DEVELOPMENT OF A LOCK PRODUCED BY ADDITIVE MANUFACTURING WITH ECONOMIC AND ENVIRONMENTAL ANALYSIS

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ABSTRACT

Additive manufacturing has grown a lot in the last few years. Its initial function of rapid prototyping and accelerating product development is still its main function, but it has also started to evolve into the manufacturing of end use products. Due to their characteristics, AM processes seem to have their space in the market on the production of small series and customized products.

This thesis addresses the development of a non-metallic, customizable lock produced by AM, for a window developed by a Company, considering the costs and environmental impact of its production. The 3D printer used was Mark Two from Markforged, which is the only commercially available printer capable of reinforcing its parts with continuous fibre.

The methodology of product design and development was applied, with the establishment of needs and specifications which led to the generation and selection of concepts. Prototypes of the most promising concepts were produced and tested to establish final specifications.

With the measurements of material and energy taken from the production of the prototypes, a cost model was developed to calculate the unitary cost of the lock, with some alternative options presented as well as sensitivity analyses.

By last, applying the methodology of Life Cycle Assessment (LCA) and using LCA software SimaPro, an environmental impact analysis was carried to the production process, comparing to the more traditional method of injection moulding,

KEYWORDS: Additive Manufacturing (AM); Fibre Reinforcement; Customizable Lock; Product Development; Production Costs; Life Cycle Assessment (LCA).

1. Introduction

The Additive Manufacturing (AM) industry has been and still is growing. As companies look to modernize and become more competitive they look to the advantages AM can bring such as design flexibility and quick time to produce parts directly from CAD data. The initial and most common area for AM is still prototyping and accelerating the process of product development. However, it has already started to be used for end use products [1]. This has been especially prominent in the aerospace and medical fields, due to the possibility to produce complex geometries, simplifying assemblies and to the relative low cost of “one-off” customized parts [2].

Composite materials in AM are still underdeveloped compared to metals. Materials with short/chopped fibres are used, but are far from the advantages presented by traditional composites in terms of mechanical properties. Research in ongoing however, on AM processes with continuous fibre reinforcement. The 3D printer used in this work is the first (and so far only) commercially available printer capable of reinforcing parts with continuous fibre. The process used by this machine is the Fused Deposition Modelling (FDM) [3].

In collaboration with a company, an opportunity was identified to produce an end use product by AM, taking advantage of the cost effectiveness for small batches of production as well as the design flexibility which offers great potential for customization. The product is a non-metallic lock intended for a new window designed by the company. Relatively small orders are expected and customization offers great added value to this product.

The goal of this work is therefore to develop a concept for this product and assess its economic and environmental sustainability. Furthermore is assessed the need to reinforce parts with continuous fibre and a comparison is made with the more traditional injection moulding in terms of costs and environmental impact.

The methodology of product development was applied, including the establishment of customer needs and specifications. Prototypes were built and tested for the setting of final specifications. A part was reinforced locally with continuous fibre to comply with a loading case from a specification. During the process of product development, the house of quality method was also used, allowing a general view of concentrated information in any phase.

The measures taken from the production of the prototypes were used in the economical and environmental analyses. A cost model was developed and a value for unitary cost was calculated. Sensitivity analyses were performed to characteristics of the process, as well as a comparison with injection moulding and additional AM options were considered. An environmental impact analysis was also performed, using the LCA methodology and Simapro 8 software. The analysis was made as a comparative analysis, considering the same AM and injection moulding options discussed in the economic analysis.

2. Product design and development

2.1. Mission Statement

The methodology of (Ulrich and Eppinger 2011) was applied and the first step of the developing process was to make a mission statement, which specified the opportunity along with the inherent objectives and constraints.

Mission Statement: Customizable Non-metallic Lock for Evolution Minimal Window.

Product Description: Customizable, non-metallic, simple to use latch lock for Evolution Minimal Window.

