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Where do the environmental impacts of Additive Manufacturing come from? Case study of the use of 3d-printing to print orthotic insoles

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Résumé - La Fabrication Additive (FA) est un processus de plus en plus répandu et comme toute nouvelle technologie ses impacts environnementaux sont encore peu connus. Certains auteurs étudient et analysent ces impacts en utilisant une démarche d'Analyse du Cycle de Vie (ACV). Cet article présente une étude réalisée à l'aide de l'ACV pour identifier les hotspot des impacts environnementaux d'une start-up qui utilise la technologie d'impression 3D pour imprimer des semelles orthopédiques. Les résultats suggèrent que lorsque la fabrication additive est utilisée, comme ici, par des utilisateurs experts en CAO et impression 3D pour imprimer de petits produits en plastique, c'est le processus d'impression 3D qui génère les impacts environnementaux les plus importants. L'imprimante 3D, en raison de sa consommation d'énergie, provoque le hotspot environnemental et mérite une attention particulière, surtout si des arguments environnementaux doivent être associés au produit fabriqué.

Mots clés – Fabrication Additive, Impression 3D, Impact Environnemental, ACV

Abstract – Additive Manufacturing (AM) is becoming more popular each day, and as all disruptive technology, its environmental impacts are still little known. Some authors have been studying and analysing its environmental impacts using Life Cycle Assessment (LCA) that is the most common method for this. This paper presents an experiment performed by using Life Cycle Assessment to identify the environmental hotspot of a start-up that uses 3d-printing technology to print orthotic insoles. The findings suggest that when AM is used by expert users (CAD and 3d-Printing) as a business opportunity to print small plastic products, the Printing process is the most impacting phase regarding environmental impacts. The 3d-printer machine, due to the energy consumption, causes the environmental hotspot and deserves special attention, particularly if environmental arguments have to be associated to the final product.

Keywords – Additive Manufacturing, 3D-Printing, Environmental Impacts, LCA

1 INTRODUCTION

Since the Industrial Revolution in the 19th century, the production of goods is synonymous with heavy industry, machine tools, production lines and economies of large scale [Bouffaron, 2014]. Nowadays, several reports and researches show that many important environmental problems as global warming affecting our planet ecosystems are due to pollutions, such as greenhouse gas emissions released by our industrial manufacturing systems in the atmosphere.

Industrial Manufacturing (IM) although recognised as one of the biggest cause of the environmental impacts, works to satisfy the population consumption standard. To satisfy the

personal desires of the consumer is a new challenge for the IM but it is also becoming a business opportunity to enterprises and market, especially because of the product customization trend. According to [Bouffaron, 2014] modern consumers now require highly customised products, fast service, and a lightning delivery.

Facing economics world changes and new consumption standards, the concept of Additive Manufacturing (AM), a type of manufacturing that produces physical objects from digital information layer-by-layer, starts to become increasingly popular. Nowadays, the development of this new manufacturing process is called by many authors "The New

Industrial Revolution” [Thompson, 2016]. The basic principle of AM technologies is the fabrication of parts using an additive approach. A model initially generated using a three-dimensional Computer-Aided Design (3D CAD) system, can be fabricated directly without the need for process planning.

As all disruptive technology, AM is breaking many manufacturing paradigms, and some authors have been studying and analysing the environmental impacts of it using Life Cycle Assessment (LCA), the most common method. In this context, [Wilson, 2013] quoting Dr Bert Bras, Professor of Mechanical Engineering at the US Georgia Institute of Engineering, said that ‘to look for evidence of environmental benefits of Additive Manufacturing, sustainability professionals have to seek proof using ISO 14001 standard Life Cycle Analysis (LCA)’.

This paper presents the results of a study performed in a start-up that uses 3d-printing technology to print orthotic insoles.

An LCA was carried out to compare the environmental impacts of two similar orthotic insoles: one made by classic handmade production and the other one made by using 3d-printing technology. The goal is to discover how environmental impacts are addressed in additive manufacturing in comparison to a classic manufacturing and which phase is the most representative regarding the impacts.

2 METHOD AND PROCEDURES

A young innovative start-up that uses 3d-printing to print orthotic insoles was investigated, and its activities analysed during six months (February to July 2016). The experiment consisted in 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. Both were analysed with the same scale production (custom product), to find how environmental impacts are addressed in this model of AM usage in comparison with a classic manufacturing.

