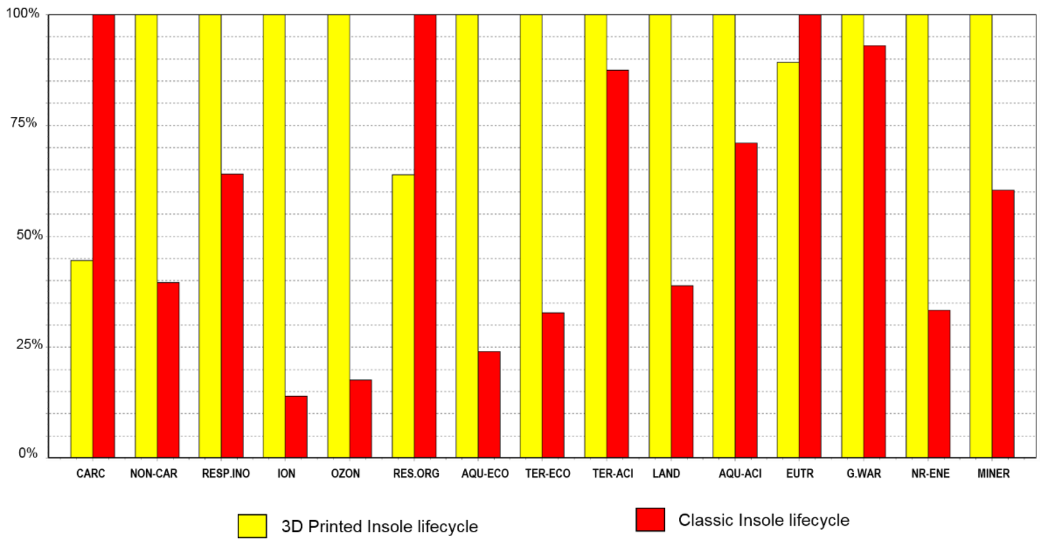
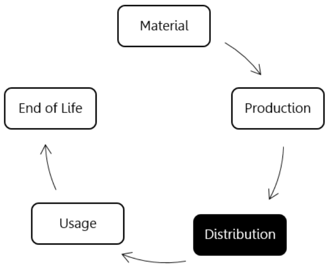


Figure 72 - Comparison (Production phase - 15 impacts categories)

For the *Distribution* phase, 3D-printed insole impacts less (-35%) on the three categories (figure 73). These results come from the comparison base (1 vs. 1.5) affected by the bigger lifespan of a printed insole.



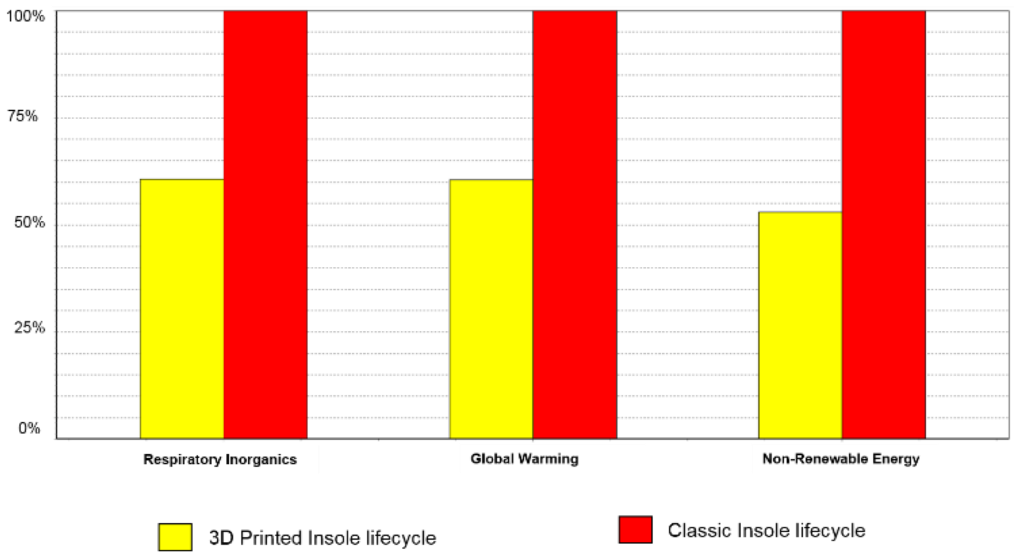
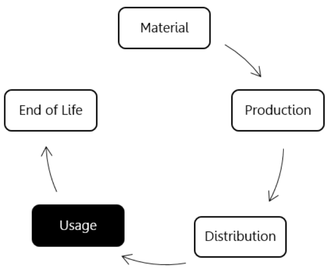
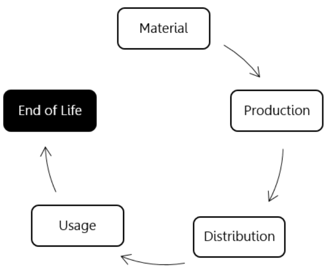


Figure 73 - Comparison Distribution phase

Concerning *Usage* phase, given the fact that there is no water/soap consumption to clean the insole during the use and the fact that 3d-printed insole has a bigger lifespan, in this phase, it can be deducted that a 3d-printing insole is less impactful even if the impacts were not measured.



Regarding *End of Life* phase and considering a current scenario in France, it is not possible to affirm which manufacturing system is more or less impactful. Most likely both insoles will have the same destination after usage, a common incineration.



In the literature, it can be found that EVA and TPE materials can be recycled/reprocessed/reused by different methods for different purposes. However, there is not information about this operation in France.

All these findings show that, the 3d-printed insole impacts less than a Classic insole 3 phases. However, this not represent that it is globally better regarding the environmental impacts. The impacts in the Production phase can be bigger than the other three together. (Fig. 74)

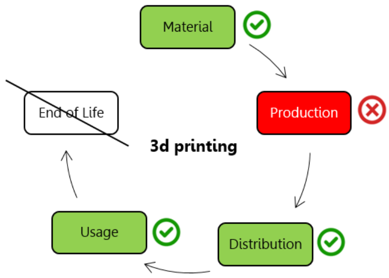


Figure 74 - Comparison of impacts

These results are strictly linked to the Functional Unit established to compare (1 printed insole vs. 1,5 classic insole). When we compare 1 classic insole vs. 1 printed insole, the results are very different. The 3d-printed insole delivers higher impacts in all 15 impacts categories as illustrates in figure 75.

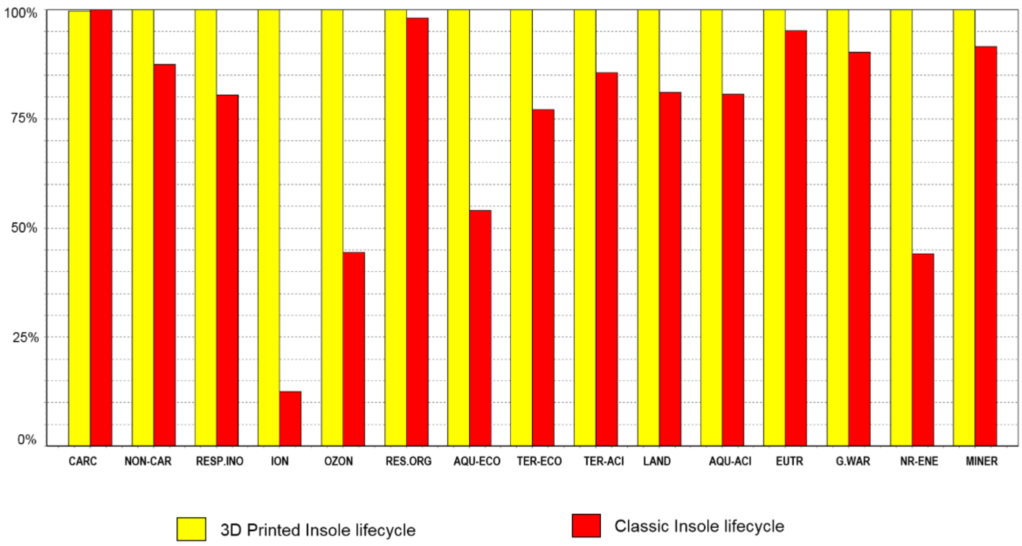


Figure 75 - Insoles Life cycle comparaison (1 vs.1)

Analysing only the Production phase the gap is +60% in Respiratory inorganic, +40 in Global Warming and +80% in Non-renewable energy.

The electricity consumed during the printing process (13.800Wh/insole) is the biggest responsible for these impacts. It represents 85%, 86% and 95% in each midpoint category respectively. (Fig. 76).

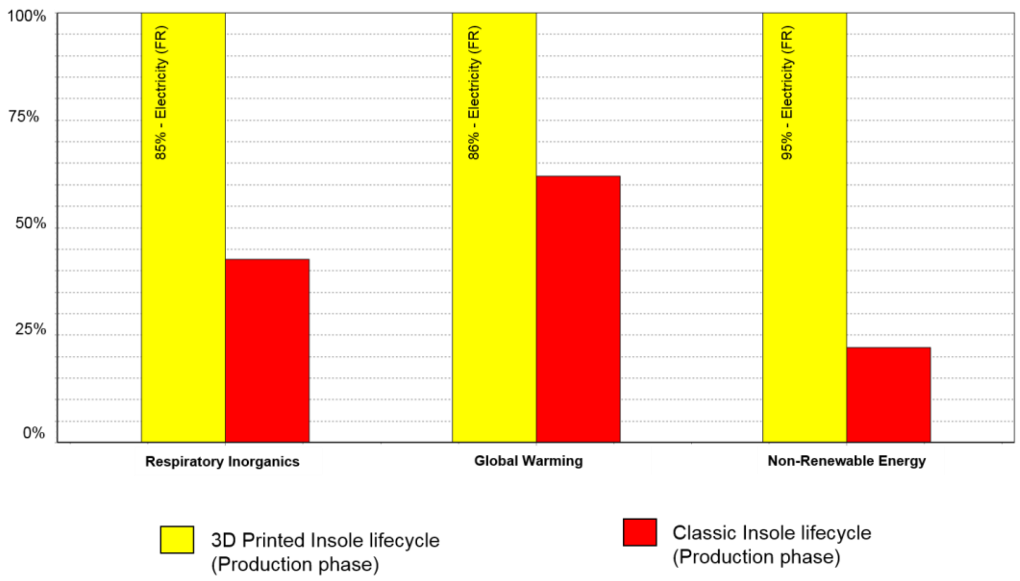


Figure 76 - Comparison Production phase (1 vs.1)

To better understand the relation between the printing process and energy consumption in this case study, figure 77 shows a comparison of different printing duration for one printed insole and different types of energy. Due to confidential issues, the following nomenclature will be considered in the figure: Xh = Real printing duration/ Yh=Reduced printing duration by 2 hours. The endpoint categories will be used in this analysis because the variation is equivalent in all impacts.

When the printing duration is reduced by 2 hours (yellow bars), the impacts in the four impacts categories (Human Health, Ecosystem Quality, Climate Change and Resources) are reduced by about 30%. When solar energy is used instead of Nuclear, the reduction of impacts reaches 95% in Resources and 75% in Climate Change (blue bars).

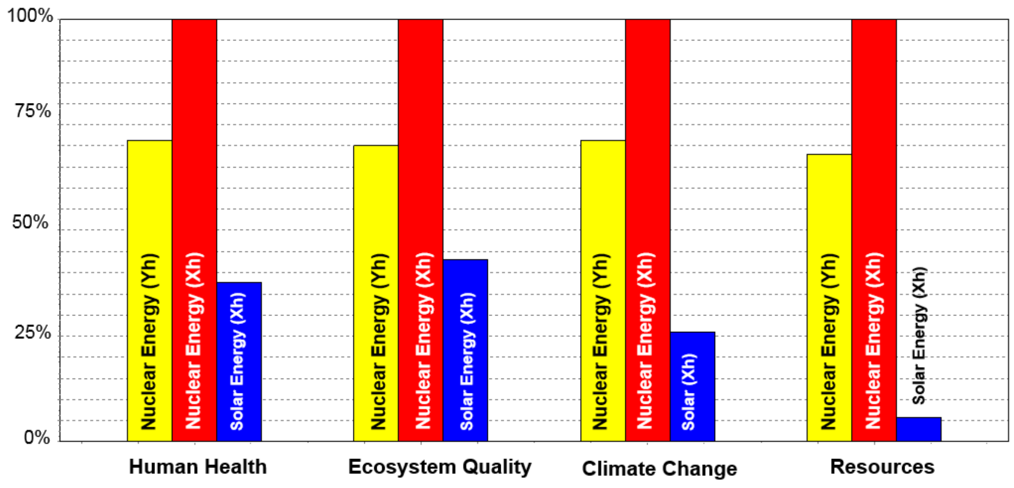


Figure 77 - Printing time vs energy type

All of these results allows to highlight two important factors to be considered when the environmental impacts of AM are being assessed via comparative LCA.

The first one is the importance of the equality between the two compared systems. In this scenario (Business use), differently from Personal Fabrication, the two systems have the same production scale, function, goal and customers. This make the comparison valuable and provide reliable results. In several LCA's found in the literature comparing AM with a classic production this fact is not considered. This is, certainly, one of the causes of the ambiguity of many studies.

The second point concerns the Functional Unit. A precise and realistic FU make the difference in the results. In this study, when a sensibility analysis was done using the same lifespan (1 vs. 1) to compare both insoles, the results presented always better to a classic production. So, when the AM is compared with other system, to verify the accuracy of the FU seems to be imperative.

However, the goal of this study is not the comparison itself, but the identification of the hotspots of impacts in the Business use of AM. In such context, the results strongly suggest that the Production phase affected by the energy consumption (Technical aspect) is the hotspot of impacts in this type of AM use. This finding is supported by (Muthu & Savalani, 2016; Gibson, I. & Shukla A., 2016):

> *'The amount of energy required for many of the 3D-priting processes is quite high in relation to the number of parts when compared to volume manufacturing. Users must, therefore, consider the intrinsic value of parts before a commitment to build them is made.'*

Regarding the Human Aspects, (imperative in Personal Fabrication), in this case, the *User's CAD and Printing expertise* do not represent significant impacts when compared with other phases. This occurs because the users (chiropodist and manufacturer) are already experts, and consequently, their mistakes are minimised. Additionally, the CAD and Printing duration are fixed and controlled.

Hence, when a small plastic part is made by an expert user (CAD and 3D-Printing), the 3d-printer machine (Printing Process – Technical Aspect) is the most important point to be controlled regarding the environmental impacts generation (Fig. 78). The impacts are associated with three elements at least: Technology, Machine manufacturing and the Power consumption.