Benefit Proposition: Resistant to corrosion in any circumstance, non-metallic; Customizable – aesthetically pleasant for costumers.

Key Business Goals: Complement the new concept of minimal windows in the company with a unique product which adds value; Have a product in a segment in which competitors also have products, but with differentiating factors; Sale of 100 units per year.

Primary Market: Boavista Windows.

Secondary Market: Other companies who sell minimal/sliding windows; other costumers who already have minimal/sliding windows; Customers looking for customizable accessories.

Assumptions and Constraints: Exterior/aesthetic part of the lock will be customizable; Lock cannot have any metallic parts; Lock should be adapted to set up on the already existing design of the Evolution minimal window; Design allows for posterior inclusion of key cylinder; Available AM machine Markforged Two; Material: Nylon, fibreglass, carbon fibre; Adequate cost.

Stakeholders: Costumers; Companies who sell windows; Designers, managers, marketers and operators; Manufacturers of parts/materials from outside the company; Manufacturers of machines and materials used to produce the product.

2.2. Establishing the needs

The following step was to establish the needs, which are attributes desired for the product, expressed in everyday language, stating what the product has to do and not how to do it. Table 2-1 the needs identified with the assigned importance.

Number	Lock must be	Imp.
1	Easy/simple to use	5
2	Ergonomically pleasant	4
3	Small	3
4	Good finishing	4
5	Rigid	3
6	Durable	4
7	Lubrication-free	3
8	Quick to produce	1
9	Quick to assemble	2
10	Easy/simple to install	5
11	Affordable	2

Table 2-1: Table of needs

The scale used to assign importance was the following: 1- Slightly important, but not a priority; 2- Important; 3- Fairly important; 4- Very important, priority; 5- Extremely important, top priority.

2.3. Target specifications

Metrics are measurable characteristics which allow assessing if the needs are satisfied. A metric and a target value form a specification.

After determining the metrics that best reflect the needs established, target values were given. The house of quality, a graphical technique used in Quality Function Deployment (QFD) [5] was used to define the relationships between needs and metrics, resulting in a relative weight for each metric. That weight was normalized and is presented in Table 2-2 with the specifications.

No.	Metric	Target Value	Norm. Weight
1	Easy to open/close with one hand	Yes	10.0
2	Allows window to close and stays closed	Yes	10.0
3	Possible to make the lock stay open	Yes	10.0
4	Friction	μ =0.3	10.0
5	Spring constant	1 N/mm	9.1
6	Outside (visible) volume	60 cm³	6.0
7	Roughness (Ra)	12.5 μm	8.0
8	Maximum horizontal force applied on bolt	222 N	6.0
9	Maximum pulling Force	140 N	6.0
10	Binding strength	414 N	6.0
11	Cycles to failure	50 000	10.0
12	UV resistance	Yes	8.0
13	Time to produce	1 day	2.0
14	Time to assemble	5 min	4.0
15	Number of parts	3	1.3
16	Time to install	10 min	10.0
17	Cost/unit	<50 €/un	4.0

Table 2-2: Specifications

2.4. Concept Generation and selection

With the gathered information it was possible to start generating concepts. It was also useful to search externally on existing products on the market and patents. Figure 2.1presents the Evolution Minimal Window (EMW) where the lock should work. Twelve concepts were generated and evaluated.

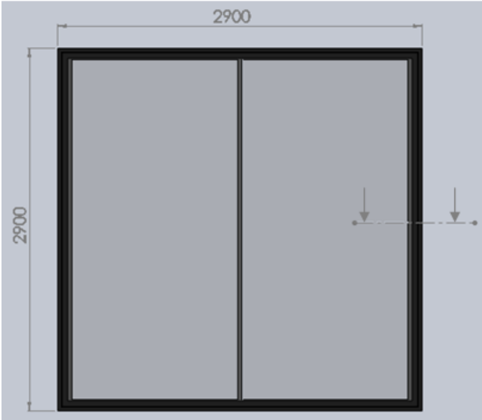

Figure 2.1- Evolution Minimal Window

With the ongoing generation of concepts, common features started to appear and so, some important subproblems were identified, namely the mode of installation and the springs. With a simple concept screening, the position of the lock relative to the window was defined, and can be seen in Figure 2.2.