The method of assessment employed was Life Cycle Assessment (LCA). It is a scientific approach for a growing number of modern environmental policies and business decision supporting the context of sustainable consumption and production. LCA examines the environmental impacts of a product/process by considering the major stages of a product’s life, which are: Raw material acquisition, Production, Usage and Waste Management/End of life. [European Commission, 2010; Williams, 2009].

The LCA was carried out using the software SIMAPRO 8 and the database prioritised was Ecoinvent 3. All data were collected by means of interviews with the company experts as well as observation and tests on site. The method for impact’s calculation is IMPACT 2002+ which divide the environmental impacts into two categories: Midpoints (15 impacts) and Damage (4 groups of impacts), as shown in figure 1. Analysis and results of this experiment will be concentrate/presented mostly in Damage Categories composed by four groups of impacts: Human Health, Ecosystem Quality, Climate Change and Resources.

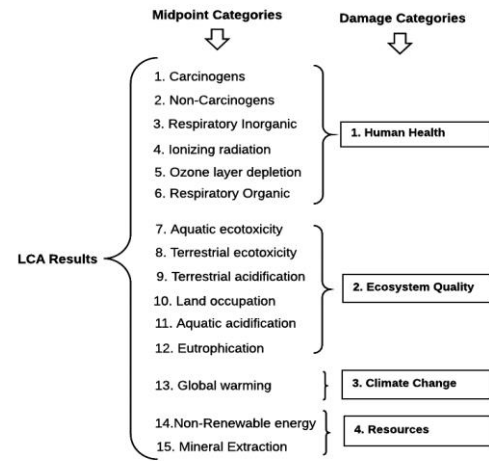


Figure 1. Impact Categories

3 LITERATURE REVIEW

3.1 Additive Manufacturing

Additive Manufacturing (AM) is the formalised term for what is used to be called rapid prototyping and what is popularly called 3d-Printing. It is a process joining materials to make objects from 3d model, usually layer by layer, the opposite way compared to subtractive manufacturing processes. It supports a wide range of activities including manufacturing, energy, transportation, art, architecture, education, hobbies, space exploration, military, medical, dental, and aerospace industries. [Thompson, 2016].

AM 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 processing such as cement to print houses, wood powder to print wood objects and alimentary materials to print food is already a reality but still not widespread.

3.2 Orthotic Insoles

An orthotic insole is a moulded part of rubber, plastic, or other material to be inserted into a shoe (Fig. 2). It corrects the alignment and cushions the foot from excessive pounding. A wide range of orthotics insoles is available for different foot problems, for sport and other physically intensive activities. They have been used for patients with diabetes, adjustment of flat feet, compensation for osteoarthritic knees and treatment or prevention of rheumatoid foot disease. [William H. Bland, 2014]



Figure 2. Orthotic Insole

4 EXPERIMENT

4.1 Life Cycle 1 (Classic handmade insole)

The life cycle of a classic orthotic insole considers the following 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 a classic orthotic insole. For this study, only the total energy used was considered. Therefore, there is no impact of machines manufacturing in this LCA. The insole is made by a Chiropodist, using a traditional multi-layer system and the different densities in the same insole are reached using small layers of specific materials added on it according to the patient feet necessity. (Figure 3).



Figure 3. Classic Manufacturing

The hypotheses assumed regarding the *Distribution phase* consider that the product is delivered without package and the patient drives about 30km to get it with three round trips of 10km each one: 1st. - The patient consults a Chiropodist, 2nd. - The patient collects the insole, 3rd. - The patient goes back to verify the insole after test/use.

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 given that, there is not an evident system of EVA recycling in France. The distance between patient's place to the disposal area is estimated around 20km. Figure 4 shows the whole life cycle modelled for a classic orthotic insole with the detail of phases, values and sort of transport.

4.1.1 Results and Analysis

Considering the whole life cycle of one insole (classic manufacturing), Production and Distribution are the most impactful phases regarding environmental impacts. In relation with them, End of Life phase becomes negligible. The impacts of these two phases are mainly focused in three impacts categories: Human Health, Climate Change and Resources, the last one being the most representative (Fig. 5).