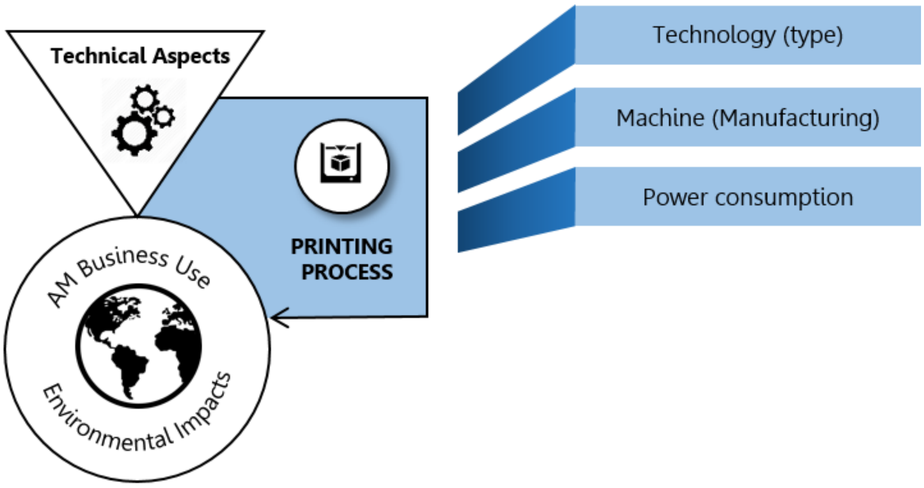


Figure 78 - Impact contributors in the AM 'Business use'

5.3 Conclusions

The use of Additive Manufacturing is currently a market trend and a Business opportunity for many entrepreneurs. There are numerous ways to use AM in this perspective, one of them is to print and deliver a final printed product adapted to the client's needs. A small company that use AM to print orthotic insoles was the study case investigated in this Business scenario.

Regarding the LCA carried out to find out the environmental hotspot, in this study, the *Production and Distribution* are widely the most impactful phases. The impacts of these two phases are focused on three midpoints impacts categories: Respiratory inorganic, Global Warming and Non-renewable energy.

The Distribution phase is affected by the use of a personal car to take the product. The worse scenario was considered and the impacts of this phase can be minimised if the car use is optimised.

In the Production phase, the 3d printer machine affecting the energy consumption is the leading cause of the environmental impacts. Therefore, this study yields to assume that, when Additive Manufacturing is used as a business opportunity, in other words, as a primary drive of a small company, the machine itself (3d-printer) seems to be the leading cause of impacts because of energy consumption. (Barros, Mansur, & Zwolinski, 2017). This results can be the same for similar cases, however, it does not represent a final conclusion. Variations is possible according to the type of business, technology and product.

Next chapter will describe the last scenario studied in this research: the Industrial use of Additive Manufacturing.

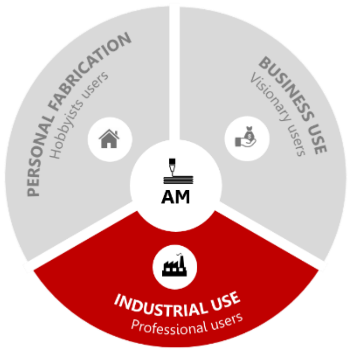
6

Scenario 3: Industrial use

This chapter describes the last scenario studied in this research: the Industrial use of AM. The first section characterizes the AM Industrial domain. In the second section, an analysis based on the literature shows the studies of its environmental impacts. Finally, the third section presents the results of a practical experiment conducted in the Gi-Nova Technical Platform with an industrial 3d-printer in order to validate the information found out in the literature.

6.1 Characterization

In recent years, European industry has been facing the challenge of losing competitiveness in mass production. Due to important factors such as lower labour costs, lower taxes or on-site access to raw materials, mass production has migrated to third world countries. (Petrovic et al., 2009)



This declaration shows a reality that has been shaking the industry sector not only in Europe: the loss of competitiveness and the necessity of innovation. One of the efforts employed by different industries to face this scenario is to move towards the production of short series of customised products with added value. In this context, AM is presented as a powerful tool that can offer the necessary means to achieve this. (Petrovic et al., 2009).

According to (Thomas, 2009), initially, AM technologies were restricted to the manufacture of models and prototypes leading to the widely accepted term, 'Rapid Prototyping', which was for many years a term used to refer to all layer additive manufacturing processes. More recently, advances in materials, processes and machine hardware meant that parts could be produced with sufficient mechanical properties to allow useful applications. This enabled layer additive technologies to be used to manufacture end-use components for the industry.

The Industrial use of AM is not new. The popularisation of domestic 3d-printers started in 2000's stemmed from industrial technologies. According to (Wohlers & Gornet, 2014) the first use of AM in industries emerged in 1987 with stereolithography (SL). The fast advances verified in technologies and materials has pushed industries forward a new standard of production in which AM is introduced to provide gain in personalization, time and profits.

The infographic presented in figure 79 shows that until 2023 AM technology will be 50% cheaper and 400% faster. Although additive manufacturing will not replace conventional production methods, it is expected to revolutionise many niche areas in different industry segments. Exponential growth is on the horizon. (Zistl, 2014)

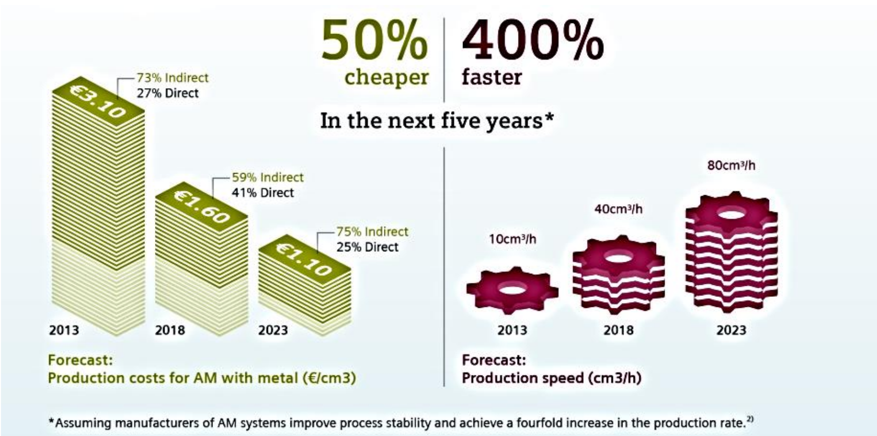


Figure 79 - Infographic about declining costs and production speed
Source: (Zistl, 2014)

Diverse AM technologies are used in industries. However, robust Polymers printers, Laser-based technologies and Electron beam based technology are the most recurrent (see Table 1). The industrial use of 3d-printers is also variable, depending on the type of industry.

According to (3ders, 2014), titanium and nickel-based alloys are very attractive materials for the industrial use of AM. The aerospace sector and new applications including test beds in space flight and turbine parts in power plant engineering and aircraft construction are currently also being devised by development engineers.

Many industries have been using AM in a ground-breaking way. These companies use it to make series of parts to compose others products such as aeroplanes and cars. This type of manufacturing is the focus of this scenario. Table 9 presents a list of 4 big companies that use AM in their production line.

Table 9 - Big industries using 3d-printing in a ground-breaking way
Source: (Gilpin, 2014)

Company	Use	Product
General Electric	Production of more than 85,000 fuel nozzles for the new Leap jet engines. The printers can make the nozzles in one metal piece, and the finished product is stronger and lighter than the ones made in the traditional assembly line.	
Boeing	One of the early adopters of 3D printing technology. It has made more than 20,000 3D printed parts for 10 different military and commercial planes	
Ford	It has been using 3D printing technology since the 1980s and recently printed its 500,000th part with a 3D printer, which was an engine cover for the new Ford Mustang.	
Nike	Made 3D printed cleats for the 2014 Super Bowl. The Nike Vapor Laser Talon has a 3D printed plate and cleats made from selective laser sintering technology, and the Vapor Carbon Elite also has parts produced with a 3D printer.	

Regarding the scope of this research, the main characteristics of the Industrial use of AM are:

- Focused on innovation and competitiveness;
- Designer and manufacturer can be the same person or not;
- Do not follow open design rules;
- Time and profit are constraints;
- Main production: Spare parts and small series of parts;
- Big and high-performance machines;

6.2 Sustainability in Industrial use of AM

As already cited previously, measuring and reducing the environmental impacts generated by Additive Manufacturing is a current challenge for many manufacturers and researchers. The studies about the effective sustainability of AM is mostly focused on the industrial use, and some authors have been studying this matter using different perspectives and analysis.

(Salonitis, 2016), demonstrates that the 'low energy efficiency' and the 'decreases power consumption for the life cycle of the product' are the two environmental challenges of powder bed AM technology. (Figure 80). The author highlights that '*the entire life cycle of the product to be manufactured needs to be considered for concluding with confidence the impacts to the sustainability'.*

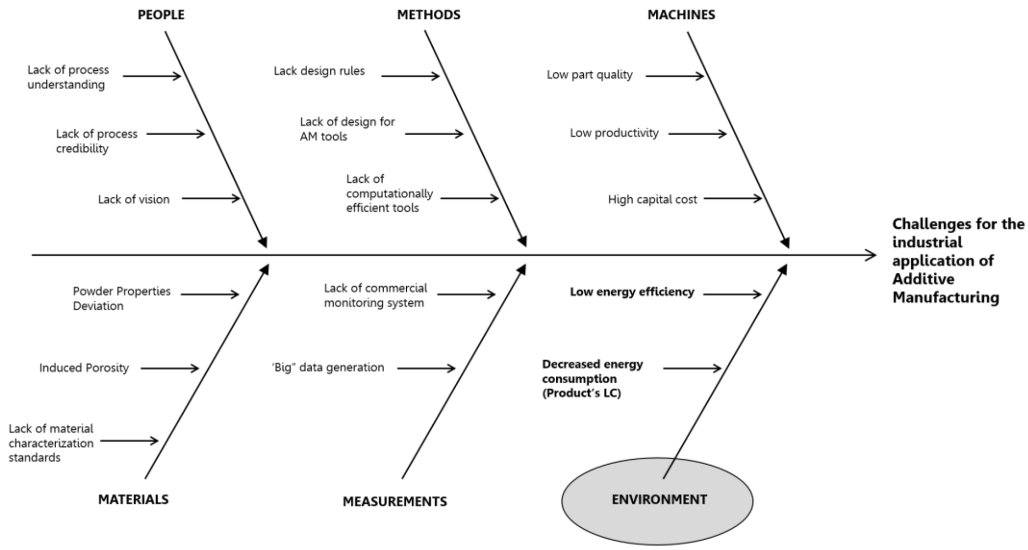


Figure 80 - Challenges in AM industrial Application (Adapted from Salonitis, 2016)

In line with this findings, (Chen et al., 2015) points four environmental impacts indicators for the industrial use of AM:

- Higher specific energy demand;
- Quality issues are not finally solved, thus involve risk of bad parts and rework;
- Longer manufacturing time;
- Ambivalent studies in terms of an environmental impact or eco-efficiency;

Studies developed by (Kerbrat, Le Bourhis, Mognol, & Hascoet, 2016) concluded that many investigations take into account the energy consumption of the manufacturing process by considering only the machine, and not all the sensitive parameters. According to the authors, the most important parameters regarding energy consumption is the total manufacturing duration, which is strongly dependent on the height to be produced.

Other sensitive parameters regarding energy consumption were studied by (Martin Baumers, Tuck, Wildman, Ashcroft, & Hague, 2016). The geometry and packing density of the part. According to the authors, for SLS and EBM machines, the energy consumption is not linked to the number of components realised and the part geometry. This confirms that the energy consumption is strongly dependent on the height of the part.

Regarding the raw material consumption, according to (Kerbrat et al., 2016) in powder bed or powder projection technologies, a part of the deposited material is not fused, and it is necessary to consider this raw material lost in the environmental analysis. The authors say that metallic powders may be sensitive to the moisture contained in the air, causing their oxidation. Usually, the nonfused powder is reused after sieving treatment, and a few studies are focused on recycling the metallic powder in AM processes.

The conclusion of the studies conducted by (Kerbrat et al., 2016) shows that, in the industrial use of AM, for same manufacturing strategies, the environmental impacts due to the electrical consumption is not the predominant one. In their case study using CLAD Process[8], material consumption has a substantial impact and has to be taken into consideration for a complete environmental impacts assessment.

Studies conducted by (Paris, Mokhtarian, Coatanéa, Museau, & Ituarte, 2016) show that, during the manufacturing of the part itself, the energy consumed by EBM and milling (Finishing process) is almost identical. The difference regarding the environmental impacts is mainly the manufacturing of the powder for EBM process and the production and recycling of the chips for the milling process. The authors also found that taking into account the knowledge on manufacturing process during the design stage, the geometry of the part can be optimised for the selected process and present later a significant positive impact on the manufacturability aspects.

(K. Kellens et al., 2011) state that, additive manufacturing processes such as Selective Laser Sintering (SLS) and Selective Laser Melting (SLM) allow near-net shape manufacturing of complex workpieces. Consequently, they inherently offer opportunities for minimum waste and sustainable production. Nevertheless, powder production, energy consumption as well as powder losses are significant and not always optimised regarding environmental impacts.

Finally, a more comprehensive literature review concerning the studies of the environmental impacts of AM (industrial use) is presented by (Karel Kellens, Mertens, Paraskevas, Dewulf, & Duflou, 2017). The authors have gathered the research findings of many authors for different AM technologies and settle:

[8] In this technology, metallic powder are injected into the CLAD nozzle to form a uniform jet. The powders melt and fuse as they move across the laser beam. (Kerbrat et al., 2016)

- Machine tool design, applied process parameters (e.g. layer thickness), machine tool utilisation (single part versus full build), selected case study material and part design explain the rather large variation in reported energy and resource consumption demand;
- Most available studies focus mainly on energy consumption. LCI data on resource consumption and direct or indirect process emissions are mostly not available.
- From an environmental perspective, the higher environmental impact caused during the AM manufacturing phase should be compensated by functional improvements during the use stage of AM manufactured parts.

Table 10 summarises the major findings of (Karel Kellens et al., 2017) separated into three processes: Material Manufacturing, Technologies and Post-treatment processes with the outcomes and sources.

