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Sustainability Analysis of 3D Printing Adoption in Distributed Manufacturing of Mobile Case Covers

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Abstract

Traditional manufacturing of short life cycle products frequently leads to overproduction and unsold waste products. This is due to excessive demand forecasts made to satisfy quick product launch and responsive fulfillment, usually achieved through Make-To-Stock (MTS) production using injection moulding. This leads to unnecessary wastes that burden the environment while, due to usual local production, the CO_2 emissions burden the region of interest, which in most cases is China. This work investigates the impact, in terms of sustainability, of adopting distributed manufacturing through Three-Dimensional Printing (3DP) compared to localized manufacturing through injection moulding, in the production of mobile case covers. 3DP technologies, including in-home recycling systems, not only enable a Make-To-Order (MTO) production, leading to drastically decrease wastes, but also empowers the final user with full control of the end-of-life product disposal management. A state of art review was conducted over recent analysis of additively manufactured products to build a comprehensive life cycle model to assess the sustainability of 3DP in all its three aspects: economic, environmental, and societal. The model was then applied to the case study through Vensim software which analyzes the impact of distributed manufacturing over a period that sees the demand for 3D printed covers and in-home recycling systems increase according to the Bass diffusion model, an equation that describes the process of how new products get adopted in a population. The analysis provides a detailed quantitative evaluation of cost, energy, wastes, and CO2 emissions in both manufacturing approaches and shows a fall in 3DP production costs and total wastes, while a slight decrease in 3D printing energy consumption does not lead to a consistent reduction in CO2 emissions which appear steady over time. The emissions however are no

more entirely burden by a single region but equally distributed over all regions, according to their cover consumption. It emerges that the adoption of 3DP technology fairly redistributes emissions towards the consumer countries however from a global perspective the benefits are not evident. The capabilities of this technology suggest improvement in sustainability, but further studies are required to validate this statement.

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Nomenclature

3DP	Three-Dimensional Printing
ABS	Acrylonitrile Butadiene Styrene
AM	Additive Manufacturing
AMP	Additively Manufactured Products
CAD	Computer Aided Manufacturing
CM	Conventional Manufacturing
EBM	Electron Beam Melting
EC	Energy Consumption
EIV	Environmental Impact Vector
EOL	End of Life
EPV	Environmental Performance Value
FDM	Fused Deposition Modeling
HTP	Human Toxicity Potential
IM	Injection Moulding
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LF	Landfill

ME	Material Extraction
MP	Material Production
MT	Material Toxicity
MTO	Make-To-Order
MTS	Make-To-Stock
PC	Polycarbonate
PET	Polyethylene Terephthalate
PLA	Poly Lactic Acid
PT	Eco Indicator Point
RC	Recycling
RS	Residue
SETAC	Society of Environmental Toxicology and Chemistry
SCOR	Supply Chain Operations Reference
SLA	Stereolithography
SLM	Selective Laser Melting
SLS	Selective Laser Sintering
SM	Subtractive Manufacturing
UFP	Ultra-Fine Particle
WP	Waste Processing

1. Introduction

In the past decades, environmental issues have become always more center of discussions of countries and their governments around the world. Air is more polluted, oceans are full of plastic wastes, and too little is done to prevent any further damage or provide a substantial recovery of the actual situation. The most industrialized countries around the world have agreed to contribute through protocols and regulations to decrease the level of greenhouse gases emitted as partially being responsible for the greatest share of emissions.

Industrial activity represents about 22% of the total final energy consumption and about 33% [1] in global CO_2 emissions. Therefore, as defined by the World Commission on Environmental and Development, the industrial sector should be considered as one of the major sectors where transformative changes are needed toward sustainability [2].

Nowadays the industrial sector is characterized by centralized mass manufacturing of usually polymer-based products which reduce the economic costs but at the same time is creating the need to mitigate the concomitant environmental burden. The advantages of large-scale manufacturing are prominent, the most relevant include reduction of costs due to economies of scale from purchasing (bulk buying of supplies, components, and material through long term contracts), favorable financing in terms of interest (access to capital and variety of financial instruments), and increased specialization of employees and managers. These, together with many other advantages, contributed to create large-scale manufacturing industries in low-labor cost countries, especially for inexpensive plastic products. The environmental impact that plastic products have on the environment is well-established; they pollute land, air, and especially water, having a very slow decomposition rate [3]. According to a WWF report, the annual global production of virgin plastic in 2016 was 396 million metric tons, and over 75% of the plastic ever produced is already waste. Marco Lambertini, Director General of WWF-International stated:

"Our existing method of producing, using, and disposing of plastic is fundamentally broken. It's a system lacking in accountability, and currently operates in a way which practically guarantees that ever-increasing volumes of plastic will leak into nature" [4]

It is clear that a shift to more resource-efficient means of production is needed to decrease input and output intensity per unit of gross domestic product to prevent further climate change impacts, disruption of ecological systems, and exhaustion of natural resources.

One recent potential method to reduce the environmental impact of plastic parts is to use distributed manufacturing with low-cost open-source 3D printers. The nature of Three-Dimensional Printing (3DP) allows for the fabrication of customized products, extremely complex geometries, and minimization of production waste compared to traditional manufacturing while maximizing material utilization. In the past years, several 3DP industries have developed open-source models of commercial rapid prototypers, which offer an alternative model of low-cost production. These inexpensive 3D printers opened the door of additive manufacturing to a wide range of potential users due to simplicity and cost while making distributed small-scale manufacturing technically possible. Moreover, the ability to change the fill composition allows the production of more complicated shapes while minimizing material use. This property together with the potential to reduce the embodied energy of transportation made available by distributed manufacturing creates the potential to have a less energy and emission-intensive production system than conventional manufacturing [5] [6] [7] [8].

3DP is a revolutionary production method that offers great potentials to create a more sustainable industrial sector however, the environmental benefits of distributed manufacturing are not yet very clear due to the potential for increases in the overall embodied energy from the reduction in scale.

Up to now, many studies have been done to explore the potential of 3DP; most of them, however, hold to analyze the method itself from the energy consumption or emissions point of view, while very few focus on a comparison between 3DP and conventional manufacturing with a broader perspective [9]. This study aims to build a clear methodological approach to evaluate the potentials of 3DP by assessing sustainability and the entire life cycle of a product including the design and the end-of-life stages. In the end, based on the developed methodology, a case study is developed, which compares Additive Manufacturing (AM) and Injection Molding (IM) production systems of mobile case covers.

2. Review on Additive Manufacturing Technology

2.1. Definitions and AM Process

AM is an industrial manufacturing process with the potential to significantly reduce energy and resource demands as well as process-related CO_2 emissions. The technology evolved in the mid-1980s when control systems and computing progressed [2]. In the last decade, it has increasingly been perceived as a revolutionary way of producing end-use goods, developing itself into a fully developed manufacturing process, with growing accessibility to different industrial sectors. It is defined as the "process of joining materials to make parts from 3D model data, usually layer upon layer" (ISO ASTM 52900,2015) [10] and it distinguishes itself from formative and subtractive manufacturing (SM) technologies, where the product is obtained either by application of pressure to a body of material or by selective removal of material [11]. AM technology process could be simply explained in the following three steps [5]:

1. A computerized 3D solid model is converted into a standard AM file format (STL).
2. An AM machine receives the file and manipulates it (e.g., it scales the part, or it changes the orientation and the position of the part).
3. The layer-by-layer building process of the part takes place on the AM machine

Usually in this research, the term "3DP" is used as a non-technical synonym of AM, it is however defined as the "fabrication of objects through the deposition of a material using printer technology" (ISO ASTM 52900, 2015) [11].

There are about 18 different 3DP processes, usually classified into three different categories depending on the physical state of the printed matter used to create the artifact which is liquid-, solid- and powder-based. The most commonly applied processes are selective laser sintering (SLS), selective laser melting (SLM), fused deposition modeling (FDM), stereolithography (SLA); and electron beam melting (EBM) [2].

2.2. Comparisons, Advantages, and limitations of AM

AM includes many promising traits compared to conventional manufacturing. The latter technology usually refers to formative (deformation based) or subtractive manufacturing methodologies, however for the sake of comprehension in this research study it should not be limited to only these two, yet it should be interpreted as any traditional method used in an industrial sector, in which a three-dimensional model is not applied.

Unlike conventional manufacturing (CM) processes, AM has many potential sustainability benefits, among them, the following stand out:

- Improved resource efficiency: improvements could be realized in both the use and production phase as the manufacturing product and process can be redesigned for AM. Conventional manufacturing processes usually require auxiliary resources such as cutting tools, coolants, fixtures, and jigs in addition to the main machine tool while AM does not require all these additional resources. This also results in an opportunity to improve the dynamics of the supply chain as parts can be made by small manufacturers that are close to the customers.

- Material efficiency: unlike conventional manufacturing, in particular subtractive manufacturing, where a large quantity of materials needs to be removed, AM creates fewer material wastes, building parts layer by layer. Moreover, leftover material is often recycled and reused with minimum processing.
- Extended product life: achieved through technical approaches such as remanufacture and refurbishment, repair, and stronger personal product affinities, and closer relationships between consumer and producer.
- Reconfigured value chains: simpler and shorter supply chains, innovative distribution models, more localized production, and new collaborations. These simplifications are encouraged by the access to digital designs which allow spare parts to be produced at the point of use in space and time to the exact specifications required. This will eventually reduce or eliminate inventory waste including obsolete and unsold parts [5] [7].

Despite the mentioned benefits, AM cannot yet fully compete with CM, especially in the mass production field due to the following limitations:

- Size limitations: materials used in AM make it unable to produce large-sized objects due to lack of material strength. Large-sized objects are also difficult to produce due to the extended amount of time to complete the building process.
- Imperfections: products produced through AM often possess a ribbed surface finish, giving the end-product an unfinished look.
- Cost: this is perhaps the major limiting factor of AM. AM is less cost-effective, especially at high volumes as the machine cost is less

economically competitive compared to CM. Moreover, AM equipment is relatively expensive; 3D printers average approximately $5,000 and can go up to $50,000 for higher-end models and these prices do not include the cost of resins, operational materials, and other accessories [5].

Further development is required to increase reliability, reduce process times, increase quality and aesthetics, and especially expand the scale of applications. Ford et al. (2015) built a list of advantages and challenges that enriches the ones listed above (Figure 1) [8].