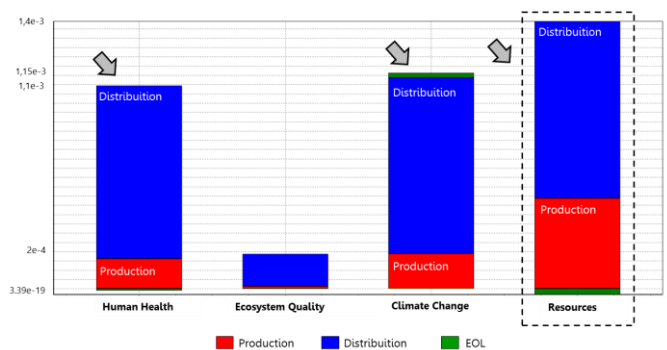


Figure 5. Life Cycle Impacts (normalisation)

When the whole life cycle is analysed by percentage (Fig. 6), it can be noted that Production phase represents in average 19% of impacts and Distribution respond for 80%. The two main factors that contribute to the impact on Production phase are the material EVA and the Energy consumed (electricity). The total of emission and impact in Distribution phase came from the patient's car use.

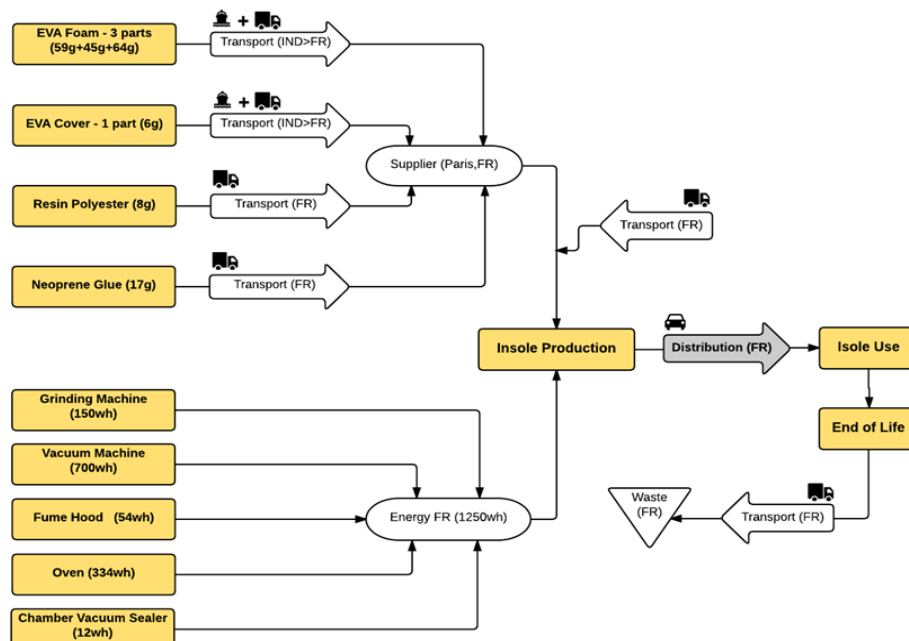


Figure 4. Life Cycle (Insole classic manufacturing)

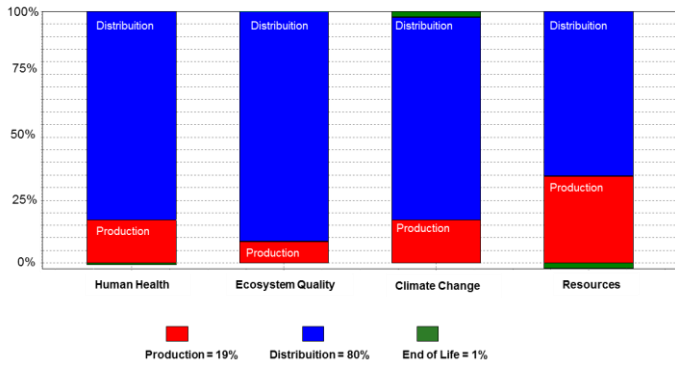


Figure 6. Life Cycle Impacts (percentage)

4.2 Life Cycle 2 (Printed insole)

The manufacturing process of a printed insole is composed of four stages as illustrated figure 7:

- 1) Feet are scanned by the Chiropodist using a 3d-scanner and a specific software;
- 2) The Chiropodist designs the insole using a specific software;
- 3) The Company prints the insole using a specific plastic (confidential information).
- 4) The finishing process is made putting a thin cover of EVA on the top of the insole.