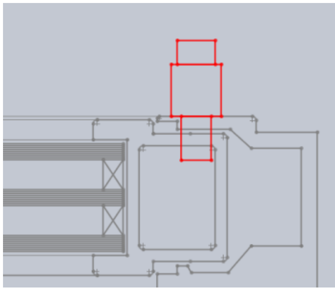

Figure 2.2- Position of the lock

The lock is installed in the outer part of the frame and enters the stile from the side. A concept scoring was also applied for the springs. The chosen spring is an injected moulded part, from Lee Spring [6]. It was the only option with the target spring constant of 1 N/mm (approximately). From a concept scoring to all the concepts, two most promising concepts emerged: concept 10 and concept 12. Both concepts have the same general geometry and same way of locking the window, as would be expected. The main difference between the concepts is that in concept 10 the handle and latch bolt are one part only and the spring is rolled up on it, whereas in concept 12 the handle and latch bolt are fixed together with the use of a fitting. These parts are presented in Figure 2.3.

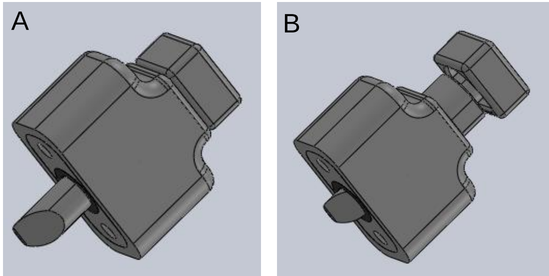

Figure 2.3- Concept 12: A) closed; B) opened

2.5. Printing of the lock

As seen in Figure 2.4, the parts were printed horizontally, to increase resistance to shear and tensile forces, which are in the specifications of this product.

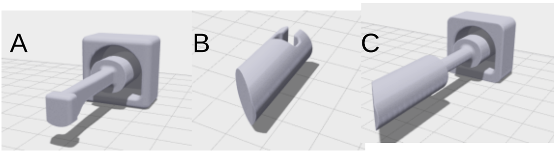

Figure 2.4- Printing orientation of A) handle (concept 12); B) bolt (concept 12); C) handle bolt (concept 10)

This orientation is not ideal for the printing of a cylindrical surface, but an adjustment was made to the geometry and post processing was used to compensate for that.

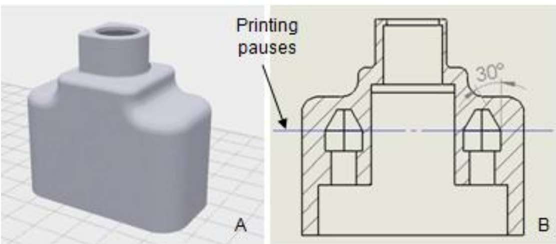

Figure 2.5- Housing (concept 12): A) print orientation; B) cross section

The orientation presented in Figure 2.5 A) allows stopping the print in a layer where the nut can be put in place and the machine can subsequently carry on printing above it. This factor contributes to the aesthetics of the product, allowing for a continuous exterior surface. It is important to note the 30º roof of this blind hole. It was designed so that the Eiger software does not create supports in the “floor” of the space for the nut, at the same time it gives some clearance space for the tip of the screw.

The lid follows the same orientation of the housing (Figure 2.6).