Advantages	Challenges
• Small batches of customised products are economically attractive relative to traditional mass production methods • Direct production from 3D CAD models mean that no tools and moulds are required, so there are no switch over costs • Designs in the form of digital files can be easily shared, facilitating the modification and customisation of components and products • The additive nature of the process gives material savings, as does the ability to reuse waste material (i.e. powder, resin) not used during manufacture (estimated at 95-98% recyclability for metal powders) • Novel, complex structures, such as free-form enclosed structures and channels, and lattices are achievable • Final parts have very low porosity • Making to order reduces inventory risk, with no unsold finished goods, while also improving revenue flow as goods are paid for prior to being manufactured • Distribution allows direct interaction between local consumer/client and producer	• Cost and speed of production • Changing the way that designers think about and approach the use of additive manufacturing • Removing the perception that AM is only for rapid prototyping and not for direct component and product manufacture • Development and standardisation of new materials • Validation of the mechanical and thermal properties of existing materials and AM technologies • Development of multi-material and multi-colour systems • Automation of AM systems and process planning to improve manufacturing efficiency • Post-processing is often required. This may be due to the stair stepping effect that arises from incrementally placing one layer on top of another, or because finishing layers are needed • Support structure materials cannot be recycled so need to be minimised through a good build-up orientation • Intellectual property issues, particularly regarding copyright • Deficits in designers and engineers skilled in additive manufacturing • Non-linear, localised collaboration with ill-defined roles and responsibilities • Continuously changing set of competitors

Figure 1 - advantages and challenges of additive manufacturing [8]

2.3. Make-to-order Model of AM

The MTO model is ideal for the economics of AM, it allows the production of spare parts for replacement in-situ at any time (enabling extended product life), and lower cost for personalization and customization. Moreover, holding a database of the digital designs of the parts to be produced, allows products to be made on-demand using AM. This helps to reduce or even eliminate inventory waste and reduce inventory risk by not having unsold finished goods, with the potential to improve revenue flow as goods are paid before being manufactured [8].

When a product produced through conventional manufacturing breaks, the customer either replaces it or repairs it depending on the value of the product and the cost of repair. Usually, the repairing process requires obtaining a replacement component from the distributor or the manufacturer and for such organization to exist, inventory of replacement parts is required. It is a costly operation and there is great uncertainty over the future demand for these parts. The only alternative to this organization is to produce the parts on-demand, but this is prohibitively expensive using traditional technologies. This is not the case for AM, which makes the production of spare parts more cost attractive, with the added benefit that 3D CAD (Computer-Aided-Design) files containing component designs can be easily shared once they are created [8].

2.4. Assessing AM Sustainability

As previously seen, AM holds many sustainability potentials that could revolutionize the industrial sector. Particularly FDM technology is evolving in a wide range of applications. However, most research found in literature investigate sustainability implications of AM either from a broad level or from a highly focused perspective on a particular issue such as energy or material consumption. Albeit these indicators are essential to perform a correct comparison between manufacturing technologies, they are not proper measures of AM's global environmental performance. To name a few, also carbon, material, and toxic substances' intensity should be measured. All flows exchanged between product/process and the environment from a life cycle point of view represent a proper approach to provide dimensions to possible benefits and quantify potential impacts. Hence, exists the need to develop a detailed model to evaluate sustainability. Any "green" claim without proper measurement lacks meaning and risks leading to burden shifting [12].

A model is needed to exhaustively assess the environmental impacts of AM process and provide a detailed comparison with the conventional manufacturing process. This model could result essential for effective decision-making. However, understanding the environmental impact from a life cycle perspective is challenging. Knowledge of materials, physics, mechanics, and chemistry and technologies in information, mechanical, manufacturing, and energy engineering is required. Up to now, researchers have recognized the importance to analyze from a life cycle perspective, but such systematic analysis of AM is rather limited. No firm conclusions are made that AM is more environmentally friendly or more energy-efficient than existing CM processes. Insufficient data inventory and limited direct measurement on AM environmental impacts are some of the methodological difficulties in the application of the Life Cycle Assessment (LCA) of AM [13] [14].

This research aims to perform an exhaustive comparison between AM and injection moulding technology for mobile case covers. To do so, however, it is essential to have a deep understanding of how to perform such analysis. Therefore, the following chapter unfolds all the steps of the LCA model and applies it to AM. This has been done by gathering most of the papers written up to now that perform some sort of evaluation of the AM technology from a sustainability perspective.

3. Life Cycle Assessment of Additive Manufacturing: framework and recent investigations

As environmental constraints grow significantly in manufacturing technologies, the number of published research on LCA referring to AM are growing as well. The ways of structuring and performing a LCA are many-fold, and they all hold the potential to influence the study outcomes, at varying levels [15]. To properly interpret the eventual environmental impacts measured through LCA, it is important to comprehend the methodological reasoning of this assessment.

3.1. ISO 14040:2006 Environmental management - Life cycle assessment - Principles and framework

The International Organization for Standardization ISO 14040:2006 (ISO, 2006, a) [16], increased its interest in developing methodologies aimed at quantifying environmental impacts due to a global awareness increase toward environmental protection and its implications, concerning both production and consumption. One of the most comprehensive tools used to analyze the environmental impacts and its aspects is the LCA, defined by SETAC (Society of Environmental Toxicology and Chemistry, USA and Europe) as a methodology to assess the environmental impacts involved with the usage of a process, production, product or activity within certain limits starting from the extraction of raw material, following through the process of production, transportation, usage, reuse, maintenance, recycling and final disposal [1].

The LCA helps to identify opportunities to improve the environmental performance of processes and products, select environmental performance, and subsidize information for decision-makers on industry and government organizations. According to ISO (2006b) [16], the life cycle assessment study consists of four phases: goal and scope definition, inventory analysis, impact assessment, and interpretation of results (Figure 2). The findings obtained through LCA are presented at the end of either the Life Cycle Inventory (LCI) or the Life Cycle Impact Assessment (LCIA). The LCA's purpose is to organize all the results and convert them into meaningful and comprehensive information for decision-makers.

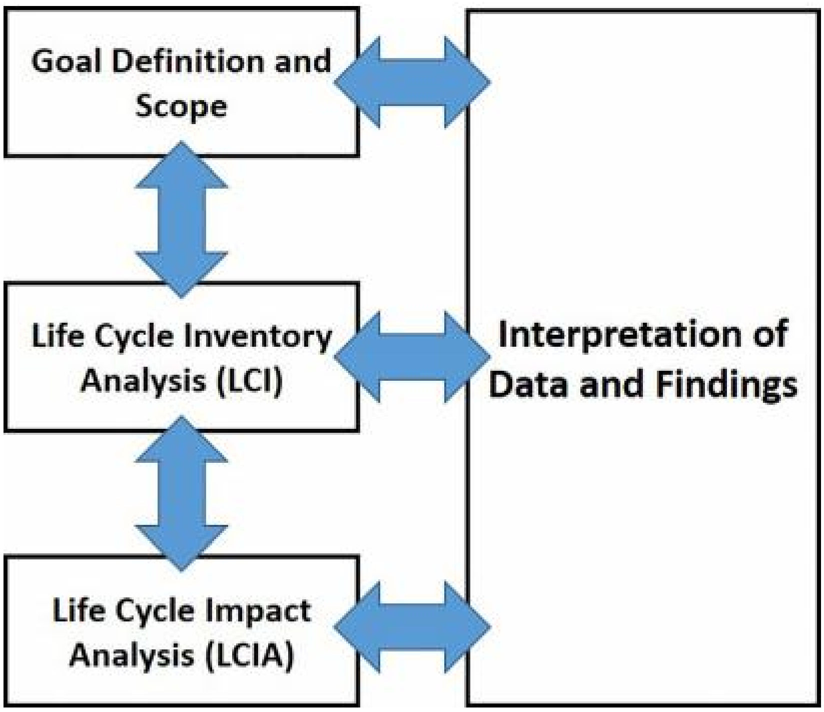

Figure 2 - LCA framework (adopted from ISO 14040:2006)

3.2. Goal Definition and Scope

The goal is the objective of the research. For instance, the goal of most scientific articles analyzed in literature for this research, refer to the evaluation of the ecological impact (i.e., energy use, waste, toxicity, etc.) of a particular AM process or product, to inform decision-makers which technologies are best for their production system.

The Additively Manufactured Products (AMP) life scope is determined by the product lifespan. A product's lifespan consists of:

- 'Stages' represent a certain period in a lifecycle, such as production.
- 'Processes' represent steps during an AM stage, such as setup or printing
- 'Systems' means an independent function unit, such as an AM machine or ventilation system

Research done from the Mississippi State University [1], identifies two most common life scopes in recent studies of production systems involving AM:

- Cradle-to-gate: the lifespan is from raw materials to the moment it leaves the manufacturing plant.
- Cradle-to-grave: the lifespan is from raw material to the moment the product reaches the End of Life (EOL) phase.

The research points out, however, that all studies neglect an important stage of the lifespan of AM: the design stage, which appears from literature to have a significant impact on sustainability over the entire product life cycle. Studies that include the design stage are known as "conception-to-grave", which begins with product designing and planning and ends with EOL handling. This lifespan correctly covers all life cycle activities (Figure 3), leading to more precise outcomes than the other two and can be summarized into four distinct stages:

- Stage 1 is the design stage; it is responsible for product architecture design and planning [1].
- Stage 2 is the AM stage; the product/component is fabricated utilizing the CAD model, selected materials, and pre-determined AM process in the previous stage. This stage includes also an upstream process that supports the AM process. For example, if we are dealing with an FDM 3D printer that works with Poly Lactic Acid (PLA), the upstream process consists of turning the PLA material into filament [1].
- Stage 3 is the service stage; it begins when the product leaves the manufacturing plant for delivery to the customer and ending when products are out of usage [1].
- Stage 4 is the EOL stage; it includes all strategies needed to maximize the residual value of the product/component. These options include reuse, remanufacturing, repair, recycle, and disposal [1].