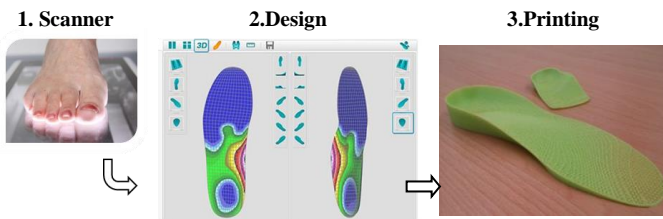


Figure 7. 3d-printed insole process

The type of plastic used to print (more resistant than EVA) gives to the insole a bigger lifespan if compared with others similar products. Additionally, this plastic allows printing variable densities in the same insole using a unique material (Fig. 8). These are the main differential elements of printed

insoles compared to classic ones.

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

Figure 9 illustrates the whole life cycle of a 3d-printed insole.



Figure 8. Different densities in the same insole

The 3d-printed insole is manufactured using three different machines: a computer, a 3d-scanner and a 3d-printer. Table 1 shows machines, power consumption and the total of energy used for one insole. For that study, the machine manufacturing is not considered, just the energy consumed.

Table 1. Machines and energy consumption

Machine	Use	Power (w)	Use time (minutes)	Energy (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

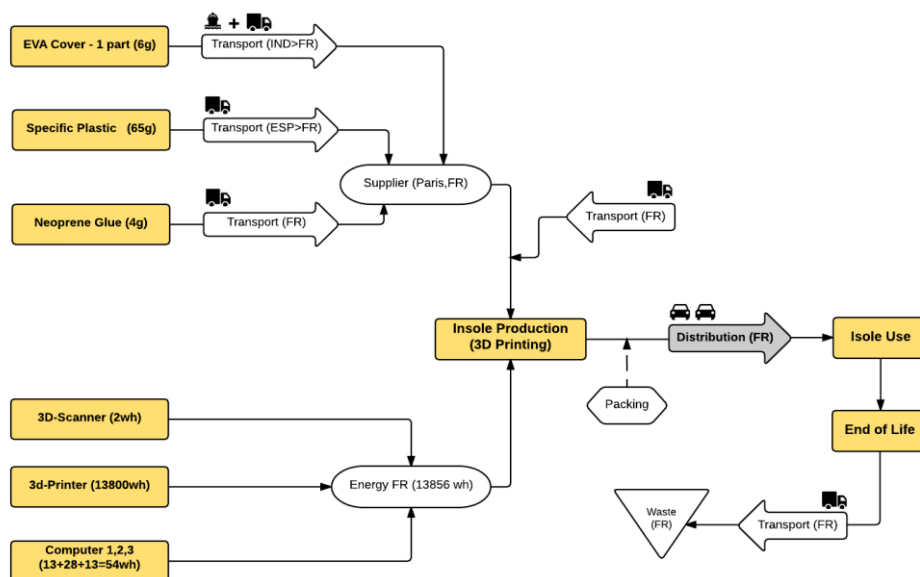


Figure 9 – Life Cycle (Printed insole)

Concerning the Distribution phase, as shown in Figure 10, the patient goes three times to chiropodist clinic; the chiropodist sends the file (insole design) to the 3d-printing company by internet, and the company send the printed insole to the chiropodist's place (5km) using company's car. The frequency is once per day and 60 units of insoles delivered. The 3d-printing company uses a paper package to transport insoles. Usage and End of Life phases are exactly similar to the classic orthotic insole.

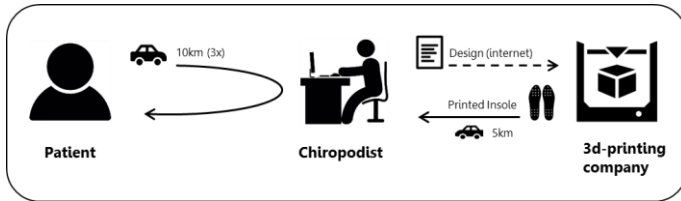


Figure 10. Distribution phase (3d-printed insole)

4.2.1 Results and Analysis

The graphic in figure 11 shows that, in average, regarding the four big groups of impacts (Human Health, Ecosystem Quality, Climate Change and Resources), the Distribution phase of a 3d-printed insole impacts the most (61%) followed by Production phase (39%). End of life phase releases a small impact in climate change category (2%).