Table 10 - Findings in different studies about the EI of AM according to (Karel Kellens et al., 2017)

	Type	Findings	Source
Material Manufacturing	**Metal**	• Compared to conventional manufacturing processes, AM processes need very specific feedstock materials. • Extra material preparation steps result in additional environmental impact. • AM feedstock materials are less well documented in terms of their environmental performance. • For metal powders, there are an additional energy required to atomise the material;	(Karel Kellens et al., 2017)
Technologies	**SLS (Selective Laser Sintering)**	• The created waste powder fraction (up to 50%) causes approximately half of the environmental impact.	(K Kellens et al., 2011)
	SLM (Selective Laser Melting	• Process energy is in almost all scenarios the dominant factor (66 to 75%) in the generated environmental impact (ReCiPe H/A method).	(Faludi, Baumers, Maskery, & Hague, 2016)
	EBM (Electron Beam Melting)	• Weak connection between extra product shape complexity and increasing per layer manufacturing energy requirements; • Cross-sectional melting area must be viewed as the most determinant factor of energy consumption per layer;	(M. Baumers, Tuck, Hague, Ashcroft, & Wildman, 2010; Paris, Moktarian, Coatanea, Museau, & Ituarte, 2016)
	FDM (Fused Deposition Modelling	• Machine energy demand is the most investigated item; • Approximately 60% of the energy consumption occurs during the warming up phase of the FDM system. Therefore, a significantly decreasing SEC value can be noticed when multiple parts are consecutively produced.	(Karel Kellens et al., 2017; Yoon et al., 2014)
	Stereolithography	• The mask image projection stereolithography presents a better energy performance than standard machines;	(Malshe, Nagarajan, Pan, & Haapala, 2016)

Post Treatment	**Metal**	• The energy of EDM process (Erosion process to finishing parts) can be up to 25% of the total energy consumption during AM part manufacturing; • Despite these post-treatment processes are a vital part of the AM process chain, the related impacts caused by these processes are often neglected or underestimated in environmental comparisons of alternative process manufacturing routes.	(Faludi et al., 2016; Karel Kellens et al., 2017)

All of these studies summarise three elements as the impacts contributors in the industrial use of AM: Energy consumption, Material and Gas/fluids consumption, being Energy consumption widely the most cited one. For each of these elements, different sources of impacts are related. However, except for few studies that also considers the Finishing Process in their environmental analysis, the most of them are focused only on the Printing Process. The CAD Process is never cited.

To validate/verify the literature information, a practical experiment (LCA) was carried out to measure the environmental impacts delivered from a set of parts printed using EBM technology. Next section presents the results of this experiment.

6.3 LCA of printed parts using EBM technology

In this experiment, the goal is to compare the three phases constituting the AM industrial process (CAD, Printing and Finishing phases) to find out which one is the more representative regarding the impacts on EBM technology.

6.3.1 Materials and Methods

The experiment was performed in the Gi-Nova Platform at Grenoble Alpes University from February to April 2017. The study was made in partnership with a master student and three other PhD students from G-SCOP. (Figure 81).

Figure 81 - Research team

The CAD process was made by a PhD student using the Solid Works software and specific software linked to the AM machine.

The technology used to print the parts was EBM (Electron Beam Melting) using Ti-6AL-4V (Titanium alloy) as printing material. (Fig. 82-a). During the printing stage, the energy consumed was measured using the professional equipment CA 8335 - Power and Quality Analyser Chauvin Arnoux. (Fig 82-b)

The Finishing process was carried out by a specialised technician using a CNC Threads Machining technology. (Fig. 82-c).

Regarding the environmental impacts assessment, it was performed using the software Simapro 8 and the calculation method Impact 2002+. The life cycle inventory (LCI) was composed by primary data collected on site during the experiment and secondary data from Simapro Databases.

a)

b)

c)

Figure 82a – EBM | b) Power counter | c) CNC machine

Figure 83 illustrate the LCA framework designed for this experiment with all phases and elements considered and analysed.

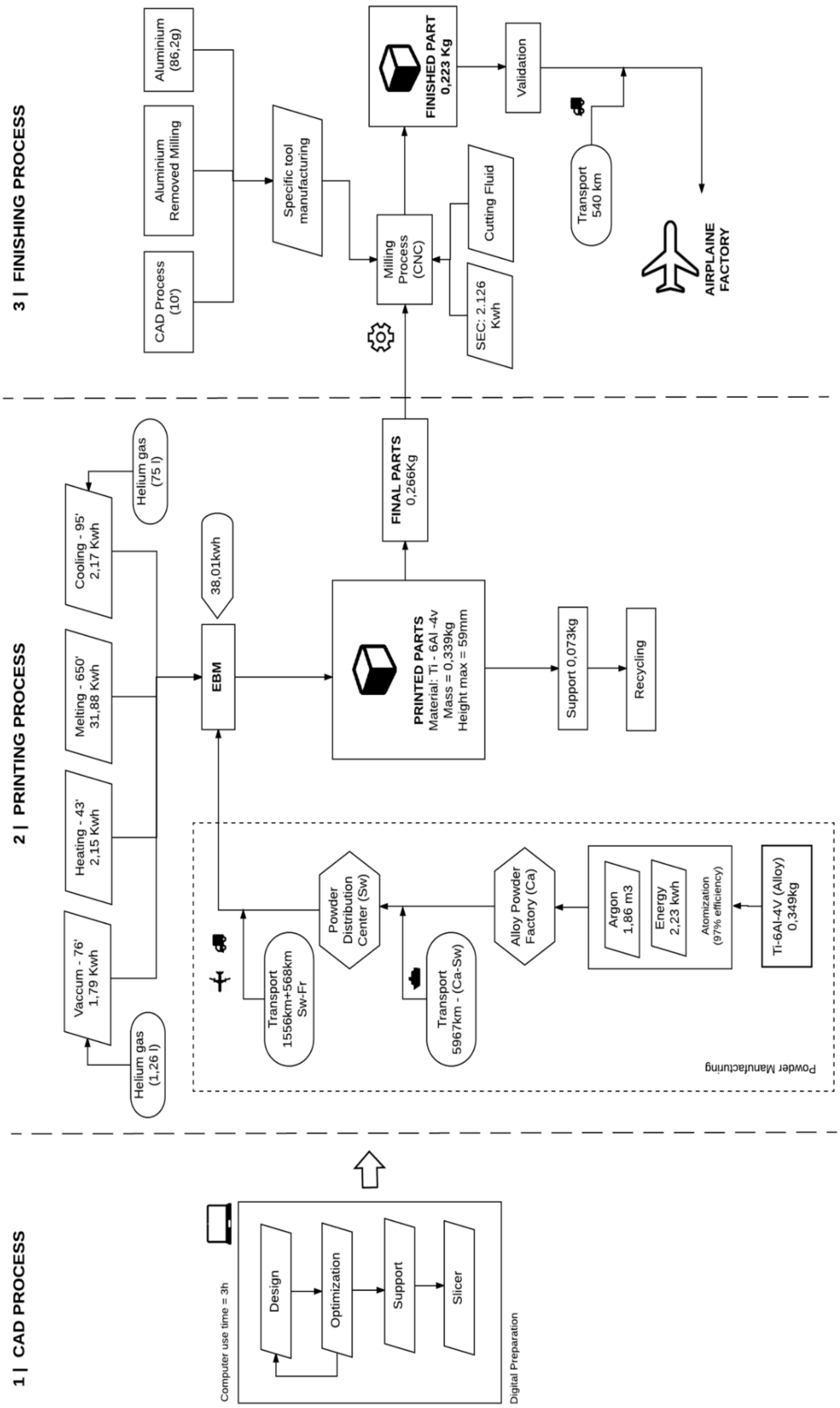


Figure 83 - LCA - EBM Process

6.3.2 CAD Process

This process called 'Digital Preparation' is composed of four steps: Design, Optimisation, Support and Slicer. The first and second steps aim to create the part and find the best shape structure using geometry optimisation. The third step calculates the supports necessaries to print as well as the organisation of the parts in the machine. Finally, the fourth step allows slicing the pieces to compose the layers that will be printed.

For this study, the second step (optimization) was not made, and the computer use duration for the others steps was 3 hours. Figure 84-a,b show the CAD design of the parts printed. In the LCA was considered the impacts of the computer use duration.

a) b)

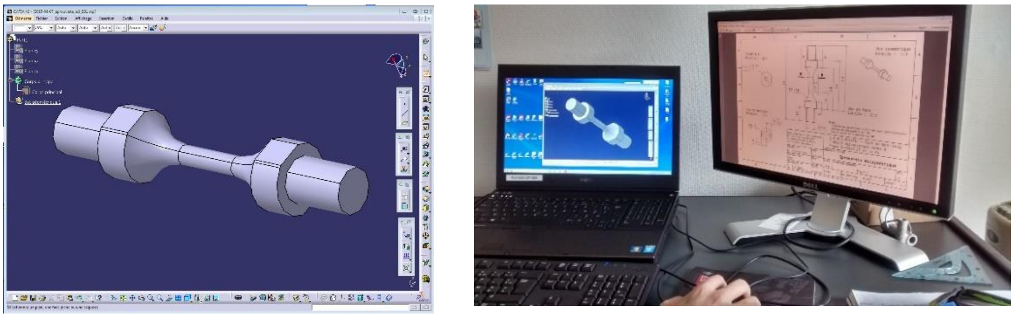


Figure 84 - CAD Process

6.3.3 Printing Process

This process was made using EBM (Electron Beam Melting) technology (Fig. 85). According to (M. Baumers et al., 2010) the principle operation of this technology is:

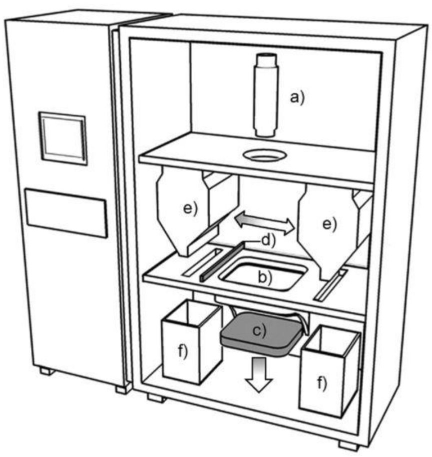


Figure 85 – Main components of EBM system
Source: (M. Baumers et al., 2010)

- An electron beam is emitted by a filament within a beam column (a).
- The focused electron beam selectively melts the surface of a powder bed (b) layer by layer;
- The build platform (c) moves down by an increment in the vertical direction;
- A "powder rake" (d) deposits a fresh layer of metal powder (Titanium) in the horizontal direction;
- The powder is dispensed from a stationary powder hoppers (e).

The Life Cycle Inventory (LCI) of this process considers the metal powder manufacturing and the printing process. The first one is composed by the Atomization process and the transports. For Atomization, data used were defined by (Paris, Mokhtarian, et al., 2016): 1kg of powder consumes 5.5m^3 of argon and 6.6kwh of energy with 97% of efficiency.

The transportation considers a ship from the factory in Quebec (Canada) to the Distributor in Gothenburg (Sweden); an airplane from Sweden to Paris (France) and a truck from Paris to Grenoble (Fr).

Concerning the printing process, it was taken into account the total energy consumed by the EBM system (38.01kwh) to print 0,339kg of parts with height maximum of 59mm.

The total of energy is the sum of the energy consumed in the four printing phases: Vacuum, Heating, Melting and Cooling measured on site. It was measured using a professional equipment (Fig. 86-a).

The set of parts printed is composed of 9 cubes and 11 tests tubes as illustrated in figures 86-b and 86-c.

The waste derived from the supports (0,073kg – Fig. 86-d) are collected and saved to be recycled by a company located 7,2km away from the production site. The impacts of this phase were not measured.

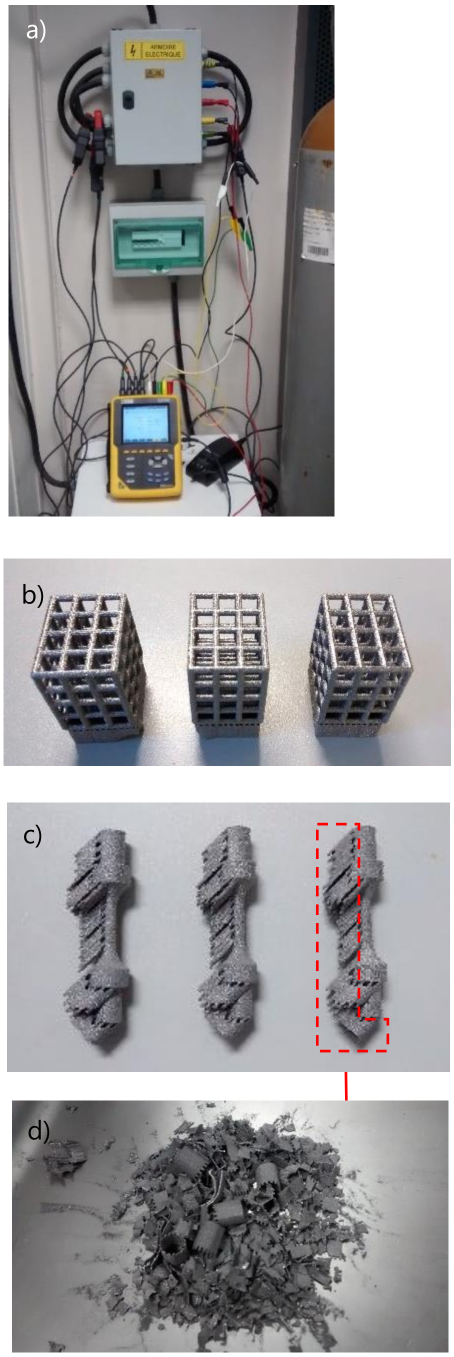


Figure 86 - Printing Process and parts

6.3.4 Finishing Process

This post-treatment was carried out to create a screw extremity on both sides of the printed parts as illustrated in figure 87-a.

The set of parts printed sums 0,266 kg of Titanium alloy (after support withdrawal). From this amount, only 0,103 kg (tests tubes) goes to the Finishing Process. However, to get a more feasible comparison base, it was considered that the total of parts (0,266 kg) is going to be finished by using the CNC technology. (Fig. 87-b)

In order to carry out the machining operation, a specific tool to hold the tubes was manufactured (Fig. 87-c). The manufacturing of this tool was considered in the LCI. (86,2g of aluminium, the Machining process itself and 10 minutes of CAD process).

The total of energy consumed in the CNC machining process (2.126 Kwh) was calculated taking into account data provided by (Paris, Moktarian, et al., 2016) in which the Specific Energy Consumption (SEC) for a Milling process is 0.129 kwh/cm^3. The cutting fluid consumption was not considered because of the lack of coherent data. A simulation with an aleatory amount proved that the results do not change significantly.