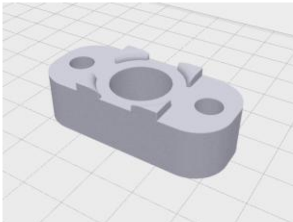

Figure 2.6- Print orientation of the lid (conc. 12)

Since both the holes and walls will have to be aligned, it makes sense to print in the same orientation, with the best possible geometric accuracy. Additionally this orientation allows for a concentric reinforcement of the holes with continuous fibre if needed.

2.6. Testing and setting final specifications

The design related specifications, which had a binary target, were accomplished on both concepts. Regarding friction, there is not a practical way to measure this metric. However, the use of low friction plain bearings, along with sanding of the 3D printed parts where necessary and also the existence of clearance between the bearing and the parts, guarantees a good ergonomic feel to the product. For the metric UV resistance there was not also a practical way to measure. It was considered the application of UV and moisture protecting coating. In the future, new materials or addition of UV stabilizers to the filaments could make unnecessary extra protection. The installation is equal for both concepts and is easy and within the specification, as it should be since it was addressed as a critical subproblem

For the metrics outside volume, time to produce, time to assemble, and number of parts, the values were different and are presented in Table 2-3.

	Vol. (cm³)	**Time to produce (h)**	**Time to assemb. (min)**	**No. parts (list)**
Concept 10	64	14.60	5	3
Concept 12	58	11.35	3	4

Table 2-3: Metrics with different values

The metric roughness is related to the good finish of the part. With the help of sanding and painting, improvements were obtained in the finishing of the parts. The use of a rotary tool revealed to be very helpful in speeding up the process and reaching better quality. A rugosimeter was used to assess the roughness of the surfaces on two parts with and without post-processing. The results showed a significant improvement from a measured Ra of 9.9 µm in the first part to a measured Ra of 1.4 µm in the second, corresponding to ISO grade numbers N10 and N7 respectively.

For the specifications which address mechanical efforts, tests were conducted in the Instron 3369 machine. Figure 2.7 A) and B) show the apparatus of the tensile and bending test.

A cycle test was also carried out for the target number of cycles. Table 2-4 sums up the information obtained from the tests.

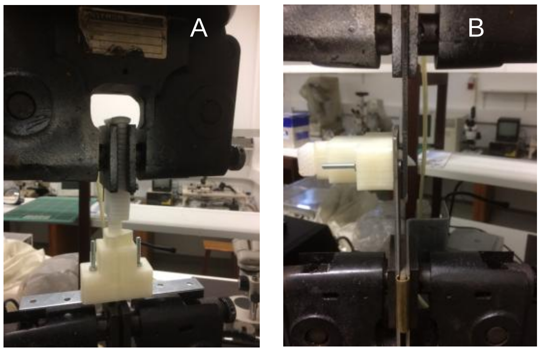

Figure 2.7- Apparatus of A) tensile test; B) bending test

	Tensile test	Bending test	No. cycles
Target	140 N	222 N	50 000
Conc. 10	203 N	212 N	50 000
Conc. 12	192 N	212 N	50 000

Table 2-4: Results of mechanical tests

For the bending test the results weren't reliable for concept 10, so the same value of concept 12 was given. This value was below the target, so reinforcement was applied. It was chosen to reinforce only concept 12, since the fitting didn't affect the results of the bending test, as it only needed approximately half the amount of fibre.

A new bolt (concept 12) was printed, reinforced with two concentric rings of continuous fibreglass in 6 layers, together 2 by 2 as shown in Figure 2.8. This will increase strength against bending around the z axis and will also strengthen the surface which suffers impact.

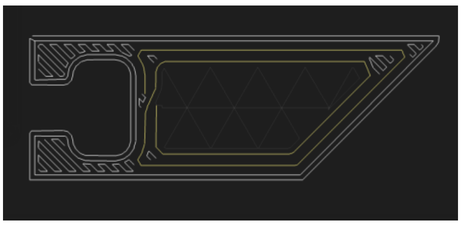

Figure 2.8- Reinforcement of bolt with concentric rings

A new test was carried out and the value obtained was 342 N. For the binding strength the calculations were made for two M6 PVDF (polyvinylidene fluoride) screws [7], with the efforts corresponding to the mentioned specifications, and a final safety factor of 1.3 was obtained.