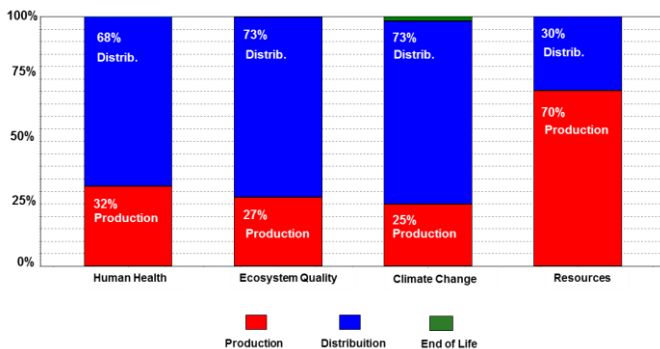


Figure 11. Impacts - Life Cycle of a 3d-printed insole

When the impacts are analysed separately, in Resources group, *Production phase* is responsible for the biggest part of impacts (70%). Observing this phase in details (Fig. 12), it can be noted that Electricity (FR) is responsible for 95.9 % of impacts. In that category, the impacts are located in 'Non-renewable energy' and 'Mineral Extraction', the last one certainly linked to Uranium extraction necessary to produce Nuclear energy.

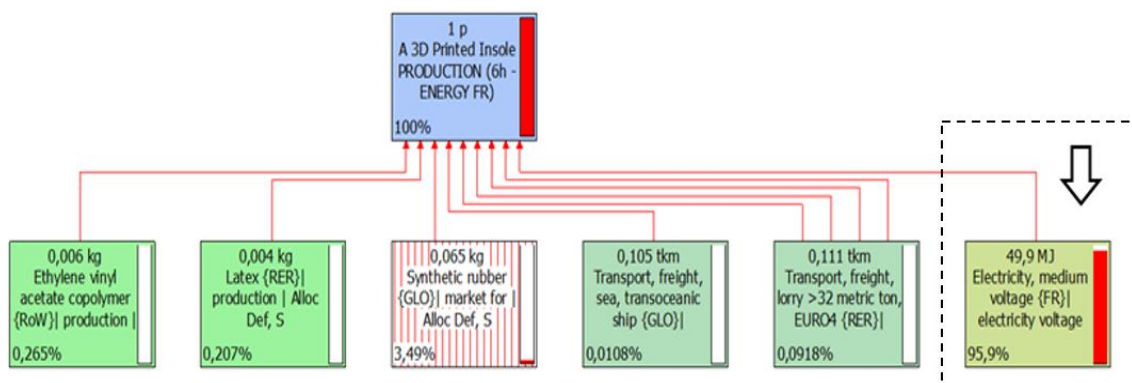


Figure 12 – Production Phase (Impacts in Resources)

Concerning *Distribution* phase, the main cause of impacts is the use of patient and 3d-printing company cars, patient's car being the most impactful, similarly to a classic insole. Overall, regarding the manufacturing of a 3d-printed orthotic insole, similarly to a classic orthotic insole, the Distribution and Production phases are widely more impactful than Usage and End of life phases in tree main impacts categories: Human Health, Climate Change and Resources.

4.3 Life Cycle Comparison (Classic vs. Printed insole)

According to [Teulon, 2015], an LCA does not compare products/services itself, but its function. In this study, considering the differences between both manufacturing processes, the finished products are naturally slightly different (materials, lifespan, structure). However, both products fulfil the same function: providing comfort and correction to the patient's foot needs. Furthermore, both insoles are made on the same scale production level, this is a tailored product.

All of these characteristics make this comparison feasible and reasonable. In order to carry out the study, the following Functional Unit (FU) was defined: *Provide an efficient aid 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 four months bigger than a classic one. So we have a 12 months lifetime for a 3d-printed and 8 months lifetime for the other one. Regarding this scenario, 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. This amount certainly determines the difference of impacts as illustrated in the bar chart presented in figure 13.

Regarding the four main impacts categories (Human Health, Ecosystem Quality, Climate Change and Resources), it can be noted that: in Ecosystem Quality category, the gap between the two results is less than 15%, so, it will be not considered in this analysis because it is not significant enough. In Human Health and Climate Change, a 3d-printed insole is about 20% and 25% less impactful respectively. In Resources category, 3D Printed insole overcomes by 35% the impacts of a classic insole.