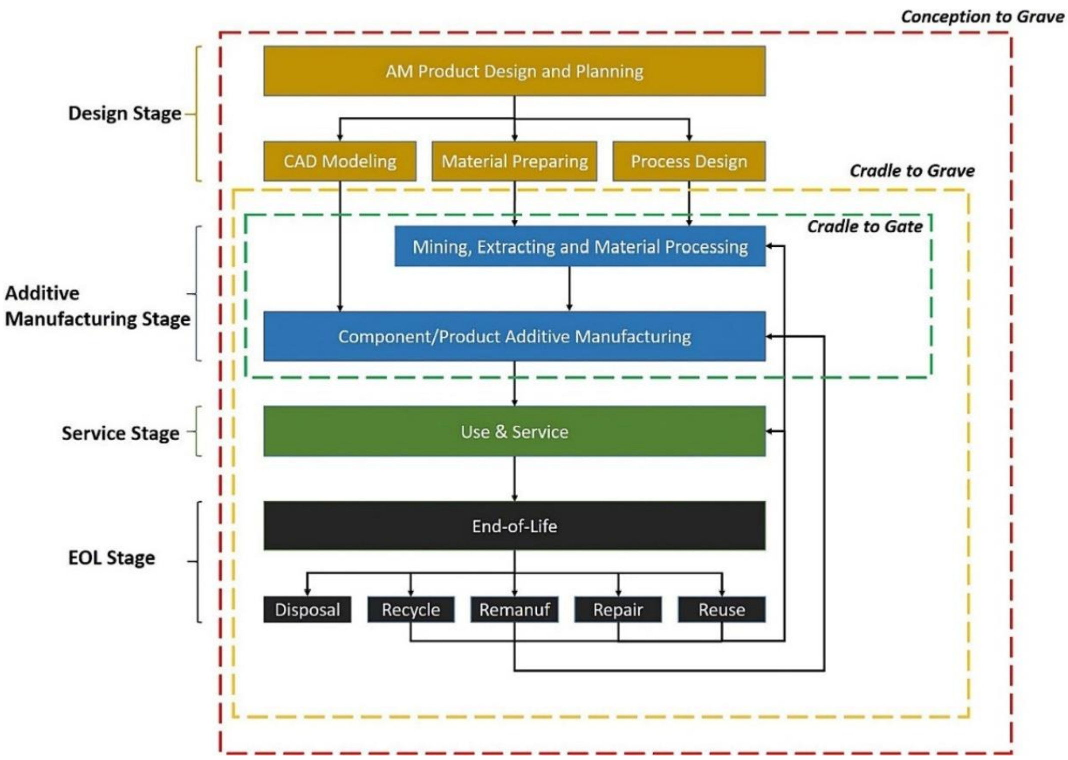

Figure 3 - Conception-to-grave lifespan of AMP

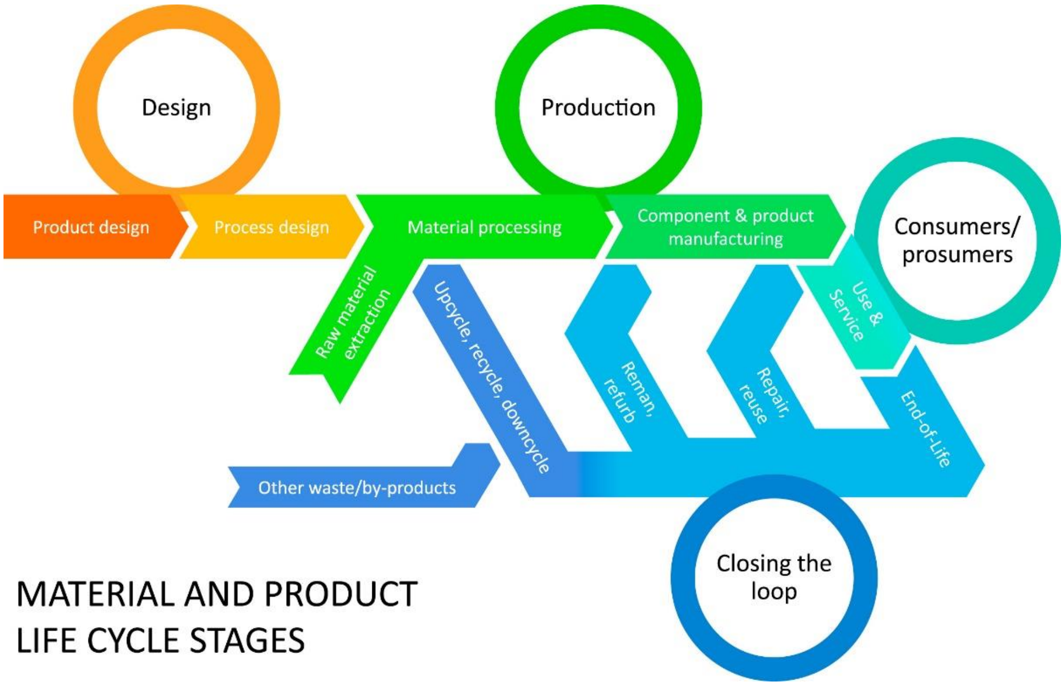

Figure 4 - Life cycle perspective for identifying sustainability benefits of AM

Previously to this research, a study conducted by the University of Cambridge [7] explored the advantages and challenges of AM sustainability and illustrated the conception-to-grave lifespan highlighting the processes where the loops close (Figure 4).

3.3. Life Cycle Inventory Analysis

ISO 14040 2006a [16] describes this phase as a compilation and quantification of inputs and outputs for a given product system throughout its life cycle. Compared to the other phases of LCA, LCI is considered a rather straightforward procedure.

Inputs are usually classified into two categories: material and energy. Material inputs are linked to different kinds of environmental aspects such as people, ecosystem contaminant exposition and resource utilization, etc. Energy inputs are present in most of the product life cycle and each type of source of energy (hydraulic, solar wind source, nuclear, fossil fuel, etc.) contains identifiable environmental aspects [17].

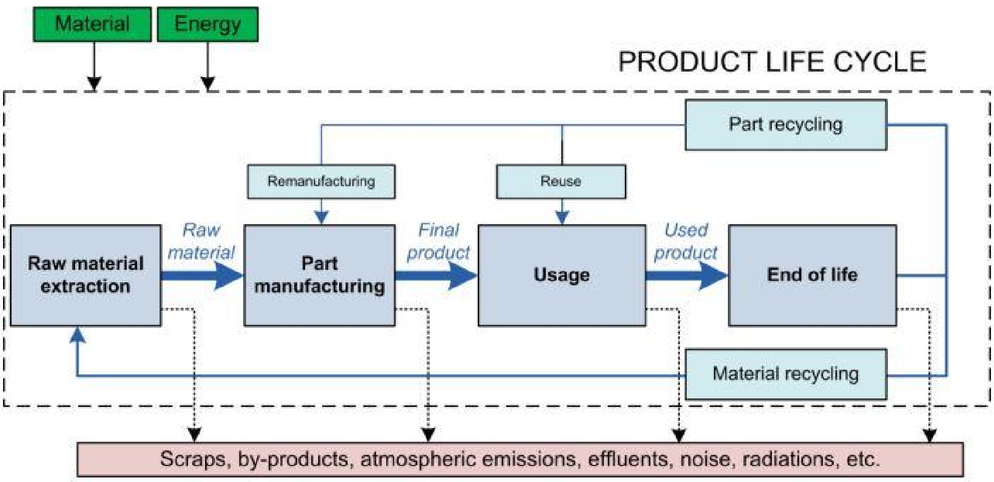

Figure 5 - Generic product life cycle inventory

The outputs created during the product life cycle are usually related to:

- Atmospheric emissions (vapors and particle in the air, gas emissions)
- Scraps generated at each life cycle step
- By-product and co-product
- Effluents (substances emission in superficial water)
- Radiations
- Noise
- Electromagnetic fields, etc.

Generally, the inventory results in a long list of consumed resources and emissions. This inventory list should then be crunched and transformed into a limited number of indicator scores. These indicator scores show the relative severity of an environmental impact category [17].

Figure 6 shows a simple example of an AMP life cycle where the outputs are directly shown as indicators: cost, environmental impact in mPt, and human potential toxicity. With these three indicators, it is possible to generally assess sustainability in all its three aspects: economy, environment, and society (Figure 7) [1].

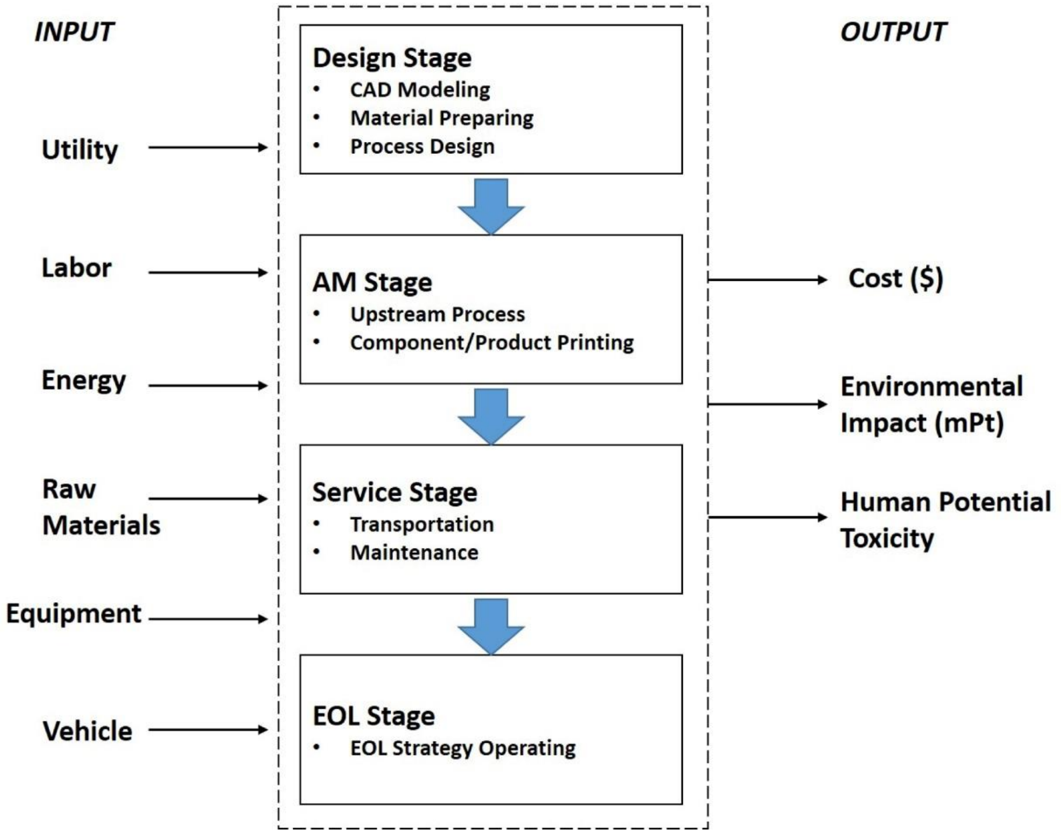

Figure 6 - AMP life cycle sustainability assessment framework

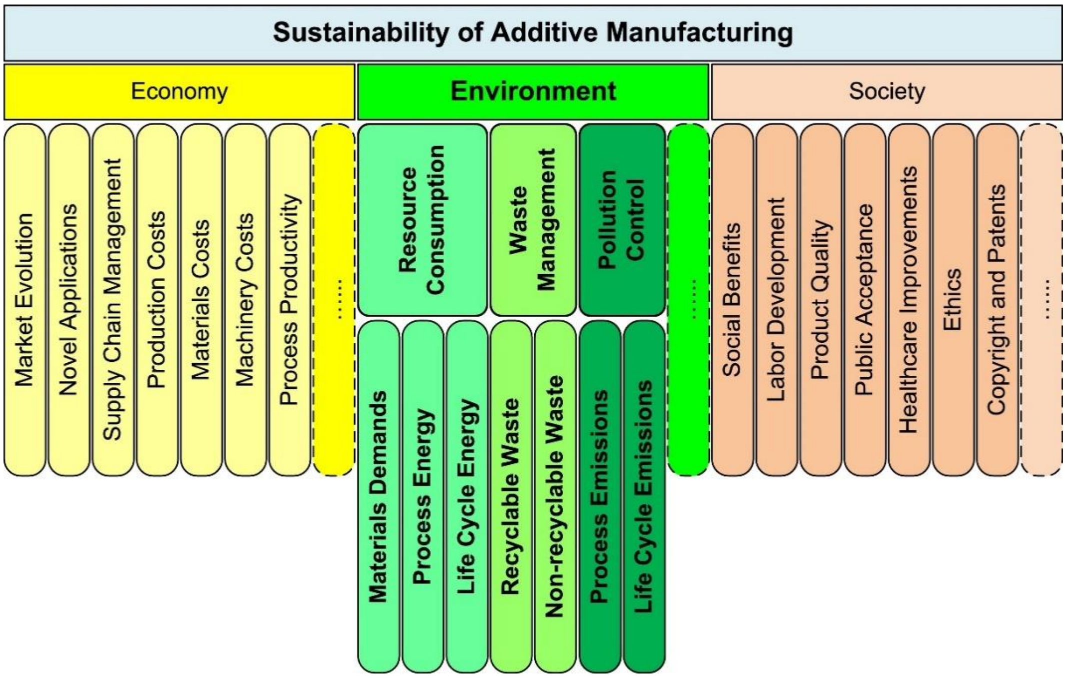

Figure 7 - Three aspects of environmental impact in the context of SAM

3.3.1. Environmental Impact

The environmental impact of AM is principally studied in three aspects: resource consumption, waste management, and pollution control.