3. Production costs

In this chapter, the unitary cost of production of the lock was calculated. The structure of costs considered included the acquisition of the equipment (3D printer), raw material, energy, purchased parts, labour and post-processing.

The machine was considered to have a depreciation time of 5 years with an opportunity cost of 10%. Raw material and energy measurements were taken during the production of the prototypes. Purchased parts included the spring, two plain bearings and two screws. The labour cost accounted for a worker to make the assemblies and post processing, while another specialized worker, works with the software and printer. By last, the post-processing accounted for the materials/equipment used divided by the number of units it could be used for. The costs for the concepts with nylon and fibreglass are presented below in Table 3-1.

	Nylon + Fibreglass	
Costs	Concept 10 (€/unit)	Concept 12 (€/unit)
Equipment	24.5	19.1
Raw Material	14.2	9.5
Energy	0.3	0.2
Purchased parts	7.9	7.9
Labour	8.5	8.5
Post Processing	2.1	2.1
Total	**57.4 €**	**47.2 €**

Table 3-1: Unitary cost of concepts

A great impact of cost from the cost of equipment is noted. Also, concept 12 is considerably less costly.

3.1. Sensitivity analyses

Sensitivity analyses were made to the effect of productive hours on unitary cost for non-dedicated equipment, reflecting the flexibility of AM machines to work almost 24 hours per day. Figure 3.1 presents the results.

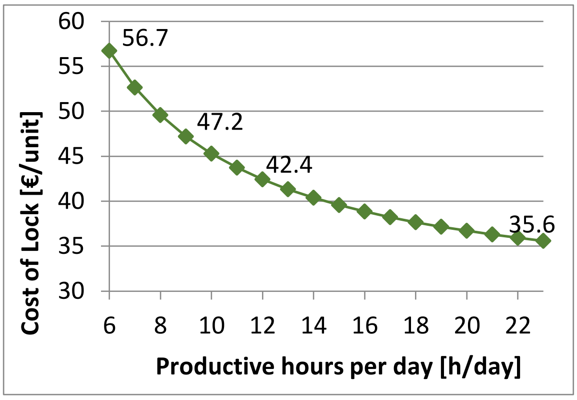

Figure 3.1- Effect of productive hours on cost of the lock

For non-dedicated equipment, the more time the machine is occupied, contributes to reduce the cost of the lock.

An analysis was also made to the effect of annual production on the unitary cost, for dedicated equipment. The behaviour found was similar to the first analysis and for the maximum of 500 units produced per year, the unitary cost found of 35.7 €, was very close to the 35.6 € calculated for 23 productive hours per day on non-dedicated equipment.

3.2. Alternatives

Two alternatives were considered to the studied process. The first option was the more traditional method injection moulding. To calculate costs for this method, quotes were requested of [8], for the tooling of the moulds, costs of setup and production. Three parts equivalent to concept 10 were considered, as concept 12 has four parts, which would mean the need for one more mould. The same production from the mission statement was considered. Cost of purchased parts and labor were adapted and the results are presented below in Table 3-2.

	Annual cost (€)	Cost per unit (€/unit)
Cost of moulds	2002.5	20.025
Setup	1498.5	14.985
Production of parts	-	6.580
Purchased parts	-	7.1
Labour	-	0.4
Total	-	**49.5 €**

Table 3-2: Unitary cost for injection moulding

The unitary cost obtained was very close to the cost of concept 12 in AM. However, the AM model has the added value of customization.