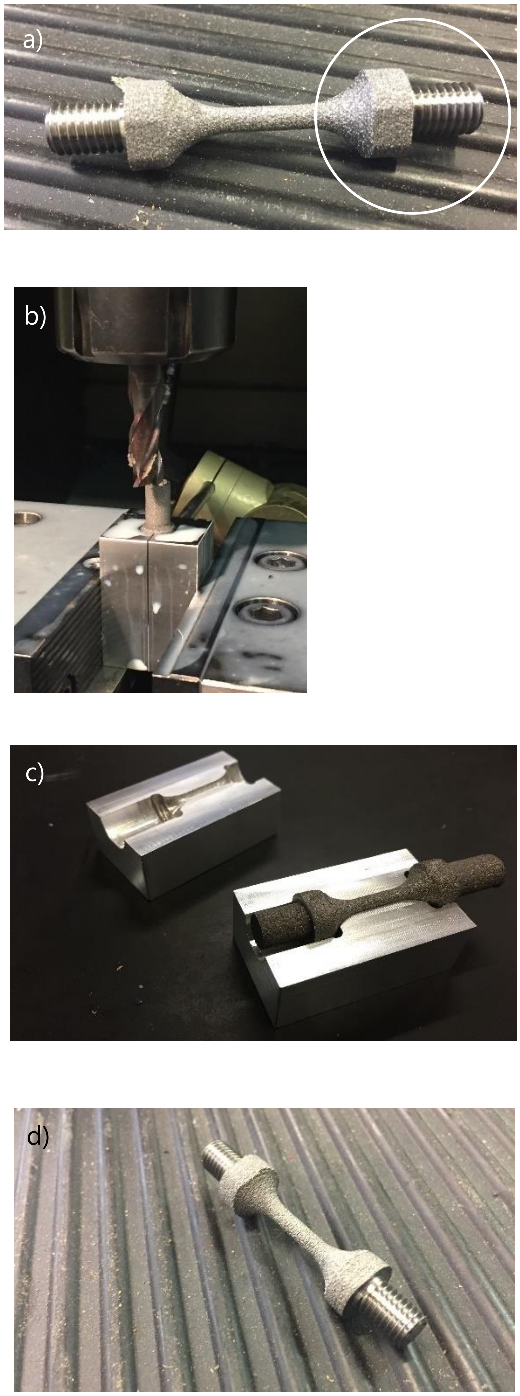


Figure 87 - Finishing Process and parts

Finally, figure 87-d illustrates the part finished. This study considers the hypothesis that these finished parts will be transported by truck to the aeroplane factory located 540km far from the production site.

Table 11 presents the complete life cycle inventory used in this LCA.

Table 11 – LCI for an LCA of printed parts using EBM technology

LIFE CYCLE INVENTORY – LCI

		Data	Quantity	Source
CAD PROCESS		Computer use (Desktop with liquid crystal display)	3h	Primary data and Simapro Database
PRITING PROCESS	Powder Manufacturing	Material: Ti-6AL-4V Alloy for EBM (For 1kg)	Titanium – 0.089 kg Aluminium – 0.06 kg Vanadium – 0.04 kg Carbon – 0.0003 kg Iron – 0.001 kg Oxygen – 0.0015 kg Nitrogen – 0.0001 kg	(Biamino et al., 2011)
		Atomization: Argon	3.3126 kg (1.86m^3)	(Paris, Mokhtarian, et al., 2016)
		Atomization: Electricity High Voltage Canada	2.23 kwh	(Paris, Mokhtarian, et al., 2016)
		Transport: Transoceanic Ship freight (Canada – Sweden)	0.339 kg x 5967 Km	Primary data and Simapro Database
		Transport: Aircraft (Sweden - Paris)	0.339 kg x 1556 Km	Primary data and Simapro Database
		Transport: Truck (Paris – Grenoble)	0.339 kg x 568 Km	Primary data and Simapro Database
	Printing	Electricity Medium Voltage France	38.01 KWh	Primary data and Simapro Database
		Helium consumption	0,013 kg (76,26 l)	(Martin Baumers et al., 2016)
FINISHING PROCESS		Aluminium Alloy	0.0862 kg	Primary data and Simapro Database
		Computer use time	10 minutes	Primary data and Simapro Database
		Aluminium removed by milling	0.23*0.862 kg	Primary data and Simapro Database
		Specific Energy Consumption (SEC): Titanium removed by milling process	0.219 kWh/cm³ x (43g/(4.43 g/cm³)) = 2.126 kWh	(Paris, Moktarian, et al., 2016)
		Cutting Fluid	Not considered because of the lack of coherent data.	
		Transport: Truck freight	0.223*540 km	Primary data and Simapro Database

6.3.5 Life Cycle Assessment

The environmental impacts assessment in this experiment aims to investigate and compare the impacts generated by three processes: CAD, Printing and Finishing Process.

Figure 88 shows that comparing the three process by normalisation, the Printing Process responds for the biggest part of impacts in three midpoint impacts: Respiratory Inorganic; Global Warming and Non-renewable energy.

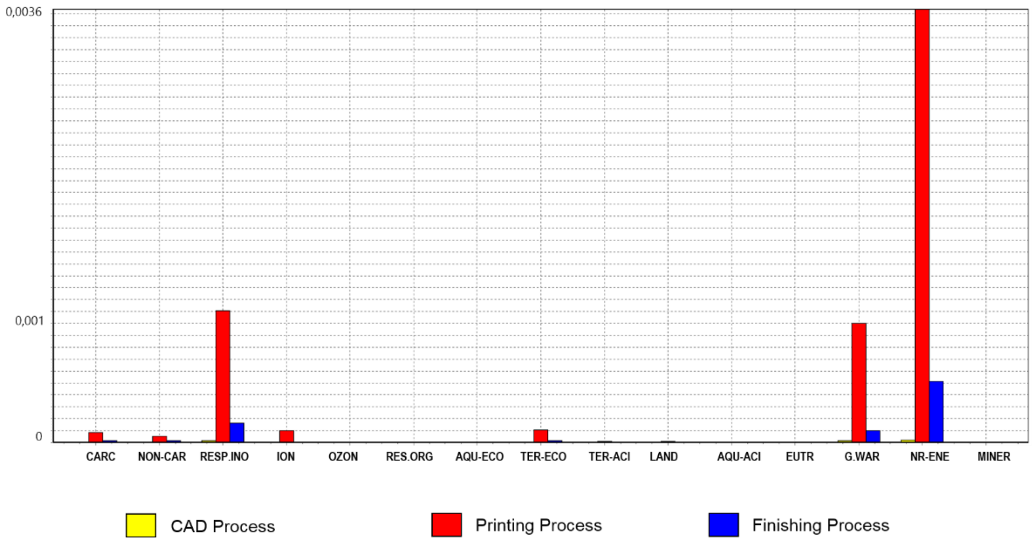


Figure 88 - Comparison among the three process in EBM technology (normalization)

Observing the 15 impacts midpoints, a linear tendency is recognised. The Printing Process is widely the most impactful in all categories. The Finishing Process appears in second place representing 21% of impacts in average, and the CAD process is always the less significant (2,5% of impacts). (Fig. 89)

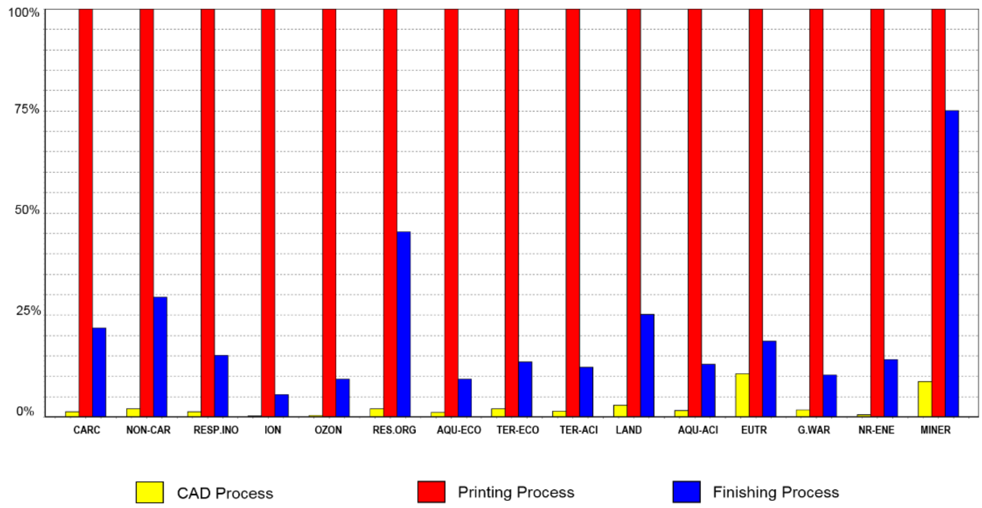


Figure 89 - Comparison among the three process in EBM technology (percentage)

Analysing each process in details (by single score considering the same variation tendency), it can be observed:

In the Printing Process (Fig. 90), the Electricity (medium voltage France) used by the EBM machine to print the parts (38.01 Kwh) represents 64,1% of impacts. The Powder manufacturing (Atomization+transport) covers 35% of the total impacts. In the Power manufacturing stage, an important amount of impacts come from the use of Argon[9] to atomise the powder (27%).

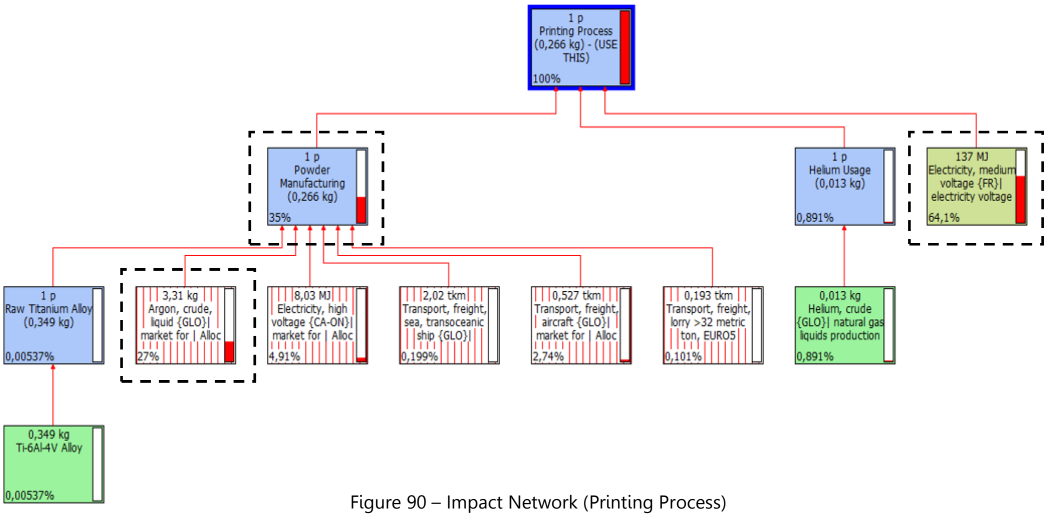


Figure 90 – Impact Network (Printing Process)

Concerning the Finishing Process, as observed in Figure 91, the electricity consumed by the CNC machine represents 38% of the impacts. The biggest portion of impacts come from the manufacturing of the specific tool necessary to hold the part (61,4%) affected by the use of aluminium alloy (43,7%).

The impacts generated by the CAD process is very small and, therefore, negligible.

[9] Argon is the most abundant noble gas in Earth's crust. It is produced industrially by the fractional distillation of liquid air. It is mostly used as an inert shielding gas in welding and other high-temperature industrial processes. (Wikipedia, 2017)

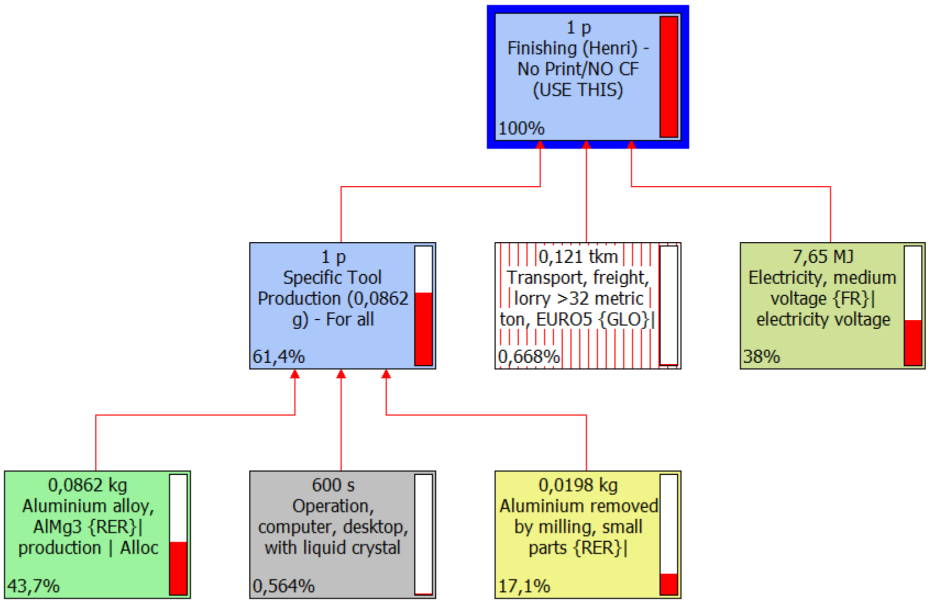


Figure 91 – Impact Network (Finishing Process)

This study validates many findings found in the literature in terms of impact contributors in the industrial use of AM. It has proved that the energy consumed during the printing process is the main responsible for the impacts. Also, it was observed and confirmed that the energy consumption is strictly related to some product features such as the height and the orientation on the printing table.

Moreover, this study has highlighted some unexpected results.

First of all concerns the percentage of impacts released from the Powder Manufacturing (35%). Although this is subject cited in few studies, it is not given the proper relevance to it.

A second important result found out in this study and rarely highlighted in the literature concerns the impacts from the Finishing Process (21%). Almost the totality of the parts printed using titanium alloy (EBM) needs a post-treatment to fit the design requirements. This can represent a very important part of impacts according to the machines used and the product features such as mass, volume, geometry, complexity and surface required.

In short, it is possible to affirm that, any LCA carried out to assess the impacts of a product printed by using EBM technology/Titanium alloy that does not consider the impacts from the powder manufacturing and the Finishing Process, is incorrect.

Finally, this LCA demonstrated that the CAD process does not represent a significant part of impacts. This is explained by the high amount of impacts released by the Printing Process and the user level of experience. In this context, it can be seen that in the industrial use of AM, due to the specific utilisation, the machine complexity and the costs of the technology, it is not common to see 'beginners' users managing the machine. In general, people who work with these robust machines have already a good experience, and then, it can be assumed that the impacts from Human Aspects is negligible.

So, the findings indicates that the environmental hotspots in AM (Industrial use) lie in two Technical Aspects: the *Product features* and the *Printing Process* each one with different contributors. (Figure 92).

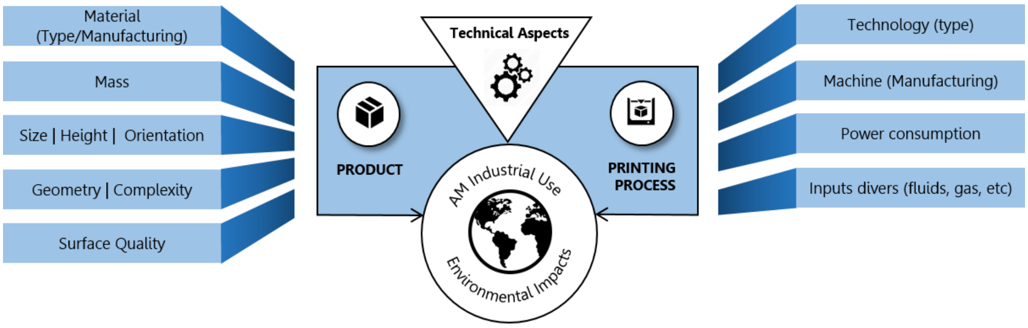


Figure 92 - Leading impact contributors in Industrial use of AM

6.4 Conclusions

Investigation of the impacts generated by AM (Industrial scenario) was made by means of literature analysis and confirmed by a LCA of a set of parts printed using EBM technology. The impacts produced by the three different phases (CAD, Printing and Finishing) were compared.