The main resource consumptions in AM are energy and material consumption. Energy is mainly consumed by the AM equipment and auxiliary sub-systems, and material consumption includes the primary materials (e.g., polymer filament), secondary materials (e.g., support structures), protective gas (e.g., nitrogen), and cooling water. CM, compared to AM, usually consumes more types of materials (e.g., coolant, lubricant, and tooling). Even though AM is theoretically 97% material efficient, in real applications, the material efficiency is much less, also energy consumption is usually above theoretical level due to relatively low productivity, especially for those processes that involve lengthy processing at high temperatures [12].

To produce a product, SM usually produces up to 90% more wastes than AM. AM wastes include material powders that are no longer recyclable, support structures produced for overhanging parts, and scraps generated by unexpected defects. Up to now, limited research has been conducted to optimize the support structure and the printing path for material reduction, especially for FDM. The main reason behind this could be because AM still represents a comparatively small share [12].

For what concerns pollution control, the main forms of pollution include gas, liquid, solid, and sound. Studies must be conducted especially on particulate matter (powder), during their formation and handling due to their high toxicity and harmful effects. AM, compared to CM, uses fewer harmful chemicals, such as cutting fluids, forging lubricants, and casting release compounds. For example, FDM uses non-toxic thermoplastic materials such as Acrylonitrile Butadiene Styrene (ABS), Poly Ethylene Terephthalate (PET), and PLA, at a low noise level and melting point, demanding less heating energy for the worktable and nozzle. However, caution should be taken when operating in an unvented or unfiltered indoor environment due to the emissions of ultra-fine particles (UFPs). Generally, the material used for AM are not necessarily greener than materials used in traditional manufacturing, the one exception may be PLA, classified as a biopolymer [12].

3.3.2. Economic Impact

3DP is considered a 230-550 billion US$ market by 2025, whose main economic impacts are stated for markets with low volume, high-value, and customized products, enabling a more cost-effective manufacturing process for these products. Moreover, a reduction in production-related capital investment is stated for 3DP due to shorter production chains and related processes, and reduced need for tooling [2].

Economic sustainability uses ‘cost’ as the primary indicator to discuss the economic performance of AM. Among each life cycle stage cost, production costs usually represent the largest share of the total cost. They are determined by various aspects as machinery, material, labour, and pre- and post-processing.

It is assumed that production cost structures will shift towards higher shares (45-75%) of machinery cost in the total production cost, depending on the case. Also, material costs depend on the case and are estimated at (only) 12% of the total 3DP-production costs [2].

Although material prices for 3DP are much higher compared to raw materials for conventional processes, they are amortized due to much higher material efficiency. 3D printing enables complex and improved geometries as well as complex designs, therefore it is usually expected that product life cycle costs are lowered.

Being the 3DP processes fully automated and only requiring human workforce in pre- and post- processing is also expected a shift in labour patterns. Implications related to this shift show different patterns in developed and developing countries. In developed countries, the high degree of automation could be beneficial with ageing societies, while it is destabilizing in developing countries if the production, and therefore the production volumes, re-shift to consumer countries. It is also expected a relative decline in exports/imports. It is projected that exports shift back to consumer countries as 3DP reduces the technological advantage of countries like

Japan and Germany and the labour cost-related comparative advantage of countries like China. Rural areas with low-economic profiles could be positively affected by open-source-based applications, as 3DP bridges the spatial gap to the next market of, consumer products, tools, or spare parts [2].

Through 3DP the need for centralized manufacturing and tooling is reduced, and therefore it is expected supply chains to be shorter and less transport intensive. Furthermore, supply chains undergo a shift from physical goods to digital ideas/design, leading to a more dynamic supply chain and resulting in a reduction in the time-to-market. It is also expected that the global supply chain relatively shifts from final products to raw materials as material raw production is spatially bound to its reserve while final goods manufacturing becomes more localized [2].

3.3.3. Social Impact

The third pillar of sustainability evaluation is social sustainability. This area is still poorly understood and receives less attention due to difficult quantifications and complicated explanations. Although it is less analyzed than the other two areas, is not at all less important because it greatly influences society and relates to human being [2].

3DP induces changes in social and labour structures due to the high degree of automation and a shift is expected in consumer countries towards more localized means of production. As previously mentioned, developed countries have beneficial effects from the high degree of automation, while social insecurity and unemployment could be consequences in developing countries. Labour is mostly required for pre- and post-processing, therefore information technology education for the workforce is needed, as companies shift their portfolio to more digital ideas/designs [2].

Depending on the societal entity, social acceptance of 3DP varies. Governmental acceptance is high as governments are moved by the eventual reduction of the resource-intensity of manufacturing and stimulate promising new market developments to potentially re-shift production capacities to domestic markets. The US government has shown high interest through high governmental funding in R&D, however great concerns are focused toward open-source availability of fire arms which raise awareness of security threats [2].

Market acceptance is high as cost reductions in technology enable more applications of 3DP and new applications to arise. Furthermore, markets for new supply chain structures and mass customization offer opportunities for new business ideas [2].

Community acceptance is mixed; on one side there is a constantly growing community for open-source applications of 3DP indicating an increasing public interest, reflected as well in the growing sales number of consumer 3D printers. On the other hand, security threats induce reservations against 3DP [2].

3.4. Life Cycle Impact Analysis

In the LCIA phase, the evaluation of the potential environmental impacts stemming from the elementary flows obtained in the LCI takes place. It consists of the following steps:

1. Select the impact categories (environment, economy, and society)
2. Classification: assign the elementary flows to the impact categories
3. Characterization: obtain an indicator for the impact category and model the potential impacts

3.4.1. Environmental Indicator

One of the most interesting research, conducted by the New Jersey Institute of Technology, studies a method for analyzing the environmental performance of solid freeform fabrication and dates back to 1999 [18]. Although more than two decades passed since this research was published, many studies found in the literature are based on this method, it is, therefore, worth mentioning it.

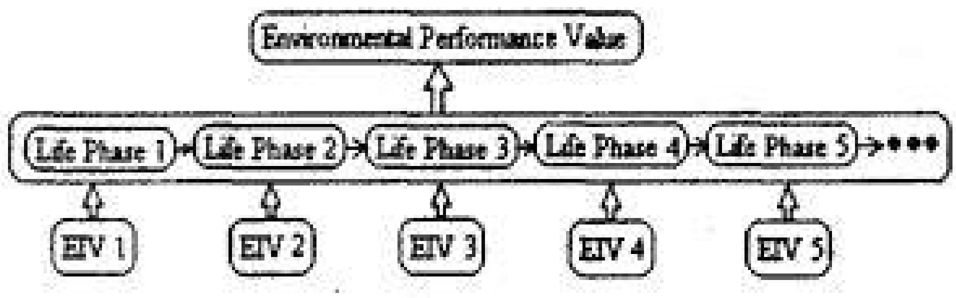

Figure 8 - Process Model for Environmental Performance [18]

The model links the process mechanics with the environmental concerns in each of the process steps. Based on the life cycle methodology, a general process model is defined with three hierarchical layers as shown in Figure 8

The top layer is referred to the overall environmental performance values, the middle is the life phase identification, and the bottom one is the environmental impact vector (EIV) corresponding to each life phase. The research defines the life cycle stages differently compared to how they have been described in the first part of the chapter. It does not consider the design stage and the transportation part of the “use and service stage”, instead it gives major importance to the manufacturing stage by splitting it up into three parts: material preparation, build, and post-process. Eight elements are identified for the EIV: Material Extraction (ME), Material Production (MP), Energy Consumption (EC), Residue (RS), Material Toxicity (MT), Landfill (LF), Waste Processing (WP), Recycling (RC). The distribution of the environmental impact elements in each of the life phases is shown in Table 1 [18].

Life Phase	Name	Environmental Impact Vector
1	Material preparation	EIV1=(ME,MP)
2	Build	EIV2=(EC.RS)
3	Post-process	EIV3=(RS)
4	Use	EIV4=(MT)
5	Disposal	EIV5=(LF,WP,RC)

Table 1 - SFF Process Model Description

Once the model has been defined, it is possible to evaluate the environmental performance value (EPV) by adding up the EIVs. The EPV unit is Eco-indicator Point (Pt), which is divided into 1000 millipoints (mPt). The higher the EPV the more environmental impact an AM product causes. 1 Pt indicates one-thousandth of the yearly environmental load of an average citizen in Europe [18].

The EIVs for each material are easily acquired from the ‘Eco-indicator 99 Manual for Designers’. The only element that is less straightforward is the energy consumption element or ‘Energy in Process (E.P.). This element is perhaps the most important one as it usually characterizes the greatest share of the total environmental impact. The following equations show how to calculate E.P:

$$E.P. = f_{Celec} \cdot ECR$$

$$ECR = \frac{P}{PP}$$

$$PP = V \cdot W \cdot T \cdot \rho \cdot 3600 \cdot k$$

Where:

- f_{Celec} is a factor in Eco-indicator 99 to convert ECR to an environmental impact expressed in mPt/kg (0,57 mPt/kWh)
- ECR is the energy consumption rate (kWh/kg)
- P is the power rate (kW)
- PP is the process productivity (kg/h)
- V is the scanning speed (mm/s)
- W is the road width size (mm)
- T is the layer thickness (mm)
- Ρ is the material density (kg/mm^3)
- k is the process overhead coefficient (0.6-0.9)

Therefore, once the product's material and the additive manufacturing process is decided, it is possible to evaluate the total environmental impact.

3.4.2. Economic Indicator

According to Ma and Kremer [19], the cost is the most widely accepted economic sustainability indicator, and therefore the cost over the entire life cycle will be used to gauge life cycle economic sustainability.

The design stage involves three components: CAD modeling, material selecting, and AM process design. However, the first two entities do not involve cost (considering the software cost negligible) and therefore only human labor cost and utility cost is used to assess design stage cost [1]:

$$C_{design} = C_{labor} + C_{utility}$$

The AM costs for 3D printing can be categorized in two ways:

- well-structured costs: costs that are sufficiently defined, for example, the machine, labor, and material costs.
- ill-structured costs: costs that are not well understood due to lack of knowledge. These are the ones usually associated to build failure, inventory, and machine setup.

The latter ones relate more to possibilities for savings in a supply chain, therefore, to make better analysis and deeply understand the weight of the single parts on the total manufacturing cost, the well-structured costs are to be considered. A recent study conducted by Li et al. (2017) to assess AM sustainability, combines different cost models found in literature based on well-structured costs and builds a four-component AM cost model. These four components include energy costs, labor costs, material costs, and machine costs. The equations expressing the manufacturing costs are [20]:

$$C_{man} = C_{machine} + C_{labor} + C_{material} + C_{energy}$$

$$C_{machine} = \frac{p_{machine}}{t_{dep} * e_u} * t_{man}$$

$$C_{labor} = \frac{S_{labor}}{t_{annual}} * t_{assist}$$

$$C_{material} = C_{direct} + C_{indirect} = p_{material} * m_{material} + p_{support} * m_{support}$$

$$C_{energy} = P_{elec} * p_{electricity} * t_{man}$$

Where:

- $p_{machine}$: machine cost;
- t_{dep}: duration for machine depreciation (8 years);
- e_u: annual utilization rate;
- t_{man}: manufacturing time for a sample;
- $\frac{S_{labor}}{t_{annual}}$: average salary per hour;
- t_{assist}: time for assistance for manufacturing's set-up and samples' cleaning;
- $p_{material}$: price for build material;
- $m_{material}$: weight for build material (including waste);
- $p_{support}$: price for supporting material;

- $m_{support}$: weight for supporting material;
- P_{elec}: machine power;
- $p_{electricity}$: average electricity price.