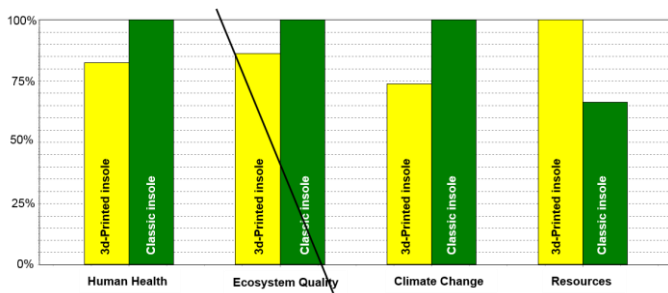


Figure 13. Life Cycles Comparison

A special remark regarding those results concerns the fact that the 3d-printed insole is made in France, using nuclear energy, and then justifies a low level of impacts in the Climate Change category. These results could be different if the product was printed in other countries with other sources of energy.

Analysing each phase separately as shown in figure 14, it can be noted that concerning *Material phase* (A), impacts from 3d-printed insole are 65% less than a classic one in the four impact categories.

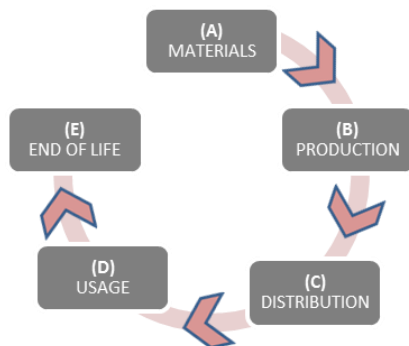


Figure 14. Life cycle phases

In *Production phase* (B) (material + transportation + energy), 3D-Printed Orthotic Insole outweighs the impacts on Human Health (+35%), Ecosystem Quality (+60%) and Resources (+60%). To further delve into this analysis, figure 15 shows that among 15 impacts categories, the *Production phase* of a 3d-printing insole overcomes the Classic production in 10 categories, excluding three because the gap is less than 15%.

This result, as already seen previously, comes from the use of electricity during the 3d-printing process (13.856Wh p/insole). In the 'non-renewable energy' category (14), for instance, the impacts of 3d-printing is 70% higher than the other one. As a result, even considering the comparison of 1 printed insole vs. 1.5 classic insoles, in average, the Production phase of 3d-printing insole overcomes the impacts of a classic production around 60% regarding ten impacts categories.

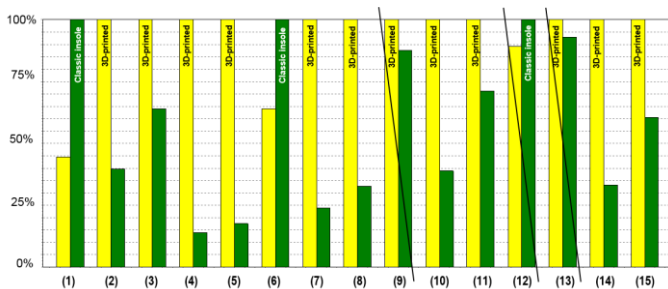


Figure 15. Comparison: Production phase (see Fig. 1 to relate numbers to impacts)

Concerning the *Distribution phase* (C), the 3D-printed insole impacts 35% less on all the four categories. Indeed, a Classic

insole uses less transport. However, to satisfy the defined FU, more quantity of insoles is needed, then, as a result, in term of transport, a 3D-Printed insole impacts less than a classic one when it considers one year of use.

Concerning the *Usage phase* (D), 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 (12 months) in comparison to a classic one (8 months), it can be deduced that a 3d-printing insole is less impactful.

Regarding *End of Life phase* (E) 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. It can be found in the literature that EVA and the plastic used to print can be recycled/reprocessed/reused by different methods for different purposes. However, there is not information about the availability of these specific treatments in the France municipal waste collection.

4.4 Discussions

Taking into account the four groups of environmental impacts (Human Health, Ecosystem Quality, Climate Change and Resources), the 3d-printing orthotic insole manufacturing impacts less than a Classic manufacturing considering Material, Distribution, and Usage phases. End of life phase is the same for both products, and in the Production phase, the impacts of 3d-printing manufacturing overcome the other one (Fig.16).