Within AM and even Markforged, other alternatives were considered. The model used in this work is the Mark Two, which is the higher model of the desktop printer, capable of printing with several materials including carbon fibre and Kevlar. However, only nylon and fibre glass were used. A lower model, which is the same machine but limited in terms of materials used, could therefore be used. The lower models only use Onyx instead of nylon as a base material though. Onyx is a filament made of nylon with chopped carbon fibres. It is more expensive, but also it has better mechanical properties and dimensional stability. It would have to be tested if an onyx only lock would need fibre reinforcement, but the cost was considered to present a viable alternative. Table 3-3 presents the costs calculated for the production on the Onyx One and Onyx Pro.

	Onyx One (Material: Onyx)	**Onyx Pro** (Material: Onyx + Fibreglass)
Cost machine (€/unit)	6.0	11.5
Cost material (€/unit)	10.3	10.6
Other costs (€/unit)	18.6	18.6
Total Cost (€/unit)	34.9 €	40.8 €

Table 3-3: Unitary cost on the lower model printers

4. Environmental Impact

A LCA analysis was carried to the production methods using software SimaPro 8.

4.1. Goal and Scope

Goal: the objective of the study is to evaluate the environmental impact of production of the developed lock using the AM process with the different materials considered compared with the more traditional injection moulding method. As secondary goal, this study could be used to understand the main factors which make one method more sustainable than other for a given production series.

Scope: the functional unit is one lock produced and the reference flow is 100 units per year during 5 years, resulting in 500 units. As a sensitivity analyses, 1000 and 2000 units were also considered.

The study uses a “cradle to gate” approach, which is an assessment of a partial product life cycle from resource extraction (cradle) to the factory/company gate (before it is transported to the consumer). In this case there are two separate systems to be compared, as described in Figure 4.1.

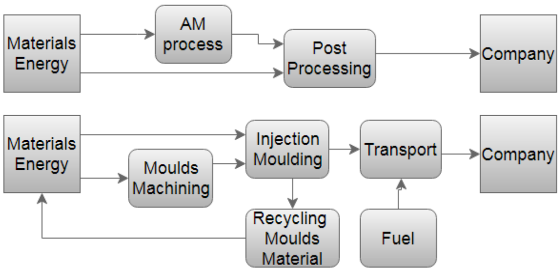

Figure 4.1- Summarized life cycle flowchart

Assumptions and limitations: data from the measurements of the AM process was used, but for the injection moulding there is no accurate date. Ecoinvent database was used where possible to obtain data regarding the inventory described in the next section.

4.2. Life cycle inventory

Table 4-1presents the values of material and energy for the AM process, taken from the measurements of the prototypes, for 1 lock.

	Nylon + Fibreglass	Onyx	Onyx + Fibreglass
Mass nylon 6 [g]	45.56	34.80	35.68
Mass carbon fibre [g]	-	12.87	13.20
Mass fibreglass [g]	0.08	-	0.08
Energy consumed [KWh]	2.156	1.839	2.156

Table 4-1: Materials and energy of the AM process

Table 4-2 presents the inventory considered for the post processing:

:

Acetone	11.79 g
Toluene	3.65 g
Propane	3.71 g
Butane	3.57 g
Ethyl 3-Ethoxypropionate	1.81 g
Medium Aromatic Hydrocarbons	0.39 g
Naphthalene	0.06 g
Methyl Ethyl Ketone	2.40 g
Methyl Isobutyl Ketone	0.96 g
Butyl Benzyl Phthalate	0.18 g
Energy	90 Wh

Table 4-2: Post-processing inventory

For the injection moulding the values of production are constant, with 56.43 g of nylon 6 and 13.05 g of glass fibre reinforced polyamide per lock. Additionally was considered a distance of 50 km from the factory to the company resulting in a value of 2.82 Kg.Km. The remaining values come from the ecoinvent database.

For the moulds, the values change according to the reference flow. It was considered three moulds with 150 kg of steel P20, 100% recycled. Also, the tooling (milling) process was considered.