Service stage costs are composed of two parts:

1. Transportation cost: it measures the cost of delivering the AMP from the manufacturing plant to the end-use customer. To simplify, usually, it is considered a B2C model, therefore no intermediate is considered.
2. Service cost: it refers to product maintenance cost (e.g., disassembly and assembly cost). Usually, AMPs do not require maintenance unless it has special requirements, therefore this cost is frequently null (or not considered).

The EOL stage cost measures the cost of handling retired AMP. The usual strategies found in the literature are categorized into five stages: reuse, repair, remanufacturing, recycle, and disposal.

To summarize, the following equation presents the total life cycle cost of AMP:

$$C_{LC} = C_{design} + C_{AM} + C_{service} + C_{EOL}$$

3.4.3. Social Indicator

Benoit et al. (2007) [21] proposed a model to study this area that is widely accepted in the community, providing a five group categorization corresponding to different stakeholders: workers, local community, society, consumers, and value chain actors

Research conducted by Ma and E. Okudan Kremer (2015) [19], provides three indicators to quantify job creation, health and safety, and inter-generational issues and relate to the five group categorization of Benoit et al. (2007) [21].

Job creation is directly related to workers and the local community and it is measured according to employment level data. [19]

Health and safety are related to both society and consumers and are measured according to indicators of human heath impacts. Human health indicators are quantified according to human toxicity potential (HTP) estimation within life cycle assessment [19].

Inter-generational aspects are related to value chain actors and society and refer to issues that reflect the interaction between current and future generations. Two of the most important inter-generational issues to analyze inter-generational effects are climate change and depletion of non-renewable resources. However, the selection of indicators to assess inter-generational issues depends on the product's material and handling method. For instance, when dealing with plastic products that undergo heat treatment, significant quantities of green gas are created and impact climate change, therefore global warming is an appropriate indicator for the case [19].

The three indicators listed above provide a thorough evaluation of social sustainability, however, most of them are either very complex to measure or not measurable at all. For this reason, most literature research focus only on health and safety, two aspects that can be quantified through the HTP indicator. A Uniform

System for the Evaluation of Substances-Life Cycle Assessment (USES-LCA) was developed in 2000 by Huijbregts. He used six impact categories to calculate substances toxicity potentials and HTP is one of them. HTP for each substance is calculated on initial emission to the compartments air, water, and soil. HTP has no unit, a high value means a high potential impact for a human being. It was found that the material weight is positively correlated to HTP and depends on the material characteristics and the process. The following equation was developed [19]:

$$HTP = a * B_a + b * B_w + c * B_s$$

Where:

- B_a, B_w, B_s are toxicity potentials concerning air, water, and soil
- a, b, c are weights for emission to air, water, and soil

The design stage does not involve activities that correspond to human toxicity, therefor the HTP will be null at this point. The AM stage, instead, generates a huge HTP since many air, water, and soil emissions are produced during fabrication. At the service stage, HTP comes primarily from transportation and maintenance, and the EOL stage produces HTP from EOL strategy handling. The following equation presents the life cycle HTP [2]:

$$HTP_{LC} = HTP_{Design} + HTP_{AM} + HTP_{Service} + HTP_{EOL}$$

$$= HTP_{Material} + \left(HTP_{Transportation} + HTP_{Maintanance}\right) + HTP_{EOL}$$

3.5. Design Stage

The lifespan of AM starts from the design stage. The primary activity is developing the CAD model using a computer as well as AutoCAD software. AM design stage is an important stage of the lifespan as it has a significant impact on the AMP over the lifelong time. Examples of product improvements include functionality and durability, greater operational efficiency, and ease of manufacturing and maintenance. AM enables the design of more optimized and complex components due to a higher degree of freedom in geometry and shape, and especially simpler assemblies comprising fewer different materials and fewer parts [7].

Greater design freedom allows the development of new material structures such as open cellular foams and porous mesh arrays. Incorporating the product with these structures could bring improvements such as increases strength, stiffness, corrosion resistance, and energy efficiency.

The revolutionizing nature of AM requires new design tools. Existing guidelines and methods created for CM, are no longer suitable under AM. An interesting design method to improve functional performance has been recently presented. It is a framework where the input is the functional description of a part rather than a particular part design. Another computational tool named Design for Environment was developed based on eco-design principles. It allows to minimize life cycle environmental impacts and generate more sustainable designs [12].

AM-enabled design capability can increase eco-design in return, designing complex geometries for better functionality, or redesigning multiple parts into a single piece. Therefore, the environmental impact and energy of CM processes, such as fastening, welding, or joining can be eliminated and the associated costs for inventory, inspection, additional process planning, and labor can be significantly reduced. AM plays an important role also in design for remanufacturing; a large amount of material and energy can be saved when a part is AM repaired rather than replaced and disposed of [12].

Eco-design is a huge opportunity for AM to make the best use of its improved design capabilities. However, guidelines and design methodologies, evaluation tools, and simulation systems are not frequently implemented when dealing with AMP [12].

3.6. Production Stage

The production stage comprises material processing and product manufacturing. This stage attracts special attention due to the many sustainability-related opportunities it offers regarding the efficient use of material and energy. It is suggested to decompose the manufacturing phase into many processes which are working individually or collectively, and different measures could be adopted depending on the chosen configuration. Measures related to the aspects that characterize this stage, such as energy flow, process nature, production time and planning, and waste recovery could ensure an eco-friendly and sustainable manufacturing phase [22].

The introduction of AM can change dramatically the configuration of the manufacturing system. The development and diffusion of consumer 3D printers in offices and homes are blurring the line between manufacturer and consumers, making them prosumers. They are now able to design and manufacture at the exact specifications required and at the point of use in space and time. Moreover, these 3D printers could also be coupled to recycling systems to convert waste back into filament and use it as input for 3D printing new products. In this way, home 3D printers are enabling us to move toward more distributed, small-scale, and localized manufacturing. Logistics are simplified as more basic and fewer inputs are needed. Inventories, as it was seen previously, can be reduced, or eliminated, thus reducing the economic losses and the environmental impacts associated with obsolete and unsold components [7].

From a sustainability point of view, AM is a more resource-efficient manufacturing process as less waste is generated compared to subtractive techniques. Although it could be argued that AM is more energy-intensive per unit produces, AM allows units to be produced to exactly match the demand (MTO) and therefore offer the potential for better absolute performance [7].

3.7. Service Stage

This stage refers to product usage and service, especially referring to the distribution of the product. It is predicted that 3D printing will revolutionize supply chains, as a single manufacturer can now make customer-specific parts for the mass market [23].

The MTO model of distribution of AMP allows direct interaction between local consumers/clients and producers, with user innovation benefits of this approach. The network 3D Hubs is an online platform that works as a link between customers and owners of 3D printers. The owners are usually prosumers that have spare printing capacity and aim to increase utilization. This gives access to local manufacturing. Apart from providing benefits such as energy and resource reduction, it also increases equipment utilization as customers do not need to own and operate their equipment. Users can download CAD files directly to print, optimize, merge, and replace parts bypassing original manufacturers [22]. The challenge of this distribution model is that a set of actors and competitors creates an uncertain investment environment that makes competitive positioning and business strategy formulation very difficult. Entrepreneurs and companies entering this market must have extreme flexibility, responsiveness, and resilience to rapidly adapt to market changes [7].

A very interesting study conducted by Dircksen and Feldmann in 2020 [24] analyzes five alternatives for the distribution system. Two alternatives represent a distribution system with warehousing in the target country and therefore the delivery of orders is served directly from the domestic inventory. The other two

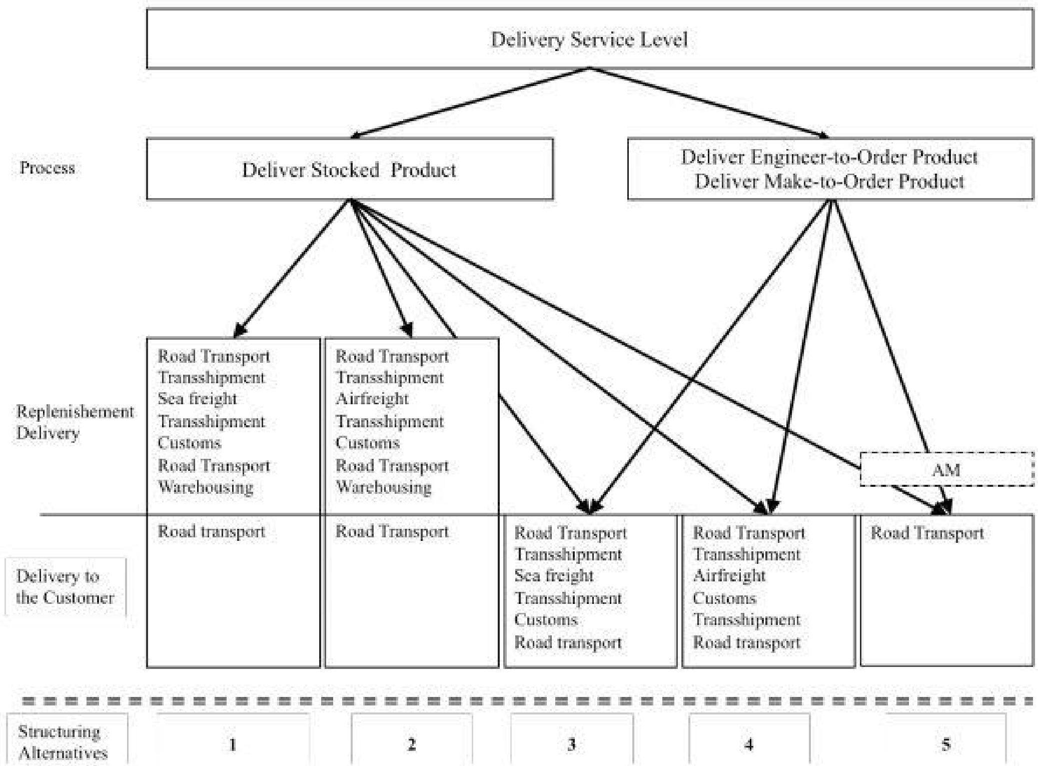

Figure 9 - Alternatives for structuring a distribution system

alternatives do not include warehousing in the target country, whilst the last alternative is the option involving AM in the target country. Figure 9 shows the five alternatives.

The case study is performed on a plastic product produced in Brazil and demanded in Germany with a consumption rate of one item per year. The study makes a comparison on three levels: cost, time, and emissions of transportation. The AM manufacturing alternative is advantageous on all three levels.