Findings show that the Printing phase, due to the energy consumption and the powder manufacturing, far overcomes the impacts of the CAD and Finishing stages. It represents 65% of impacts. The Finishing Process is responsible for 15% and the CAD process is not significant enough to be accounted. Three important results were highlighted: 1) the high amount of impacts generated by the powder manufacturing process; 2) the importance of considering the Finishing process in the LCA's and 3) the negligible impacts released during the CAD process.

Regarding the Finishing process, albeit this results represents the use of CNC machine to thread a metal part, it can be assumed that any post-treatment that uses machines should be analysed and considered.

Also, the analysis confirmed that the environmental hotspots in this scenario are related to two Technical Aspects: the Product and the Printing Process. Both are affected by different impacts contributors.

Next chapter presents the summary of contributions of this research.

7 Impact Contributors in Additive Manufacturing

This chapter outlines all contributions of this research based on the results found out in the investigations carried out in three different AM domains. It presents a systemic framework that illustrates the main sources of impacts separated by type of AM use. Also, a LCA model adapted to Additive Manufacturing is provided as a guide to researchers and professionals who aims to assess the environmental impacts of AM in a more realistic way. Gathering theses frameworks, a concept of tool (software) is proposed to estimate the impacts associated with AM production.

7.1 Where do the environmental impacts of AM come from?

The three scenarios investigated in this research (Personal Fabrication, Business Use and Industrial Use), as well as examinations of the literature, indicate that the Environmental Impacts (EI) of AM derive basically from two aspects: Technical and Human aspects.

Regarding the Technical Aspects, two key elements contributes to the environmental hotspots: (1) The Product and (2) the Printing Process. Concerning the Human Aspects, it is (3) the user's level of expertise in CAD and (4) the user's level of experience in Printing. For each key element different impacts contributors are identified.

The experiments have shown that in the Personal Fabrication scenario, the Human Aspects are the most representative. Regarding the recreational context of this scenario, the way people use the machine can generate more environmental impacts than the machine itself.

In the 'Business' and 'Industrial' use of AM, given the fact that the users are supposed to be already experts in CAD and Printing, the impacts are focused on the Technical Aspects.

Based on the three scenarios, figure 93 illustrates the summary of the identified impact contributors associated with Additive Manufacturing organised by key element. Table 12 details the impacts contributors and their source of impacts.

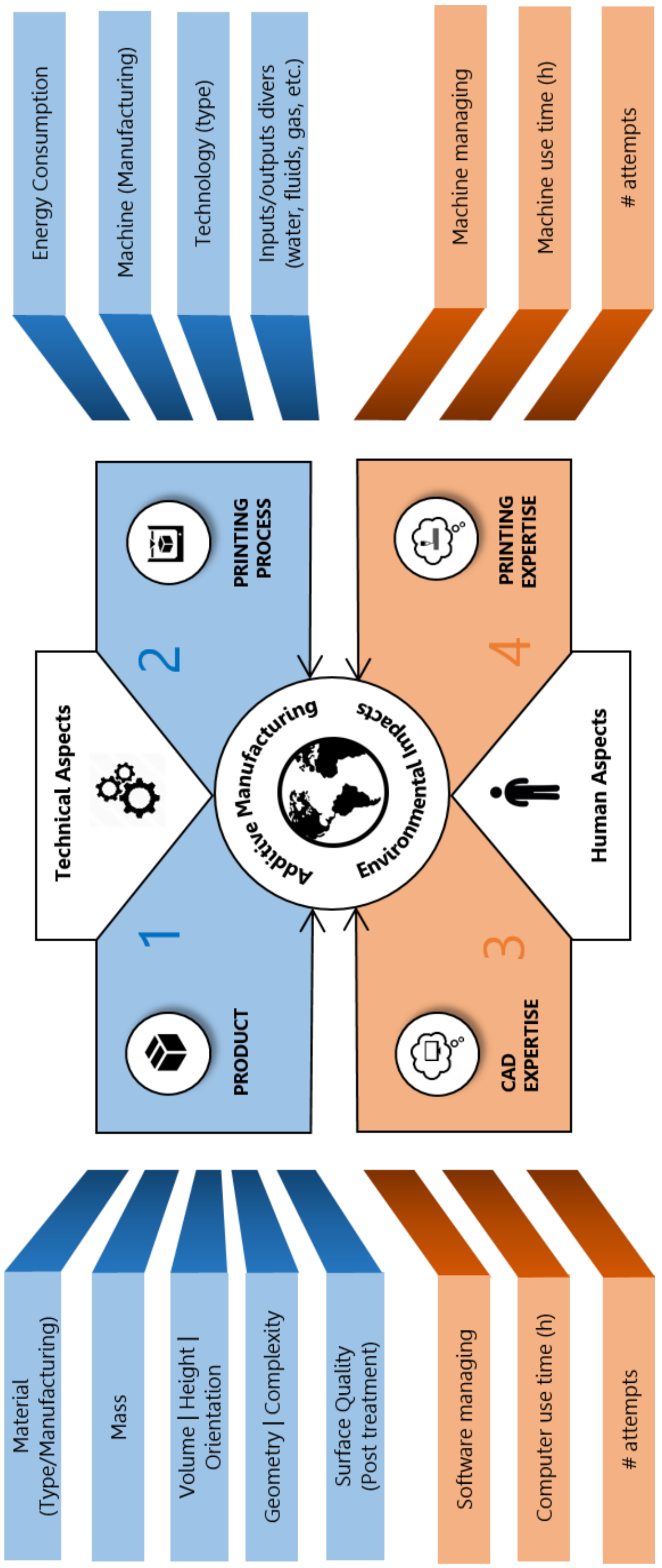


Figure 93 – Impact contributors in AM

Table 12 - Impact Contributors in AM

	Key element	Contributor	Source of impacts
TECHNICAL ASPECTS	**| 1 Product**	Material	- Manufacturing Process - Waste Generation - Non-recyclability
		Mass	- Printing Duration - Energy Consumption - Inputs/outputs - Waste generation
		Volume	
		Height	
		Orientation	
		Geometry	
		Complexity	
		Surface Quality	- Post-treatment Processes
	| 2 Printing Process	Energy Consumption	- Non-renewable Energy
		Machine Manufacturing	- Energy and resources
		Technology	- Polymer and metal-based
		Inputs/outputs divers	- Water, gas, fluids, etc.;
HUMAN ASPECTS	**| 3 User's CAD Expertise**	Software Managing	- Energy consumption
		Computer use time	
		# attempts	
	| 4 User's PRINTING Expertise	3d-printer Managing	- Energy consumption - Waste generation
		Machine use time	
		# attempts	

Gathering all these findings and analysis, a systemic framework addressed to AM users was designed. It aims to clarify about the impacts contributors elements and the sources of environmental impacts in different scenarios of AM and then, supporting users decisions stimulating a more environmentally way to use. (Fig. 94).

On the framework, the three scenarios are presented separately, per colour. The four key elements are classified in each scenario according to the level of impact delivered. This level is represented by the thickness of the line connecting the key element symbol. The thicker is the line, the more important is the impact generated by the element.

In Personal Fabrication, the two elements more representative regarding the impacts are the User's CAD and Printing Expertise (Human Factor). In Business use, the Printing Process and, in Industrial Use, the Printing Process and the Product.

Using this model, the user can localise himself in one of the three scenarios and be aware of which element is responsible for the impact of his activity. Once localised, he can see in the first brown cycle a short explanation about the source of impacts in the chosen scenario. Then, taking a look at the biggest green circle the user can see the best way to minimise the impacts of his production.

The three grey bars localised between the scenarios represents the ‘transition area’. The user who locates himself in this area, should take into account the information of the two scenarios correspondents.

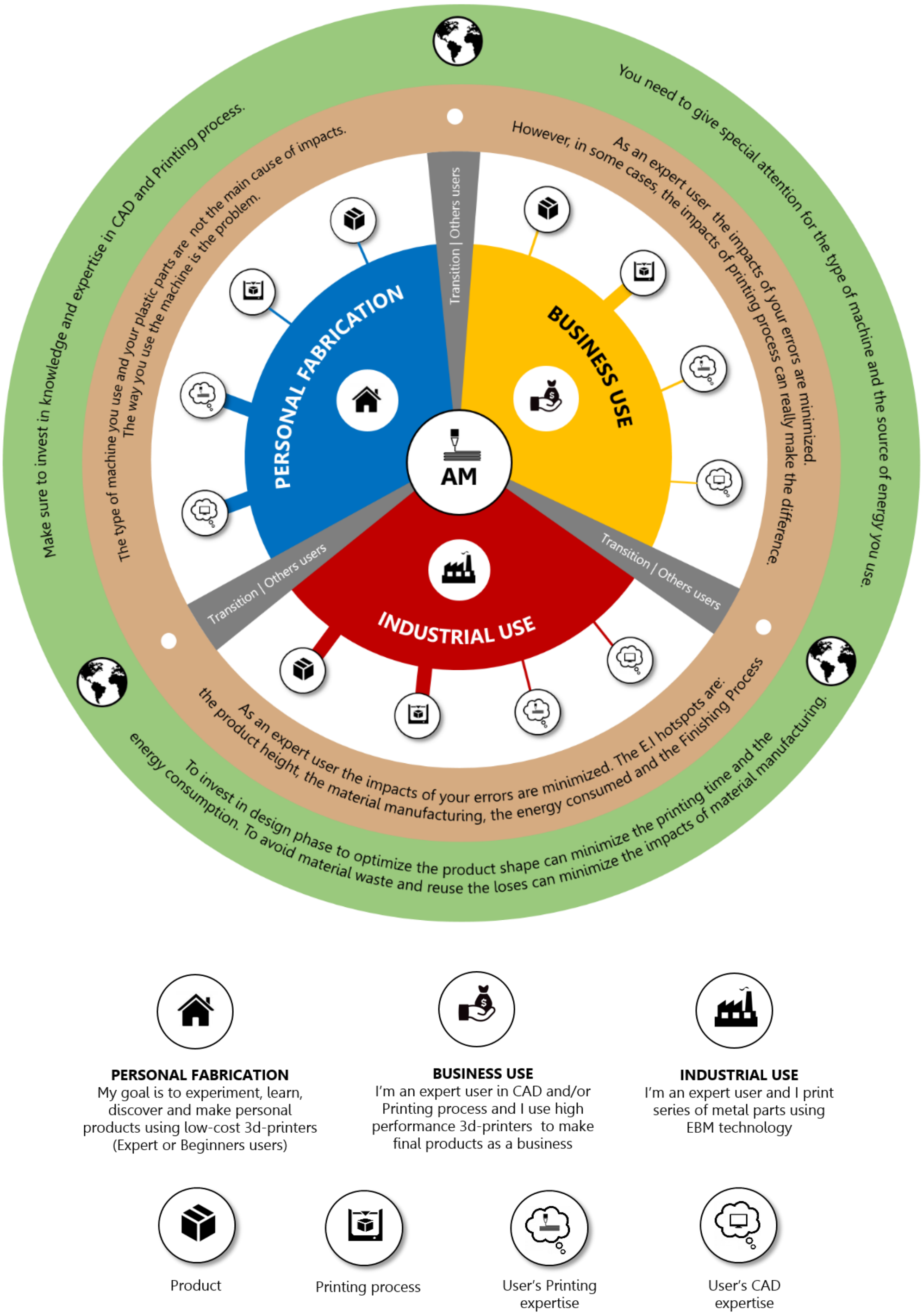


Figure 94 - Framework illustrating the sources of impacts per type of AM use

Besides the framework pointing the hotspots of environmental impacts in AM, a model to support LCA was designed addressed to researchers and professionals to improve studies carried out in the Additive Manufacturing field.

The model is based on the three LCA's results carried out in this research. It uses the five main life cycle phases (Material, Production, Distribution, Usage and End of Life) as a reference and recommends the consideration and study of some crucial components in each one. These elements are responsible for both positive and negative impacts in Additive Manufacturing. (Fig. 95).

It is expected that this model might provide more realistic and reliable results when the environmental costs of AM are being assessed. It is a systemic model that indicates the crucial points to be investigated in each phase but can be adapted according to the use.

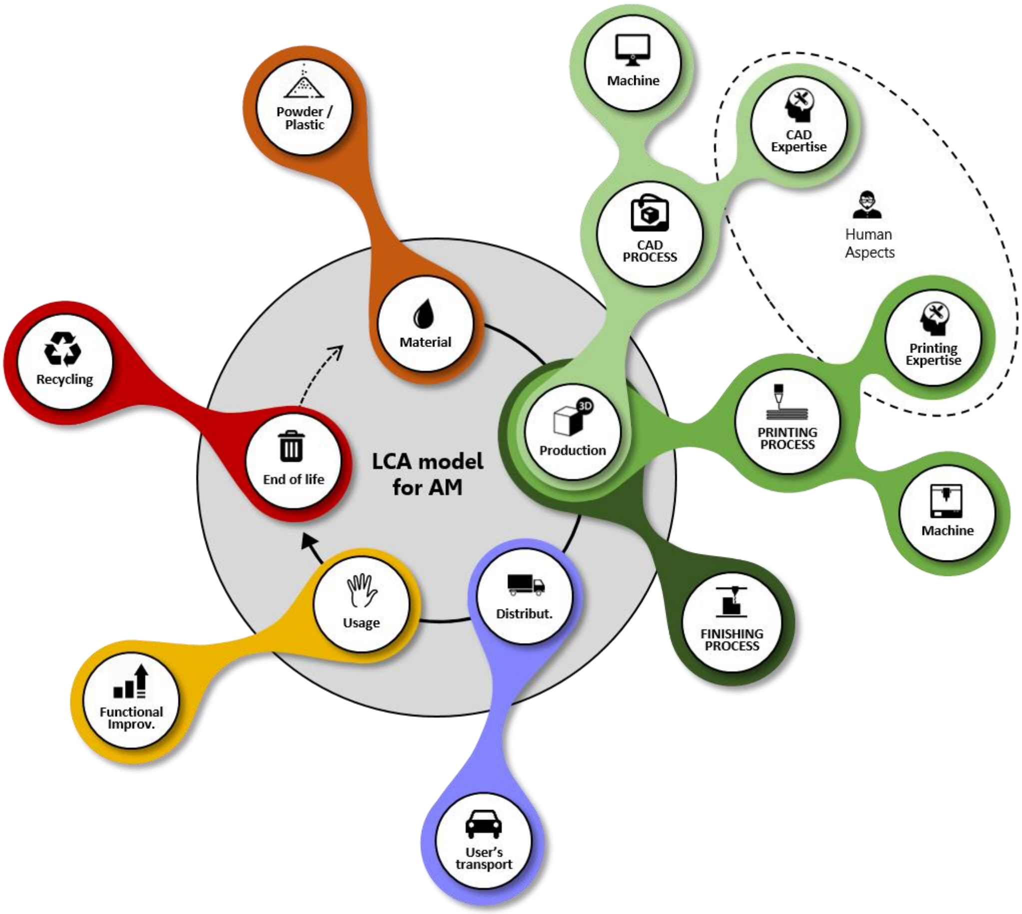
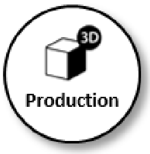


Figure 95 – Model to support LCA of Additive Manufacturing

The first life cycle phase described in the model to support LCA is the *Material.* Studying this phase in details is particularly important in AM processes. In the industrial use, it was verified that the powder manufacturing (metal-based technology) could be responsible for up to 35% of impacts.