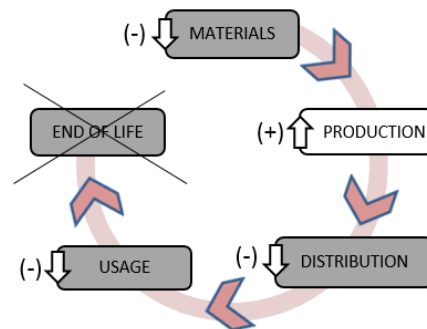


Figure 16. Impacts per phase (3d-printed insole)

However, even if the 3d-printing manufacturing presents the best results for the environment in 3 lifecycle phases (material, distribution and Usage), it is inappropriate to conclude that it is globally better than a classic manufacturing.

The way how each component in each phases impacts the environment is different in type and level. Impacts of the Production phase, for instance, can be widely bigger than the other three together.

This LCA brings forward an important fact: the high level of impacts generated by the 3d-printing process even without consider the machine manufacturing. The results can be observed especially in Non-renewable Energy and Resources. Concerning the 3d-Printing Process, for this case study, the energy consumed to print one insole is 13.800Wh, a huge amount.

In order to better understand the relation between the printing process and energy consumption, figure 17 shows a sensitivity analysis considering different printing times for one printed insole and different types of energy.

Due to confidential issues, the following nomenclature will be considered in figure 17: X_h = Real printing time / Y_h =Reduced printing time by 2 hours.

Reducing the printing time by 2h, 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. This analysis indicates that the way to reduce the environmental impacts of AM for this type of use is reducing the printing time investing in better performance 3d-printers and choosing the best energy source.

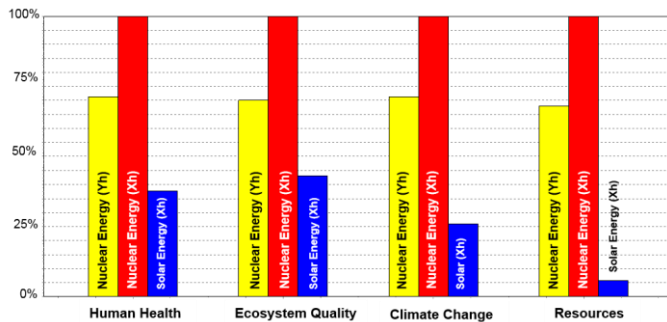


Figure 17. Printing time vs. energy type

Comparing the impacts released by the 3d-printing process with the printed part (Material, Transport), it can be observed that the energy consumed by the machine corresponds to 89% of the global impacts being more representative in Resource category.

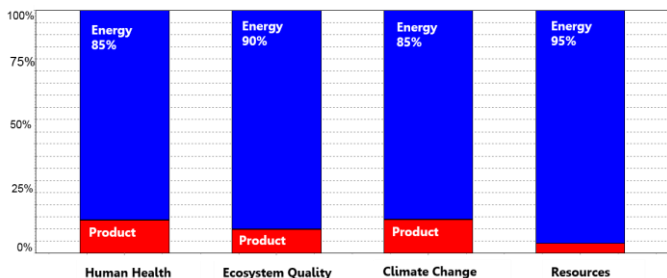


Figure 18. Material vs. Energy

Hence, when an orthotic insole is made by a specialised company in CAD and 3D-Printing, using additive manufacturing technology, the 3d-printer machine is the most important point to be controlled in term of environmental impacts generation. This scenario can also be extended to other companies having the same kind of activities.

5 CONCLUSIONS

In order to find out evidence about the environmental impacts of Additive Manufacturing compared to a classic manufacturing, an experiment using Life Cycle Assessment was performed in a start-up that uses 3d-printing technology to print plastic orthotic insoles.

The LCA was carried out to compare the environmental impacts of two similar orthotic insoles: one made by classic handmade production and the other one made by using 3d-printing technology. The goal was to find out how environmental impacts are addressed in additive manufacturing in comparison to a classic manufacturing and

which phase is the most representative regarding impacts. This study shows that Production phase due to 3d-printer energy consumption is widely the most impactful. When compared with the material, the 3d-printer machine responds globally for 89% of impacts in four categories: Human Health, Ecosystem Quality, Climate Change and Resources.

Finally, this research allows to conclude that when Additive Manufacturing is used by expert users (CAD and 3d-Printing) as a business opportunity to print small plastic products, the Printing Process is the most impacting element. The 3d-printer machine, due to the energy consumption, causes the environmental hotspot and deserves special attention, particularly if environmental arguments have to be associated with the final product.

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