3.8. EOL Stage

The EOL stage consists of closing the loop of the product life. This could be done at various stages and scales as shown in Figure 4. It includes repair and reuse, remanufacturing, and recycling.

In-situ recycling systems could be added to AM, diverting material from waste streams to new applications. However wider the diversity of materials entering the recycling system is, the greater the complexity of the process is required, along with the potential for loss of value when materials cannot be separated. Further development and validation of material properties are needed [7].

In some applications, AM process has the potential to increase the value recovered embedded in waste. For example, reusing plastic such as PET, which is commonly used for consumer products, by transforming it into fashion products. This could be done with simple AM equipment that is available to the public either as a service (3D Hubs) or directly as a product (ex. EKOCYCLE Cube) [7].

For what concerns repair, remanufacturing, and maintenance, the MTO model is applied with the same benefits of minimizing the inventory waste as spare parts are produced locally only when they are needed and with low energy intensity processes. Products are maintained on a more localized basis, potentially in-situ [7].

3.9. Recent Investigations

Up to now, studies of AMP from the view of cradle-to-gate investigated AM energy consumption and found that AM not only has less environmental impact than traditional manufacturing, but it has the potential to be improved during the fabrication and disposal stage. Some other studies that investigated FDM manufactured products compared to milling machine products from the cradle-to-grave view concluded that an FDM 3D printer has a lower ecological impact and its sustainability performance mainly depends on the printing stage.

One of the studies that stands out is the one conducted in 2019 by Feldmann and Kirsch [25]. They used a two-step approach to specify the ecological effects of AM using LCA cradle-to-grave. The first step was to visualize the life cycle of a 3D-printed object and then systemize the life cycle using the Supply Chain Operations Reference (SCOR model, Supply Chain Council, 2012). The second consisted of identifying cause-effect relationships relevant for each life cycle phase. Figure 10 shows a six life cycle stages model and identifies specific benefits and risks directly related to the ecological impact of additive manufacturing.

Sourcing activities (stage 1) appear merely insignificant on the overall impact on sustainability in the AM scenario however it is still considered more environmentally sustainable than a conventional manufacturing setup [24].

In the subsequent phase, the manufacturing (stage 2) of AM products, the main ecological drivers are involved, above all are the subprocesses “produce”, “post-processing”, and “waste disposal”. Their importance is linked to the fact that less material is used as compared to non-AM methods, however, numerous negative compensatory effects are also involved, such as additional waste due to post-processing activities [24].

Distribution (stage 3), which includes all the logistic activities needed to support the customer order, has relevant effects on the environment. The AM scenario sees less weight and shorter to no travel distance but also a higher frequency of small transport that might compensate for the transportation savings [24].

Stage 4 refers to customer use and it is especially relevant for the environment when dealing with lightweight products (easily realized through AM) resulting in less fuel consumption and emissions. On the other hand, decentralized production could lead to a so-called rebound effect (i.e., an expected increase of resource efficiency is reduced by the behavior of entities or other reaction of a system) as AM fabrication can encourage the production of more goods than is necessary [24].

For what concerns all the activities associated with maintenance, repair, and refurbishment (stage 5), AM plays an important role thanks to the material-applying process which guarantees a rapid repair. It allows for easy restoration of the original geometry of a worn or defective part and enables longer life cycles through inexpensive manufacturing of spare parts for which there are no longer any sources of supply. In contrast, the portion of replacement deliveries increases compared to the portion of repairs as the level of accessibility of the product decreases due to the complex geometries that can be manufactured through AM [24].

The final stage of a product involves the activities associated with disposing of waste at the end of a product's life cycle. By laying material just where needed, AM realizes lighter products, hence less quantity of material to be disposed of, however, the accuracy for waste disposal is lower, especially for products manufactured as hybrids that combine heterogeneous materials by melting [24].

The authors provided a structured overview of AM's effects on ecological sustainability by analyzing the various phases of the product's life cycle. The work highlights the positive impacts on the environment, making it a promising technology however it also puts into evidence the potentially compensating effects that could make the benefits irrelevant. For instance, in the making area, impacts heavily depend on the AM technology, AM machine brand, the AM material used, and the geometry of the product itself. To conclude, the authors suggest that to better understand the possible implementation of additive manufacturing in the production system, an in-depth analysis of the various stages of the life cycle is required, not only from the ecological point of view but also from the economical and societal one.

Life cycle of an AM fabricated object: ecological impacts	(1) Sourcing	(2) Manufacturing	(3) Distribution	(4) Customer Use	(5)Maintenance, Repair	(6) Disposal at End-of-Life
Advantages	• Less fuel consumption and emissions due to – lower number of inbound shipments (Petschow et al. 2014; Cerdas et al. 2017) – expedited emission-intense airfreight replaced by less intense modes of transportation (Boon and van Wee 2017) – higher degree of reusable residuals out of the manufacturing process (Pour et al. 2016) • Lower number of SKU and lower inventory levels, e. g. by substituting the movement of physical goods by sending or storing digital files (Burkhart and Aurich 2015; Mohr and Khan 2015; Ford and Despeisse 2016) • Less scrapping of obsolete raw material inventories (Mohr and Khan 2015)	• Less material used, in particular in cases of cavities and honeycomb structures (Hopkinson et al. 2006; Mohr and Khan 2015; Pour et al. 2016; Reeves 2018) • No respectivey less waste of raw materials, especially due to reuse of, e.g., support materials (Hopkinson et al. 2006; Petrovic et al. 2011; Bühner 2013; Lipson and Kurman 2013; Gebler et al. 2014; Janssen et al. 2014; Wigan 2014; Reeves 2018) • Energy costs are reduced, e.g., due to omitting diverse machines or internal transportation between different production steps (Woodcock 2011; Huang et al. 2013; Reeves 2018) • Reduced need for tooling (Petrovic et al. 2011) • No use of adjuvants such as coolants, lubricants, or other environmentally harmful substances (Gebler et al. 2014; Petschow et al. 2014; Oettmeier and Hofmann 2016) • Less scrapping of obsolete inventories (semi-finished goods)	• Less fuel consumption and lower emissions due to – shorter to no transport distance to point-of-use or point-of-consumption (Garg and Lam 2015); (Manners-Bell and Lyon 2012; Petrick and Simpson 2013; Nyman and Sarlin 2014; Pour et al. 2016) – less weight in cases of lightweight construction, e.g., cavities and honeycomb structures (Petschow et al. 2014) – expedited emission-intense airfreight shifts to less intense modes of transportation like rail, road, or water • lower inventory levels due to print-on-demand, postponement, and lower number of echelons in chain (Burkhart and Aurich 2015; Mohr and Khan 2015; Boon and van Wee 2017) • less scrapping of obsolete inventories (finished goods) (Ford and Despeisse 2016)	• Lightweight construction results in less fuel consumption and lower emissions, e.g., if objects are used in automotive or aeronautic branches (Gebler et al. 2014); (Huang et al. 2013); (Petschow et al. 2014)	• Inexpensive manufacturing of spare parts not available without AM (Woodcock 2011) • Restoring the original geometry of a worn or defective part (Petschow et al. 2014)	• Less waste to be disposed of and less material to be recycled in case of lightweight constructions (cavities and honeycomb structures) (Gebler et al. 2014)
Disadvantages	• Higher frequency of small transports might compensate for the transportation savings above (in the case of many decentralalized AM machines instead of one central manufacturing facility) (Boon and van Wee 2017)	• Higher energy consumption per piece (as a tendency) (Huang et al. 2013) • Additional waste due to post-processing, e.g., for surface treatment and removing support materials (Petschow et al. 2014) • Decentralized manufacturing by many laymen increases risk of faulty objects being disposed of (Petschow et al. 2014; Pour et al. 2016) • Emission of nano particles while manufacturing (Cerdas et al. 2017)	• Higher frequency of small transports might compensate for the transportation savings above (in the case of many decentralized AM machines instead of one central manufacturing facility)	• Consuming more products and resulting resources than really needed due to simple, decentralized fabrication, e.g., by private end customers (rebound effect, " throw-away culture") (Petschow et al. 2014)	• Portion of replacement deliveries (swaps) increases compared to the portion of repairs due to limited accessability (Feldmann and Pumpe 2016)	• Recyclability of some raw materials unknown (Bourell et al. 2009) • Unmixed disposal recyclability of two or more materials amalgamated in one manufactured object is difficult (Ford and Despeisse 2016)

Figure 10 - life cycle of an AM fabricated object: ecological impacts

4. Case Study: Mobile Case Covers

The following chapter analyzes the impact on the sustainability of the implementation of 3DP in the distributed manufacturing of mobile case covers. LCA guideline of AM, built in the previous chapter through recent investigations on AM products, was fundamental for this research, as it provides the understanding both on how to assess the sustainability of AM and on the relevant factors to look at to properly assess it. However, it is just part of the method used to assess this case study. LCA alone, gives a deepen knowledge of the product and it does so by modeling a system, but it gives straight information without living space to further analysis. The research method used in this case study, instead, tries to develop a model to solve a specific problem related to the excessive waste produced by MTS manufacturing, and finds the solution in 3DP which favors MTO and distributed manufacturing. The model is built through Vensim, a software usually used in system dynamics to analyze the effects of variables over time.

After a first part that introduces the reasons for analyzing this case study and the research method used, this chapter goes through all the steps needed to build the model; it starts with the modeling of the demand curve for 3D printed mobile case covers and in-home recycling systems through the Bass Diffusion Model, an equation that describes the process of how new products get adopted in a population and follows with the explanation of how to calculate the indicators of the three areas of sustainability: environment, economy, and society. The last part of the chapter includes the results of the analysis and different scenarios that could take place.

4.1. Introduction

Mobile phones are an interesting challenge for sustainable manufacturing as users desire to substitute obsolete devices with more innovative models in less than 15-30 months. Usually, mobile phones are accessorized by their owner with case covers for aesthetic customization reasons or functional reasons (protection). Case covers adapt to specific mobile phones and therefore share a similar obsolescence timescale [26].

Nowadays the production of case covers is a push system. They are typically made to stock, this requires producers to make forecasts on likely demand requirements, with no actual demand data. When demand is underestimated, inadequate stock satisfies the demand, while when demand is overestimated, excess stock lingers in the supply chain. The production volume of mobile covers always largely exceeds the real demand. This results in lots of unsold covers, that are out of market earlier because their design does not meet users taste or the model of the phone has become obsolete, or the market is saturated [26].

This production model results in an enormous waste of resources for accessories that are out of the market in two to three years. Usually, mobile case covers are sold in electronic shops, dedicated shops, customer service points of mobile operators (Figure 11a). Market stalls (Figure 11b) and fixed price discounter are considered second-level-retailer for distribution of lower quality covers or covers that have been succeeded by newer models. These retailers provide a useful role in achieving revenue for obsolete stock and freeing up capacity in distribution warehouses [26].

(a) (b)

Figure 11 - Case covers for mobile phones on racks in shops (a) and in market stalls (b)

Typically, the case shell is produced by injection moulding, requiring an expensive tool to be developed for the exact phone shape. This requires large production runs to recover the fixed costs. The external surface of the cover may be characterized by artworks, printing, or in-mould decorations (Figure 12). Customers have no involvement in the design or configuration of their product, leading to satisfying customer demand by the provision of variety, rather than enabling customization [26].