Regarding plastic-based AM technology, although if the PLA (plastic most used in Personal fabrication) is a biodegradable plastic, its production can represent significant impacts. Experiments of this research show that it could represent up to 39% of impacts.

The metal powder and plastic manufacturing is a non-negligible element.

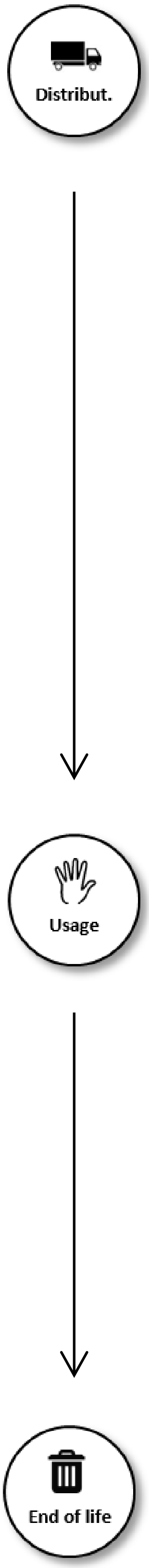


The second life cycle phase *(Production)* is the most representative in terms of impacts. Therefore, this phase must be investigated taking into account three others sub-phases: CAD, Printing and Finishing Processes.

The CAD process represents the impacts derived from the computer user time affected directly by the User's CAD expertise. In this sub-phase, it was noted that the level of expertise in CAD (Human Aspect) might represent an important source of impacts, especially in Personal Fabrication due to the computer energy consumption. In the Business and Industrial scenario, given that users are in general experts, the impacts of CAD process is minimised and sometimes can be negligible.

The Printing Process in many cases is the most important sub-phase regarding the generation of impacts. In this process, the machine manufacturing, energy/fluids consumption (technical aspects) and the user printing expertise affecting the printing duration (Human aspect) are the drivers of impacts. In Business and Industrial use, the technical aspects are very significant.

The Finishing process, required in many industrial productions, represents the impacts of all machines necessaries to finish the part. It depends on the machine, but the energy and the fluids consumption embody the biggest sources of impacts. This model suggests that all LCA carried out in Industrial AM must consider the impacts of the Finishing process.



Regarding the *Distribution* phase, many studies about the environmental impacts of AM assumes that, since the part can be produced closer to the final user, there are not impacts on this phase or it is slight. Two reasons prove that this assumption is not entirely correct.

First of all, the impacts of Distribution phase is not the most representative considering the whole life cycle of a product, even if the part is made in China, for instance. In most of the cases, products are distributed in large quantities by ships, one of the cleanest type of transport.

Secondly, the impacts of the distribution of the printed product to the final user, even for short distances, can be very significant. This is verified because the total of impacts delivered by the car use is allocated to only one product. In the Business scenario studied in this research, the impacts of distribution phase reach 61%. The model to support LCA's proposes that this Distribution phase should always be carffully considered.

The *Usage* phase is particularly different in AM. It might aid to compensate the impacts generated by others phases (Production phase, for instance) by the product functional improvements observed during the usage.

In the industrial use of AM, the usage phase may help to reduce impacts in at least three aspects. The lifespan of the printed part; the material resistance affecting the lifespan and the product usefulness; and, the weight gain, especially appreciated by cars and aeroplanes companies by improving the performance and reducing the fuel use.

Deeper and accurate studies must be done to define how to measure those impacts compensation among phases in a way to assure the effectiveness of results.

End of Life phase, as well as the Usage one, might aid to reduce the impacts. This is possible because recycling processes are available for both plastic and metal-based processes.

Regarding the plastic-based technologies, the PLA (Polylactide Acid) under specific conditions, can be biodegraded. Additionally, it is possible to find in the literature a couple of studies concerning its recyclability to reuse in the printing process. Others plastic such as ABS although recyclable, are not reused to print new parts because of quality loss.

Concerning metal-based technology, the titanium alloy used in EBM technology is recyclable. However, the environmental costs of this process and the new application are still little knowns. In fact, the recycling and reuse process of printed parts, independently of the material is a vast study field still in development.

So, the Life Cycle Assessment model proposed in this research aims to provide conditions to reach more accurate and realistic results when the environmental impacts of Additive Manufacturing are being investigated.

Based on the systemic framework and on this model to support LCA in AM field, a prototype of a tool (software) addressed to professional and researchers is proposed as the final 'product' of this research. The tool is designed to estimate the environmental impacts of different AM scenarios according to the usage profile.

7.2 Proposed Tool (Concept)

As a final contribution of this research, the concept of tool (software) to estimate the main environmental impacts of a printed part is proposed. The tool is called '3-DECO'.

3-DECO
Additive Manufacturing Life Cycle Assessment

The concept is simple: according to the printing parameters provided by the user, the tool shows which are the environmental hotspot and suggests some actions to reduce them.

3-DECO was designed to be a large database gathering different AM uses and user's profiles. In terms of impact calculation, it is possible to imagine the use of existent databases already developed to LCA software linked to the tool.

The operation is simple. Data are separated by life cycle phase. In each one, different options is given and the user should indicate an option and provide some specific information. Once the 'printing profile' is filled and confirmed, the tool shows an intuitive graphic illustrating the impacts per phase and the crucial point to be observed.

The print screen presented in figure 96 illustrates an use simulation.

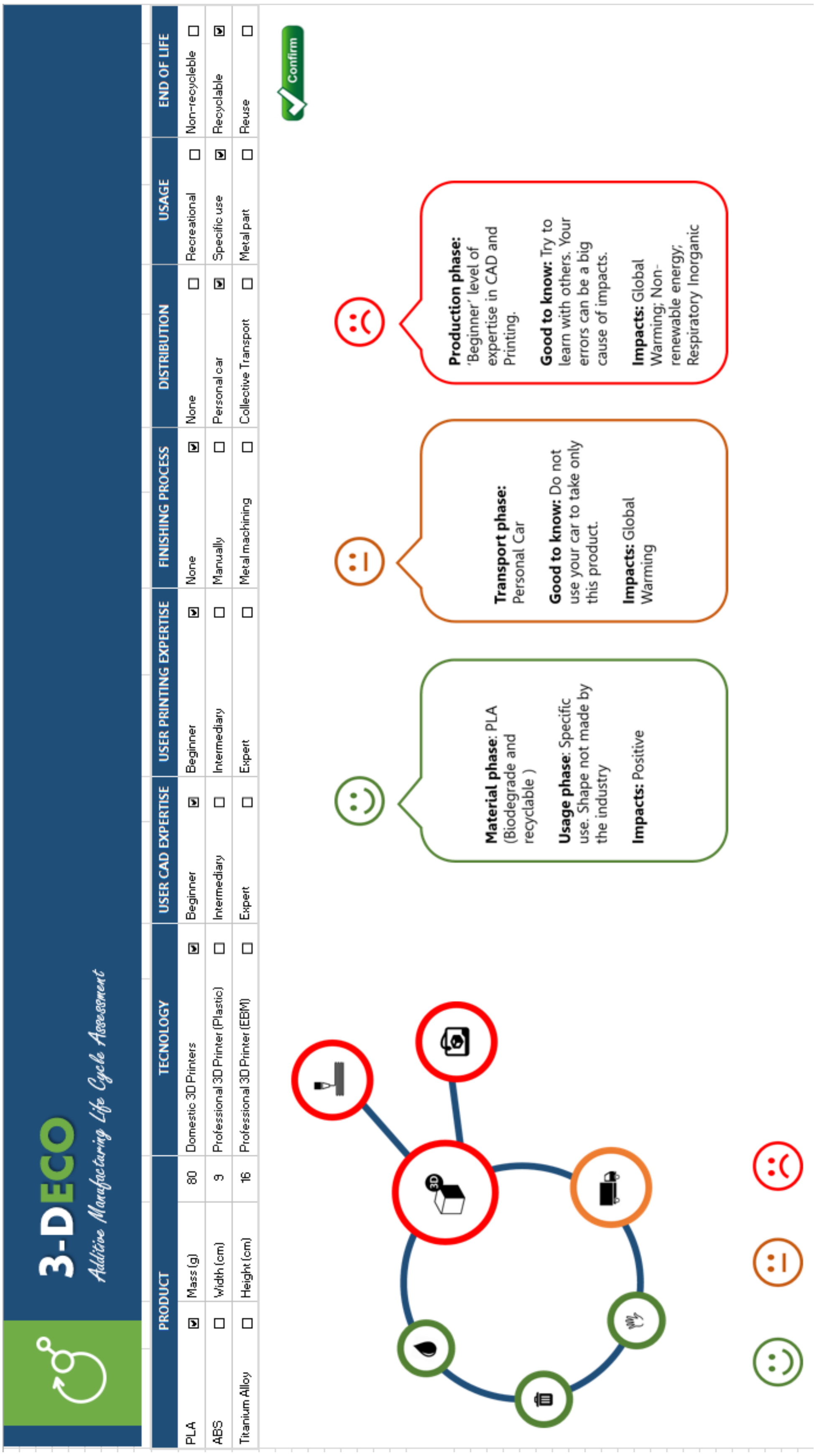


Figure 96 - Tool concept to Additive Manufacturing LCA

The simulation presented in figure 96 shows a 'printing profile' in which the Printing Process, because of the user's level of expertise (beginner) is the hotspot of impacts. This is indicated by the red circles. The green circles indicate that using PLA, a biodegradable and recyclable material and printing a specific shape may generates a positive impacts. The orange circle indicates that the transport phase because of the car use is a source of impacts and should be controlled.

This is a concept in development process and new perspectives and improvements is necessary. The tool can become an important source of information to guide AM users and researchers toward a more environmentally way of use.

7.3 Conclusions

This Chapter summarises the 'products' of this research.

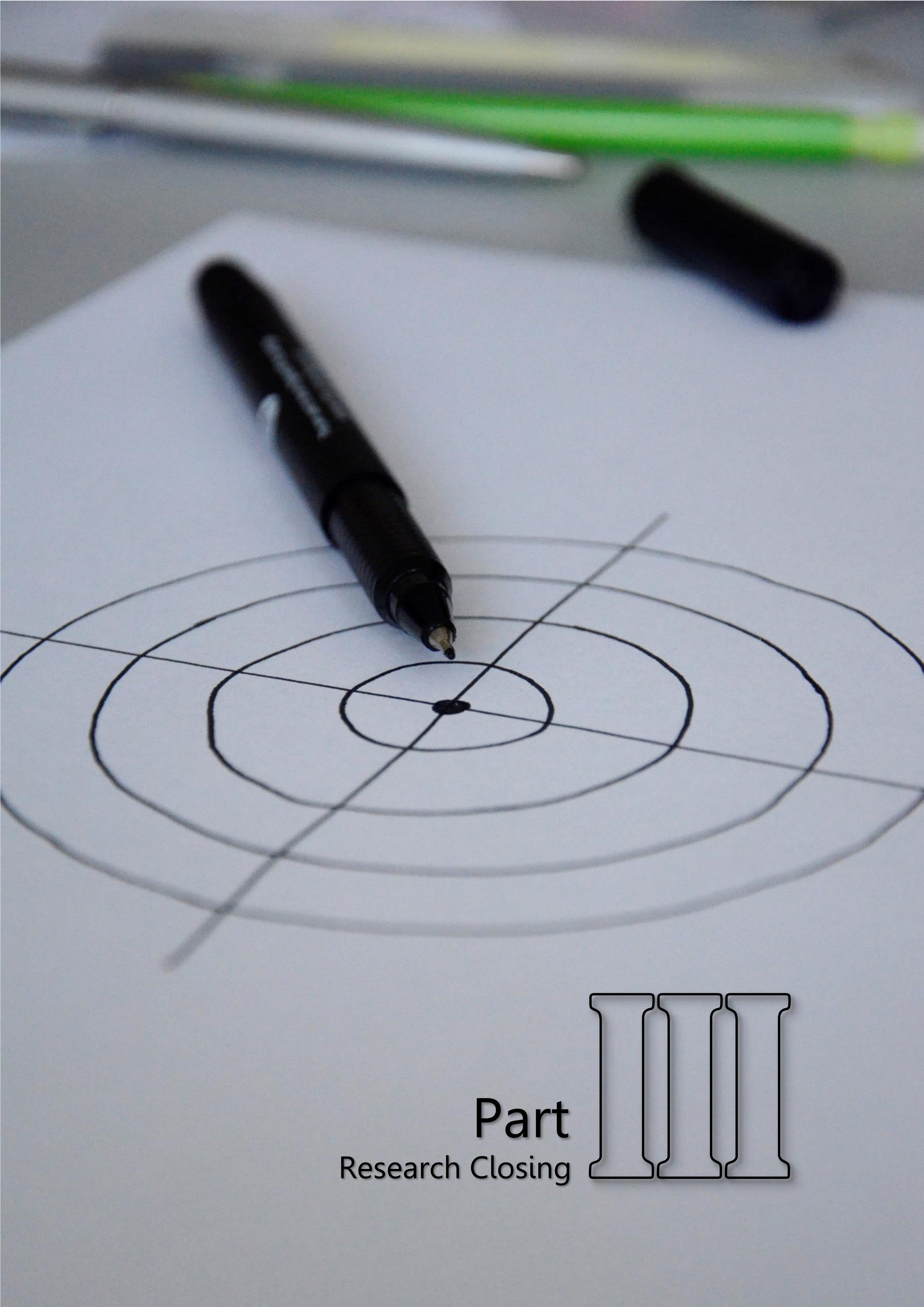
The first one is a framework gathering all impacts contributors identified in the three experiments. This framework points four key elements as the sources of impacts in AM: The product and the printing process (technical aspects) and the user's level of expertise in CAD and the user's level of expertise in printing (Human Aspects). For each key element, others impacts contributors are presented.

A second contribution is another framework addressed to AM users. It was designed to help them to locate themselves in a specific scenario and then, to know quickly which are the sources of impacts and the best practices to reduce them.

Focusing on the research community and LCA professionals, a third concrete contribution is presented. A model to support LCA adapted to AM. It indicates five life cycle phases and theirs specific branches to be investigated when a printed product is being assessed with an environmental prism.