4.3. Life cycle impact assessment results

Figure 4.2 shows the cumulative environmental impact of the studied alternatives. It is possible to see that for the AM models, the first with nylon and fibreglass has the lower impact, followed by onyx only and by onyx and fibreglass with the highest of the three, revealing the impact of carbon fibre in onyx.

Regarding the injection moulding, there is a high initial impact which has to be split by many units. For small production series the initial impact is very relevant, as can be seen by the impact for 500 units.

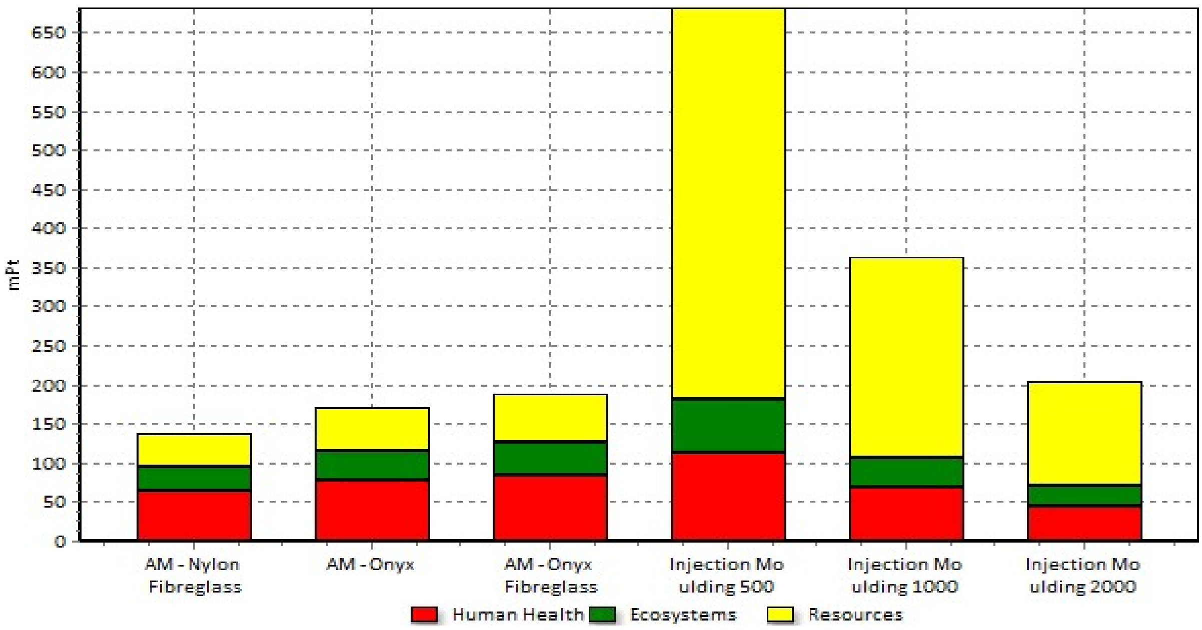

Figure 4.2- Cumulative environamental impact of the alternatives

For the reference flow of 2000 units, the injection moulding process is comparable to the AM, with lower impact on the categories of human health and ecosystems, but higher on resources. If production was increased even more, it is expectable that the impact of injection moulding would keep decreasing, whilst the AM continues constant, always with the same materials and energy for the functional unit of 1 lock.

5. Conclusions

This work was done in collaboration with a company and the objective was to develop a concept for a non-metallic and customizable lock, considering its economic and environmental sustainability.

The methodology of product design and development was applied, resulting in the identification of two promising concepts. Prototypes were made of the concepts and tests carried out for setting of final specifications.

An environmental analysis was also done, using LCA software SimaPro.

Concept 12 was found to comply with the specifications and present lower volume, time to produce, time to assemble and unitary cost.

Localized fibre reinforcement was necessary and useful to reach the target specifications.

For the considered annual production, the AM model achieved a lower unitary cost and environmental impact.

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