(a) (b) (c)

Figure 12 - Examples of injection moulded mobile case covers

To overcome this limitation and provide phone cases that meet individual customer requirements, covers could be produced through AM. AM can be used for customization in mass production according to an MTO model. The absence of specific tools and geometric constraints in AM enables the production of similar but not identical parts that can be individually customized to suit the customer's desires. Figure 13 shows examples of customized 3D printed covers. To fully exploit the advantages of AM, in terms of design freedom, AM customization should consider the fabrication of complex intricate 3D shapes or enhance the cover functionality [26].

(a) (b) (c)

Figure 13 - Examples of AM customized case covers for mobile phones

Another benefit of toolless manufacturing is that costs are cut down as no tool must be fabricated. Thus, AM allows for the fabrication of unique pieces, small batches, and large volume production with similar costs per part as the tool cost is not divided among the number of fabricated parts [26]. 3D printed covers can be ordered online or at fab-labs. The consumer can produce it with his/her 3D printer. In this case, he/she is indicated as a prosumer. In the case of fab-labs, the production is localized close to the final user, so the manufacturing is distributed and decentralized. Distributed manufacturing results in simplification of the supply chain and improved responsiveness and efficiency in the fulfillment of the demand [26].

4.2. Model for Make-To-Stock Manufacturing

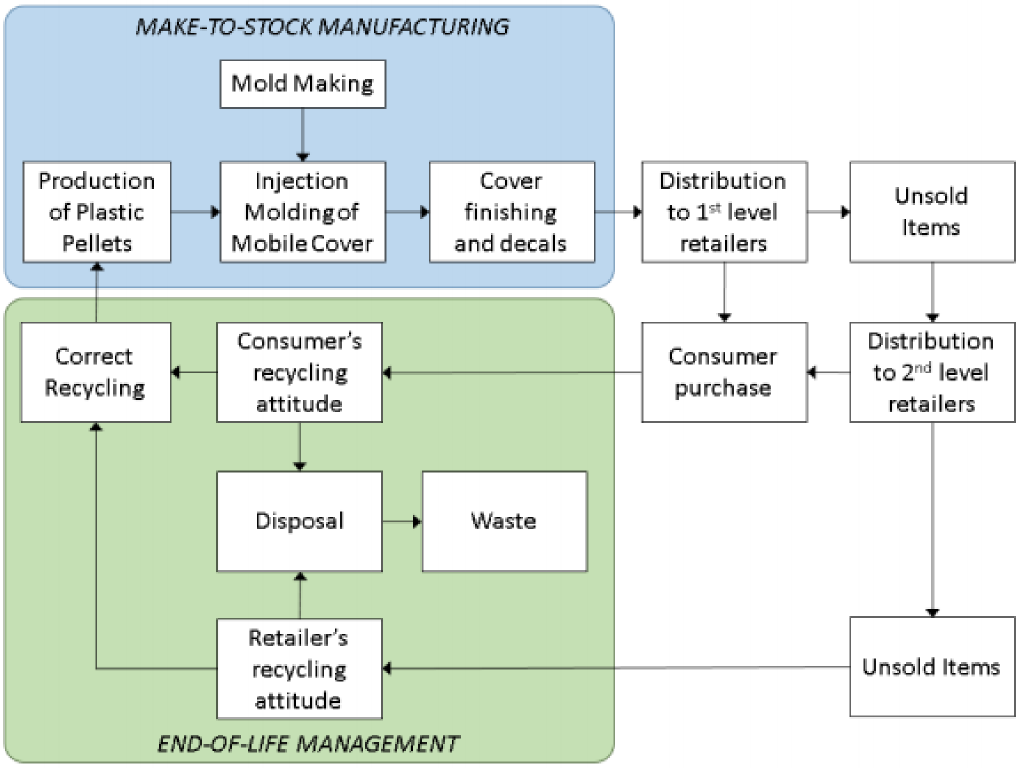

Figure 14 - Lifecycle of injection moulded covers for mobile phones

Figure 14 shows the material flow for injection moulded mobile covers. A steel mould is fabricated and used in large volume production of identical covers. The process starts by melting pellets of a polymeric material and injected into the mould through an injection moulding machine. In most cases, finishing operations are performed to improve the aesthetic to meet the wider estimated demand from the customer. Covers are usually manufactured in China and then distributed worldwide to dedicated shops. The end-of-life management of the cover depends on the user and the second-level retailer for unsold ones. If covers are correctly recycled, they will be converted into small plastic grains, otherwise, they will be disposed of in landfills or incinerators [26].

4.3. Model for Make-To-Order Manufacturing

The process of Fused Deposition Modelling, known as 3D Printing, is taken into account as an alternative to traditional injection moulding for the make-to-demand production of mobile covers. Figure 15 shows the material flow in the case of a 3D printed cell phone cover [26].

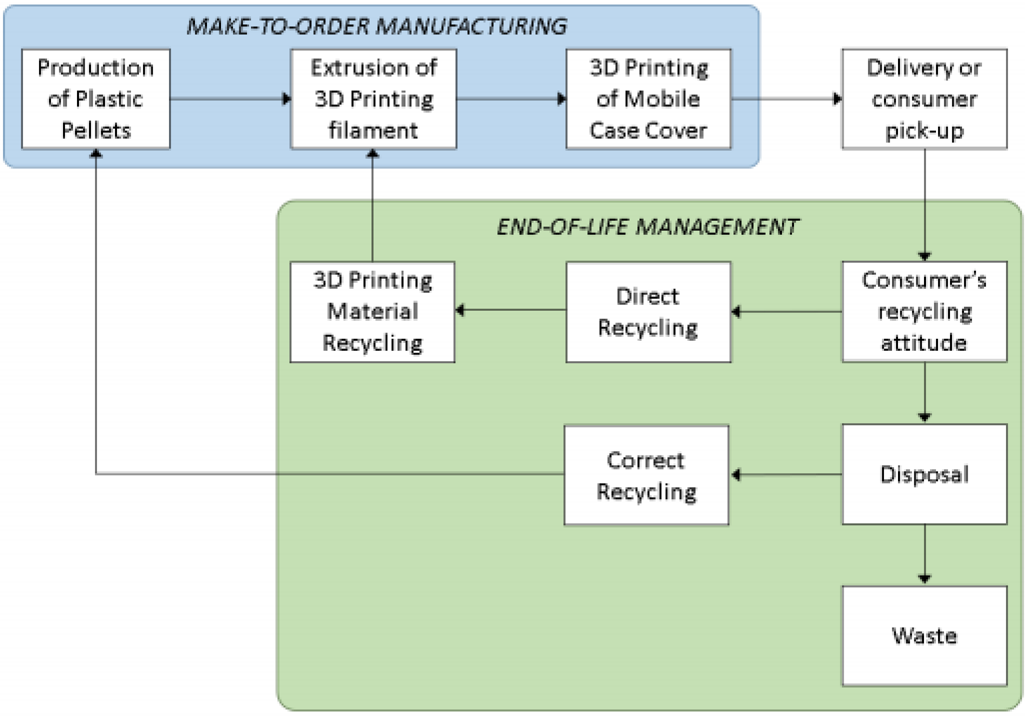

Figure 15 - Life-cycle of 3D printed covers for mobile phones

The raw polymer grains are first extruded to produce the filament which is then used to feed the 3D printer. The filament is usually stored in 1kg spools. Once the cover is 3D printed, it is delivered to the customer or the customer could pick it up at the 3D printing shop. In the case of prosumer then, the supply chain is even shorter.

Once the user does not need the cover anymore, this will be disposed of. The prosumer might have an extruder to recycle 3D printed wastes and use it to make new filaments directly. Otherwise, the cover might be recycled together with other plastic wastes. In the worst scenario, the cover is disposed of incorrectly, and the material will be incinerated or end in a landfill [26].

4.4. Vensim Software

Vensim is an industrial-strength simulation software created by Ventana Systems for improving the performance of real systems. It is primarily used to support system dynamics, an approach used to understand the nonlinear behaviour of complex systems over time using, flows, stocks, table functions, internal feedback loops, and time delays. Vensim provides the graphical modeling interface with causal loop diagrams and stock and flows, on top of a text-based system of equations in a declarative programming language. Vensim's features emphasize connections to data, model quality, flexible distribution, and advanced algorithms. It is a general-purpose software, used in a wide range of problem domains. Usual or high-profile applications include:

- transportation and energy
- environment
- project management
- business strategy
- marketing science in consumer products
- logistics
- health

The version downloaded to perform the analysis is Vensim PLE (Personal Learning Edition). This version is used to get started in system dynamics modeling and is free for educational use and inexpensive for commercial use [27]. Figure 16 shows the model built for this case study; the next chapter explains how it was built.