Finally, gathering all this previous frameworks, a concept of LCA tool (software) is proposed. It was designed to estimate the environmental impacts of any AM production using a simple and intuitive interaction.

Next Part (Chapters 8 and 9) presents the final considerations and an extend abstract in French language.



Part III
Research Closing

‘Felizes são os que transferem o que sabem e aprendem o que ensinam.’

(Cora Coralina)

8

Final Considerations

8.1 Hypothesis and Questions validation

The three different Additive Manufacturing scenarios studied in this research, as well as the discussions and analyses, yielded to gather enough content to validate the research hypothesis and respond the research questions.

Concerning the first and second hypothesis, the separation of the AM studies into dedicated scenarios based on AM user's profiles demonstrated that the particularities of each scenario represent different sources of environmental impacts. Also, it proved that LCA's performed to assess the E.I of Additive Manufacturing should always be adapted and interpreted according to the technology specificity. General conclusions do not provide reliable results.

The third hypothesis was validated in the experiments carried out in the Scenario 1 (Personal Fabrication). It was observed that studying the impacts of AM by comparing it to Industrial Manufacturing (only) is a risk. The difference between the two systems does not provide a coherent Functional Unit, and then, misunderstood, and ambivalent results can be generated.

Finally, hypothesis 4 was validated only in the first scenario (Personal Fabrication). In this study, the Human Aspects represent an important part of impacts.

The impacts of the Human Aspects (User's level of experience) seem to be not significant in relation to the impacts delivered for technical aspects of the 'Business' and 'Industrial scenario'. This occurs because, in these two last scenarios, it is expected that the users have a good level of experience in CAD and Printing.

Regarding the research questions, the following answers are presented:

How to identify and control the environmental impacts associated to the use of Additive Manufacturing technologies?

The findings yield to affirm that LCA seems to be the best method to identify the environmental impacts addressed in AM. However, specifics points linked to the type and characteristics of the AM technology and use must be considered. Since these points are known and assessed, the impacts can be measured and controlled.

Where do the environmental impacts of AM come from?

The environmental impacts of AM come from Technical and Human Aspects according to the type of technology and use.

Which elements are the main contributors to the environmental impacts in AM?

The main key elements are the Product and the Printing Process (Technical Aspects) and the User's CAD expertise and the User's printing expertise (Human Aspects). Each key element gathers others sub-elements that contribute differently in each type of AM use.

Is it possible to determine if AM is better than traditional manufacturing in an environmental perspective?

Yes, only if the analysis considers a very clear and similar comparison base and hypothesis. Comparing industrial manufacturing and personal fabrication, for instance, it does not make sense. Both are very different regarding production scale and objectives. A generalised conclusion about what system is the 'best' without considering the system differences is always doubtful.

So, the findings reported in this thesis have validated the four hypothesis and answered the four research questions successfully. Also, this investigation has provided new standpoints to the studies about the environmental impacts associated to AM. The objectives were achieved. Nevertheless, no scientific research is a closed and exact matter. New interpretations and analysis according to others viewpoints are possible and necessary.

8.2 Thesis Contributions

The major contributions of this research are:

- **Research Interdisciplinarity and subject exploration**
  During the three years of this research, 7 bachelor degree engineering students were involved in different moments. The subject 'Environmental impacts of AM' was explored in many perspectives from the PhD research to the master and bachelor levels. This interdisciplinarity fosters the G-SCOP dynamic and enhance the studies of the AM environmental costs among the future professionals.

- **Additive Manufacturing User's profiles identification**
  The survey conducted with 112 AM users provided condition to identify four different users' profiles. These profiles can be used in others investigations in the field of Additive Manufacturing.

- **AM scenarios identification**
  From the user's profiles, three AM scenarios were recognized. Also, this classification can be adopted by the AM community (professionals and researchers) to drive new studies. It can help to understand the particularities of the technology.

- **AM Life Cycle Assessment model proposition**
  The final 'product' of this thesis, a model to support LCA adapted to AM technology, as well as, the concept of the software proposed to estimate the environmental impacts associated to AM can usefully contributes to drive the technology towards a more environmentally way of use.

8.3 Conclusion

This thesis addressed the problem of the environmental impacts associated to Additive Manufacturing processes, a subject still under development.

An approach centred on scenarios was applied. Three specific Additive Manufacturing scenarios (domains) were identified and studied: 1) Personal Fabrication; 2) Business use and 3) Industrial use. Literature analysis and the method of Life Cycle Assessment-LCA provided accurate results to identify the different hotspots of environmental impacts in each scenario.

In Personal Fabrication, the study highlighted the importance of placing a greater focus on the Human aspects. Besides the technical aspects, the user's level expertise in CAD and Printing affecting the time and consequently the energy and waste generation have to be always considered in this type of production. The way people use the technology can generate more environmental impacts than the technology itself.

In the 'Business' scenario (case study of printed insoles) the findings have shown that the Human aspect (User's CAD and Printing expertise) does not represent a significant part of impacts because, in this AM domain, the users are already experts. Therefore, the Production phase because of the Printing process (Technical aspects – energy consumption) is the most representative phase in terms of impacts. Also, this study has highlighted the importance of defining an accurate and realistic Functional Unit when comparative LCA is used.

Results from the 'Industrial' scenario (EBM Technology) have suggested that the Printing Process, dominated by the energy consumption and the powder manufacturing, as well as the Post-treatment process are the mainstream impacts. LCA's performed in this domain that does not consider the impacts of the powder manufacturing and the post-treatment process will be always underestimated.

The results of the three studies were analysed and gathered in such a way to design a systemic framework of impacts contributors. Four key elements were identified: The product and the Printing Process (Technical aspects) and the User's level of experience in CAD and Printing (Human Aspects). For each key element other sub-elements (impact contributors) are associated. This framework has driven the design of a model to support LCA adapted to AM which was transformed into a software to estimate the environmental impacts correlated to Additive Manufacturing.

Finally, this research yields to summarise that using AM to print a simple product already easily made by the industry seems to be incoherent and costly in an environmental point of view. The use of AM to print products with a particular shape that industry cannot make properly, seems to be more intelligible and less costly for the environment.

It is unrealistic to think that Additive Manufacturing will replace the Classic manufacturing one day. However, it is reasonable to believe that in the future the environmental charges will be put in the frontline of this breakthrough development. The studies of the environmental benefits associated to Additive Manufacturing are only starting.

8.4 Research Limitations

Limitations and constraints are a part of numerous challenges faced during a research process, independently of the matter.

In terms of the findings, firstly, it should be observed that the survey conducted with 112 AM users provided a condition to identify three different Additive Manufacturing use domain and then, defining the three scenarios investigated in this research. However, it does not means a complete and closed setup. Others AM domains and usages can be identified and studied by other researchers using different approaches.

Additionally, the results of this research do not cover all AM technologies. It was based on three scenarios/technologies. It can be supposed that the results can be the same only for very similar cases.

Regarding the approach, it should be noted that LCA is a method that naturally presents limitations in terms of data inventory and interpretations. In this study, we tried to use as much as possible primarily data and enlarge the study boundaries to get results as most realistic as possible. Nevertheless, the results can be open to new interpretations.

In terms of research structure, this thesis was structured and designed according to the researcher profile, skills and limitations. As a Product Designer and Professor, an approach more systemic and didactic was prioritised.

8.5 Perspectives of future work

Further extensions and improvements can be considered as a continuation of this work.

Regarding the proposed framework of impacts, it would be interesting to investigate the key elements and their contributors separately. This could give answers to new questions, such as:

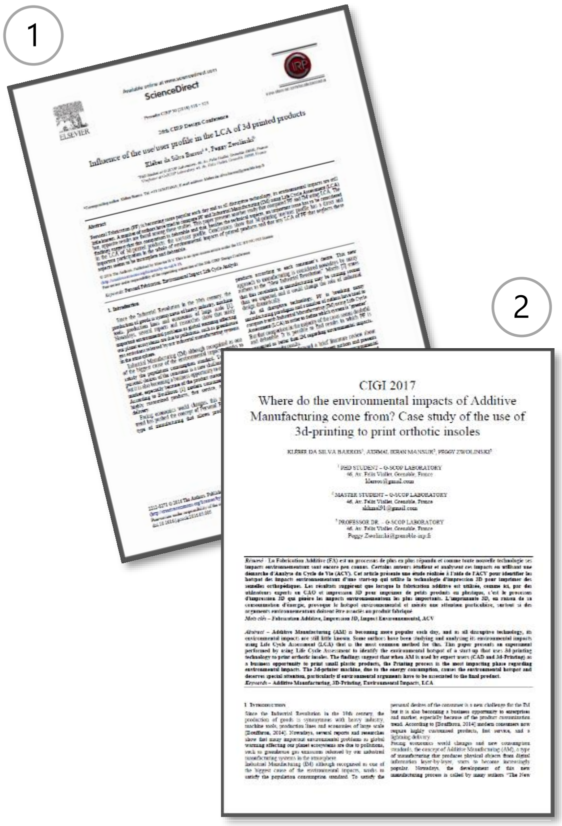
- Which are the influences of the product surface quality in the environmental impacts of a printed part?
- In EBM manufacturing, what is the main cause of energy consumption regarding the product? The mass or the height? In which proportion?
- Which AM technology/domain is the best in terms of environmental impacts?

Regarding the proposed model to support LCA, another direction for future research is to develop a method to measure/quantify in details the impacts of the Human factors (CAD and Printing expertise) in AM. This study could provide a new body ok knowledge about the social impacts of AM technology. Additionally, to investigate how to compensate the impacts of a printed part through its functionality/shape/lifespan in the use phase could justify the use of AM in many cases.

Finally, we strongly suggest the integral development of the software 3-DECO as a free tool to be available to the scientist community interested in the AM technology.

8.6 Publications

During this research, two papers were produced with different perspective and results.



The first one was published in the CIRP Design Conference 2016 in Stockholm, Sweden. It sets out the results of the studies conducted in the Personal Fabrication scenario demonstrating the importance of considering the Use/User profiles in LCA's of printed products.

The second paper was published in the CIGI 2017 (Conférence International de Génie Industriel) in Compiègne, France. It demonstrates the impacts of the use

AM as a Business opportunity, exemplifying the case study of the printed orthotic insoles.

Papers references:

1) Barros, K. da S., & Zwolinski, P. (2016). *Influence of the use/user profile in the LCA of 3d printed products*. In *CIRP Design 2016*. Stockholm, Sweden: Elsevier.

2) Barros, K. da S., Mansur, A. I., & Zwolinski, P. (2017). *Where do the environmental impacts of Additive Manufacturing come from ? A case study of the use of 3d-printing to print orthotic insoles*. In CIGI 2017 (p. 6). Compiegne - France.

9

Résumé Étendu en langue française

9.1 Contexte

La Fabrication Additive (FA) est une technologie innovante par rapport aux procédés de fabrication soustractifs. Elle prend en charge une large gamme d'applications, comprenant la fabrication de pièces en général, l'art, l'architecture, l'éducation, les loisirs, l'exploration spatiale, militaire, les industries médicales, dentaires, le domaine de l'aérospatiale, ... (Gibson, Rosen, & Stucker, 2015).

La FA présente des avantages tels que la possibilité de fabriquer des modèles plus efficaces (plus léger, plus fort, moins d'assemblages requis) et des produits personnalisés avec une totale flexibilité dans la conception et la construction. Même si de nombreux avantages sont énoncés, de nombreux auteurs soulignent également quelques défis à relever dans les domaines technique, social et environnemental liés à la mise en usage de la fabrication additive. En ce qui concerne la dimension environnementale, plusieurs articles de journaux et des thèses se trouvent dans la littérature, mais adoptent bien souvent des conclusions différentes au niveau des sources d'impacts, et ceci pour des technologies variées.

Cette recherche va ainsi chercher à mieux comprendre les raisons de ces désaccords et essayer de trouver des réponses précises et globalement acceptables lorsque l'on cherche à déterminer les effets de la fabrication additive sur l'environnement. Par conséquent, la question principale de cette recherche est:

Comment identifier et maîtriser les impacts environnementaux liés à la mise en usage des technologies de Fabrication Additive ?

La réflexion sur les préoccupations environnementales liées à la FA est devenue une nécessité. Chaque jour, de plus en plus de gens s'équipent avec des imprimantes 3d pour produire leurs produits, et nous ne connaissons pas encore les conséquences que cela aura sur notre planète et la société. Soutenir les efforts visant à employer la recherche dans ce domaine devient nécessaire et urgent.

9.2 Méthodologie

Une approche centrée sur l'analyse de scénarios d'usages a été appliquée. Trois scénarios ont été identifiés et étudiés à partir d'une enquête appliqué à plusieurs usagers: 1) La Fabrication Personnelle; 2) l'Utilisation commerciale de la FA et 3) l'Utilisation Industrielle de la FA. L'analyse de la littérature et l'application de la méthode d'Analyse du Cycle de Vie – ACV ont fourni les données nécessaires afin d'identifier les différents *hotspots* environnementaux dans chaque scénario.

Les effets sur l'environnement sont évalués en adoptant la méthode d'Analyse de Cycle Vie -ACV. Cette méthode est utilisée dans les différents scénarios d'usage de la Fabrication Additive selon leurs spécificités. En plus, des observations, des activités pratiques, des entrevues avec les utilisateurs et une revue de la littérature complètent l'approche pour la détermination des impacts environnementaux.

Le premier scénario appelé « Fabrication Personnelle » traduit un type d'utilisation dans lequel l'expérimentation et le plaisir sont dominants. Le second scenario, lié à « l'Utilisation commerciale » représente un type de FA ou l'intérêt économique est le moteur principal pour la fabrication du produit final. Le troisième scénario lié à « l'Utilisation industrielle » répond à des besoins classiques de productions de pièces par l'industrie manufacturière. Sa caractéristique principale est liée à la production de séries de pièces imprimées, en général, en utilisant les matériaux métalliques.

Les résultats des trois études ont été analysés séparément en considérant leurs particularités. Cela a permis d'identifier les contributeurs d'impacts environnementaux pour chacun de ces cas. Ils ont ensuite été rassemblés de manière à concevoir un cadre systémique montrant l'ensemble des contributeurs aux impacts dans le cas de la mise en usage de technologies de FA.

9.3 Résultats

9.3.1 Scenario 1 – Fabrication Personnelle

Des Observations et interactions avec les utilisateurs de FabLabs et de laboratoires équivalents ont montré que la majorité des usagers viennent là essentiellement car ils sont intéressés à faire des expériences, échanger des informations et explorer.

L'ACV menée dans le cadre de ce scénario a révélé que la comparaison faite entre la fabrication personnelle et les systèmes de fabrication industrielle, n'a pas de sens si elle est faite sans tenir compte de leurs différences (fonction, objectif, quantité de production, conception des produits, etc.). On ne peut donc que difficilement conclure sur une comparaison d'impacts générés par la fabrication personnelle versus une fabrication industrielle.

Une analyse plus approfondie, axée sur l'expérience de l'utilisateur, a prouvé que les aspects humains (niveau d'expertise en CAO et impression) peuvent être très représentatifs en termes de génération d'impacts. Dans le cas de la fabrication personnelle, la façon dont les gens utilisent la machine influence plus les impacts environnementaux que la machine elle-même. (Barros & Zwolinski, 2016)

9.3.2 Scenario 2 – l'Utilisation Commerciale

L'utilisation de la FA donne de nouvelles opportunités d'affaires pour de nombreux entrepreneurs et devient une tendance du marché. Il existe différentes façons d'utiliser la FA selon cette perspective. L'une d'elles consiste à 'imprimer et livrer un produit imprimé final adapté aux besoins du client. L'étude de cas investigué dans ce scenario est liée à une petite entreprise qui utilise la FA pour imprimer des semelles orthopédique.

En ce qui concerne l'ACV, elle a montré que la production et la distribution sont les phases les plus génératrices d'impacts environnementaux. Dans la phase de production, la consommation d'énergie de la machine d'impression 3D est la principale cause des impacts environnementaux. On peut ici émettre l'hypothèse que quand la FA est utilisé comme l'unique process dans la réalisation des composants pour le client, l'imprimante 3D va être la principale cause des impacts en raison de la consommation d'énergie. (Barros et al., 2017)

9.3.3 Scenario 3 – l'Utilisation Industrielle

L'étude des impacts générés par la FA dans le cas du scénario industriel a été effectuée en se basant sur la littérature et confirmée par l'ACV d'un ensemble de pièces imprimées utilisant la technologie EBM. L'ACV a comparé les effets produits par les trois phases nécessaires à l'obtention de la pièce : la CAO, l'Impression et la Finition.

Les résultats montrent que les impacts de la phase d'impression, en raison de la consommation d'énergie et de la fabrication de poudre, dépassent de beaucoup les impacts de la CAO et ceux des étapes de finition. Elle représente 65% des impacts. Le processus de finition est responsable de 15% des impacts et le processus CAO n'est pas suffisamment important pour être pris en compte.

Trois résultats importants ont ainsi été mis en évidence: 1) la quantité élevée d'impacts générés par le procédé de fabrication de poudre; 2) l'importance de considérer le processus de finition dans l'ACV du composant réalisé et 3) les effets négligeables de la réalisation CAO.

En outre, l'analyse a confirmé que les impacts proviennent surtout de deux aspects techniques: le produit et le processus d'impression. Les deux sont affectés par les différents contributeurs.

9.4 Contributions de la recherche

La première contribution est la construction d'un cadre regroupant tous les contributeurs aux impacts identifiés dans les trois expériences. (Figure a). Il montre les quatre éléments clés à la source des impacts: Le processus d'impression et le produit (aspects techniques) et le niveau d'expertise de l'utilisateur dans la CAO et le niveau d'expertise de l'utilisateur dans l'impression (aspects humains). Pour chaque élément clé, les contributeurs sont présentés.

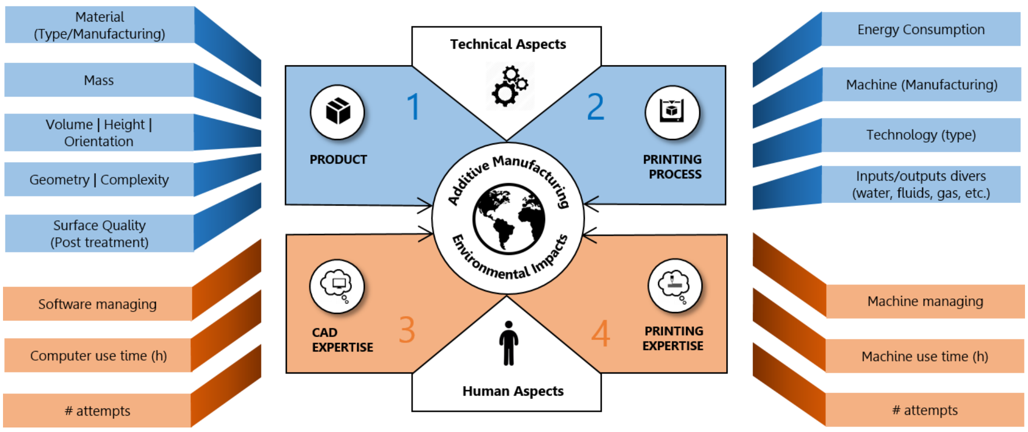


Figure a) Cadre de contributeurs d'impacts sur la FA

La deuxième contribution est adressée aux chercheurs et professionnels de l'ACV. Un modèle permettant de construire une ACV adaptée pour évaluer la mise en usage de la FA est proposé (Fig. b). Il indique les cinq phases du cycle de vie à prendre en compte, ainsi que les branches spécifiques à étudier lorsqu'un produit imprimé est évaluée dans un prisme environnemental.

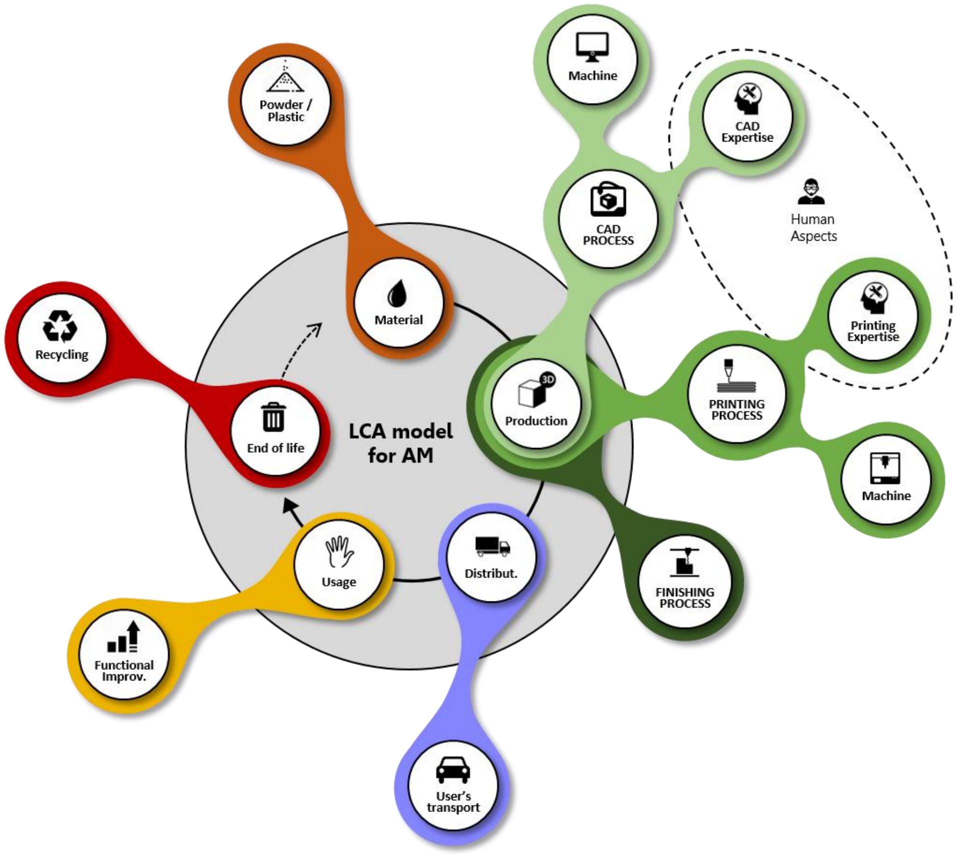


Figure b) Modèle d'ACV adapté á la FA

En rassemblant ces deux contributions, nous avons pu proposer le concept d'un outil pour mener des ACV simplifiées portant sur la mise en usage des technologies de FA. Cet outil permet d'évaluer globalement les impacts, en évitant d'omettre dans les analyses des éléments contributeurs pouvant influencer fortement les conclusions d'études d'impacts pour ces nouvelles technologies de FA. (Fig. c)

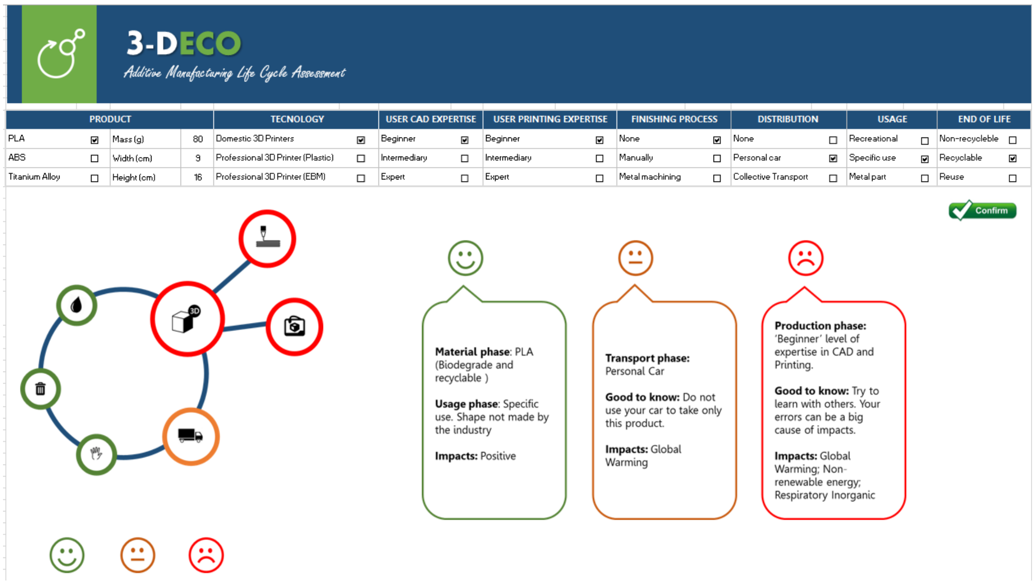


Fig. c) Concept d'un logiciel d'ACV adapté à la FA

9.5 Conclusions

La FA est une nouvelle technologie et ses impacts sur l'environnement sont encore en train d'être étudié. Cette recherche a prouvé que les impacts proviennent de différentes sources selon la technologie et sa mise en usage, et que la meilleure façon de les évaluer est de considérer les spécificités de chaque domaine d'application.

Il est irréaliste de penser que la Fabrication Additive remplacera la fabrication classique un jour. Toutefois, il est raisonnable de croire que, à l'avenir, les charges environnementales seront mises en première ligne de ce développement révolutionnaire. Les études des bénéfices associés à la fabrication additive ne font que commencer.

Annexe 1

Survey: 3d Printing users profile (Questions)

1. In which country do you live? *
Em qual país você vive?

2. In which city do you live? *
Em qual cidade você vive?

3. How old are you? *
Qual sua idade?

4. Which 3d printing user profile suits you best? *
Em qual perfil de usuário de impressão 3d você mais se identifica?

Mark only one oval.

- Expert User (professionals, printer makers, 3d hubs, skillful makers, etc)
- Amateur User 1: (Recreational use)
- Amateur User 2: (Professional use)
- Potential user: I am interested in 3d printing technology, but I have never used it
- Customer: I am not interested in 3d printing technology, just in 3d printed products
- Other:

5. Which are/were your motivations to use/start using 3d printing technology and printed products? *
Quais foram/são suas motivações para usar/começar a usar a tecnologia de impressão 3d e produtos impressos?

Tick all that apply.

- It is a work necessity
- It is a work opportunity
- I am already a maker
- I am curious about new technologies
- I just like personalized products
- Other:

6. What is your experience level with CAD (Computer Aided Design) software? [Ex. Solidworks, Catia, Creo, Rhinoceros, etc] *
Qual seu nível de experiência com softwares 3d (Ex. Solidworks, Catia, Rhinoceros, etc)

Mark only one oval.
- o Expert
- o Intermediary
- o Beginner
- o Not a user

7. To design/create a new product using CAD system, which option do you prefer?
Para conceber/desenhar um novo produto em softwares 3d, você prefere:

Mark only one oval.
- o Make it at home (house/job)
- o Make it in a FabLab (*)
- o Paid Service except FabLab (specialized websites, stores or people)
- o Free service (Friends, family, etc)
- o Download a free project on the internet
- o Other:

(*) → If you want to know more about 'What is a FabLab', please see the brief video below !

8. What is your experience level with 3d printing? *
Qual o seu nível de experiência com impressão 3d?

Mark only one oval.
- o I print frequently
- o I print eventually
- o I have just tryed it out
- o I have never printed before (Go to question 11)

9. If you have already printed a product, where have you done it?
Se você já imprimiu algum produto, onde você o fez?

Tick all that apply.
- o At home
- o FabLab
- o University / Institutions
- o Paid service (specialized websites, stores or people)
- o Free service (Friends, family, etc)
- o Other:

10. Which 3d-printer model do you/did you use ? (After, go to question 12)
Qual modelo de impressora 3d você utilisa/utilisou ? (Em seguida, vá para questão 12)

11. If you have never printed any product, which option would be the best way for you to start using that technology?
Se você nunca imprimiu nenhum produto antes, qual seria a melhor maneira/local para você começar a imprimir?
Mark only one oval.
- o At home (buy a 3d Printer)
- o FabLab
- o University / Institutions
- o Paid service (specialized websites, stores or people)
- o Free service (Friends, family, etc)
- o Other:

12. Which type of products do you print / would be interested in printing more frequently ? *

Que tipo de produto você imprime /tem interesse em imprimir mais frequentemente? Tick all that apply.

- Spare parts for replacement
- Industrial Components
- Medical objects/products
- Toys in general
- Personal objects (e.g. Cell phone cases, bijous, sport items, etc)
- House decoration items
- Gadgets in general
- Prototypes (Product/Architecture)
- Other:

13. In a linear scale below (0-6), choose the value that better represents your feeling about the environmental impacts of 3d printing technology. *
Na escala liner abaixo (0-6), escolha o valor que melhor representa sua impresão geral sobre os impactos ambientais da tecnologia de impressão 3d.

Mark only one oval.

1 2 3 4 5 6

It generates LOW impact It generates HIGH impact

14. How much would you pay for a printed mug ordered in the internet on a specialized 3d print service website? *
Quanto você pagaria por uma caneca personalizada impressa por uma empresa especializada no serviço de impressão 3d pela internet? (Por favor considere 1 Euro = 4 Reais)

Mark only one oval.

- Less than 10 euros/dollars
- Between 10 and 20 euros/dollars
- Between 20 and 50 euros/dollars
- Between 50 and 100 euros/dollars
- More than 100 euros/dollars

15. Do you have/would you like to have a 3d printer at home? *
Você tem/gostaria de ter um impressora 3d em casa ?

Mark only one oval.

- Yes, I already have one (or several)
- Yes, I would like to have one
- Maybe in the future
- Not at all
- I am not sure about it

16. If you have a 3d printer at home, what is its model?
Se você tem uma impressora 3d em casa, qual o modelo/marca?

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Tudo Passa.

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