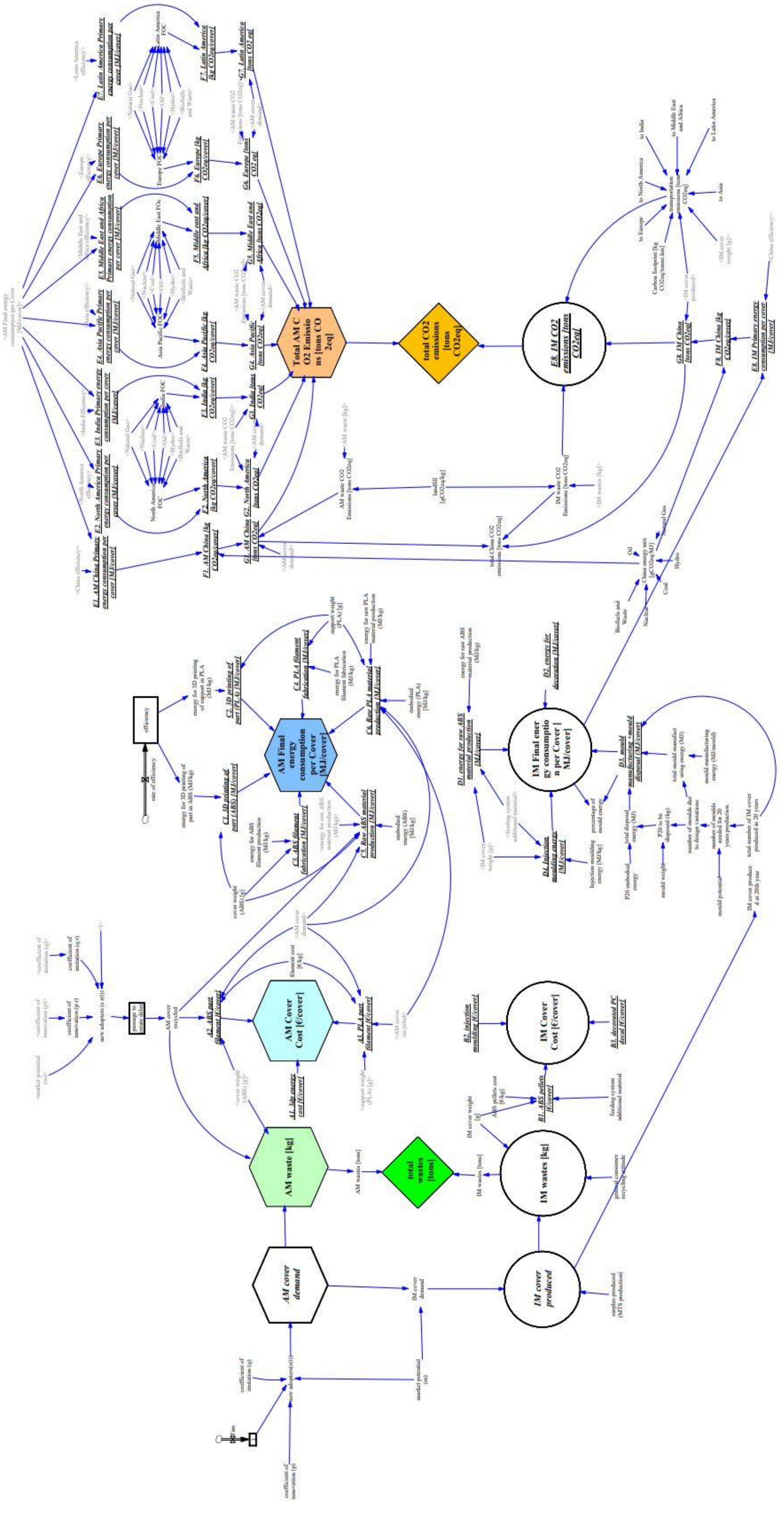

Figure 16 - Vensim Model built for Case Study

4.5. Building the Model

This case study continuous a work started by Minetola and Eyers (2018) [28] which explored the material flow in traditional MTS production using Injection Moulding, and proposed 3D printing as an alternative process suitable for MTO production with a much shorter supply chain. It studied the sustainability of mobile case cover manufacture using both MTO and MTS production. This work aims to make a further step in creating a defined methodology that can standardize assessments between studies, as this has not yet been achieved. In the previous work, the two models were compared considering direct materials cost and energy consumption of a single cover, as other costs such as operators' costs, and various indirect costs such as depreciation and overhead recovery were not considered, since the focus of the study was on environmental impact, and not to attempt to provide an exact estimate of the manufacturing costs and related profits. While this study sticks to the same hypothesis, as it focuses on the sustainability level, it refines the research by adding CO2 emissions indicators and extends the analysis on a global level.

The functional unit for the assessment is the same as Minetola and Eyers' research, an Apple iPhone 5 cover and demand statistics for iPhone 5 model adoptions have been sources from Statista. The STL model of the case cover is available for download on the Thingiverse library [29]. To perform a correct and thorough comparison, the same polymeric material for the case cover is considered for both 3D printing and Injection Moulding processes. In particular, the case covers are made from ABS, as it is one of the most common materials used for 3D printing filaments. Starting from the material flow, the analysis is a cradle-to-grave approach. Most of the material data is extracted from the CES EduPack 2016 software by Granta Design Limited [30]. [28]

The model is built through Vensim and shows how costs, energy consumption, and global CO_2 emissions of mobile phone covers will vary in future years due to the adoption of 3D printers and in-home recycling systems. Vensim adds dynamicity to the existing model. The chapters below explain first how to build the demand model for 3D printed covers and in-home recycling systems for the next years and the following ones explain how to calculate costs and energy consumption for both processes. Finally, the last chapter explains how CO_2 Emissions are calculated for both processes. The table below summarizes the major assumptions that were made when building the model.

Mobile phone model	Apple iPhone 5, 5s, 5C, SE
Period of analysis	20 years
3DP Cover demand behaviour	Bass Diffusion Model
In-home recycling system demand behaviour	Bass Diffusion Model
General Recycling Attitude	9%
Market Potential	176 Million Covers/year
IM Cover Surplus produced	50%
Mould Potential	6.7 Million Covers
LCA lifespan	Cradle-to-grave

Table 2 - Major model assumptions

4.6. Forecasting 3DP Cover Demand: Diffusion of Innovation and Bass Diffusion Model

FDM is the AM technology considered for the 3DP of the covers. The popularity of FDM started when the patent of Sir Scott Crump by Stratasys expired and the subsequent open-source Reprap project [31], which since then has become the preferred choice by makers [32]. The FDM belongs to the material extrusion category and is more popularly known as 3DP. It has a simple design consisting of a building platform, a Cartesian structure with three controlled axes, and up to three hot extrusion heads. The price for consumer-end 3D printers starts from 100USD, making them appealing and affordable to many. It can be forecasted that many people will adopt this technology soon, but precise estimates are not available. To forecast the demand for 3D printed covers and in-home recycling systems, this study relies on the Bass Diffusion Model, a model that mathematically explains the diffusion of innovation.

Diffusion of Innovation is a theory that explains how, why, and at what rate technology and new ideas spread. A professor of communication studies, Everett Rogers, popularized this theory through one of his books 'Diffusion of Innovation'. It proposes four main elements that influence the diffusion of new technology: innovation, communication channels, time, and social system. The diffusion strictly depends on human capital, it must be widely adopted to self-sustain and there is a point at which an innovation reaches critical mass.

Frank Bass contributed mathematical ideas to the concept by developing the Bass Diffusion Model. It consists of a differential equation describing the process of how new products get adopted in a population. The model is based on the premise that adopters and potential adopters interact. The adopters of the technology are classified as innovators or imitators and the timing and speed of adoption depend on their degree of innovativeness and degree of imitation among the adopters. The model has already been used frequently in forecasting, especially technology forecasting and new products' sales forecasting. The shape of the model is an S-curve.

4.6.1. Formulation

$$\frac{f(t)}{1-F(t)} = p + qF(t)$$

Where:

- f(t) is the rate of change of the installed base fraction
- F(t) is the installed base fraction
- p is the coefficient of innovation
- q is the coefficient

New adopters (or sales) s(t) is the rate of change installed base f(t) at time t:

$$s(t) = mf(t)$$

$$s(t) = m\frac{(p+q)^2}{p}\frac{e^{-(p+q)t}}{(1+\frac{q}{p}e^{-(p+q)t})^2}$$

Where:

- m is the market potential
- p is the coefficient of innovation
- q is the coefficient of imitation (also called internal influence or word-of-mouth effect)

Finally, the S-curve (adopters) is obtained by integrating the new adopters' curve s(t). Figure 17 shows the two curves.

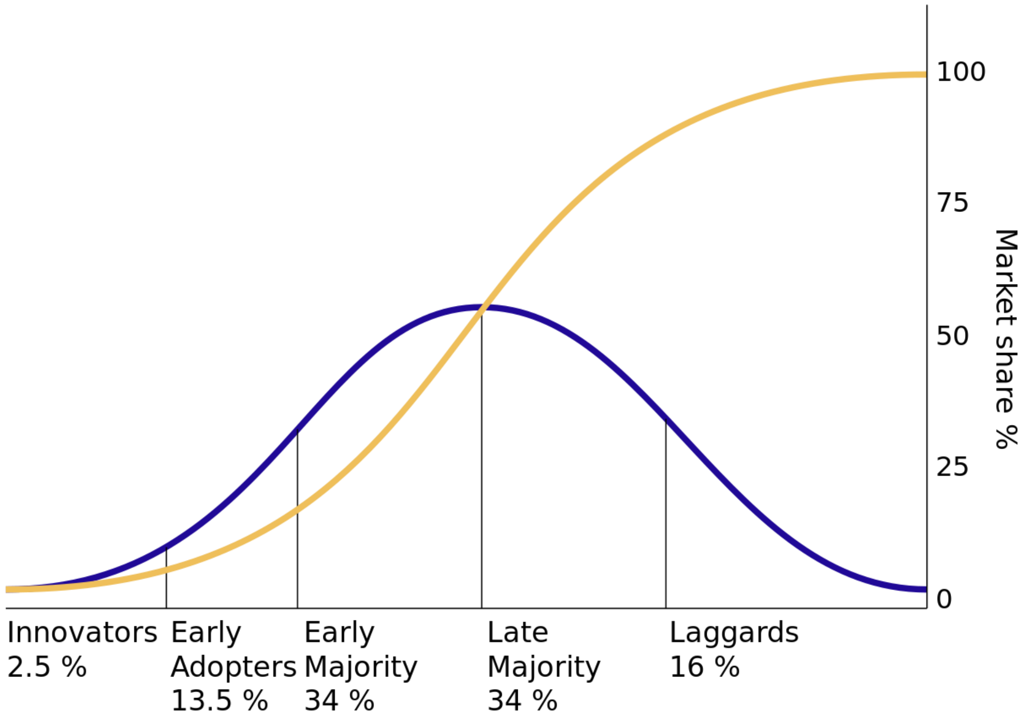

Figure 17 - new adopter (blue curve) and total adopters (yellow curve)

Figure 18 displays the graphical view of the Vensim model of the calculation of the in-home recycling systems' demand. Between the 'new adopters' curve' and the 'AM cover recycled curve' a further step had to be done to delay the demand concerning the demand for AM covers. The model considers that the only things to be recycled are the covers that have been used in the previous year, therefore recycling starts after one year. It is as if consumers change every year covers for a cover of the same mobile phone. Although this is not what happens because every year mobile phones do change, and in turn also the cover's geometry, the model is based on real phone demand values. The next chapter explains how the covers market potential has been calculated.

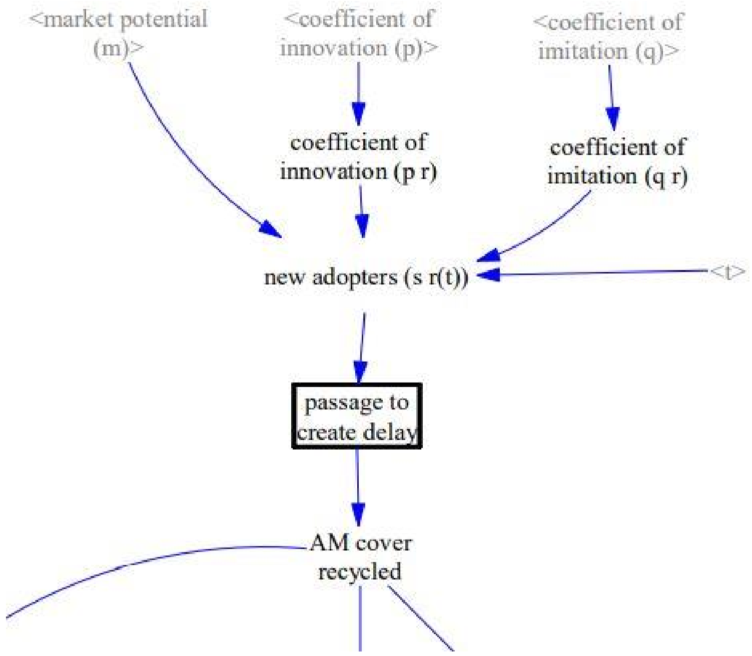

Figure 18 - In-home Recycling Systems' demand

4.6.2. Market Potential 'm'

To determine market potential was not an easy task. There are no exact values of how many covers are produced in a year, as well as how many are demanded. However, enough data has been found on Statista relative to the market of Apple iPhone demand and, by making the correct assumptions, it is believed to make with good approximation a representative analysis of the cover market impact [33]. The aim is to determine the number of covers demanded starting from the number of Apple iPhone sales.

The iPhone sales are determined by the graph in Figure 19 that shows the global Apple iPhone sales from the 3rd quarter of 2007 to the 4th quarter of 2018 [33]. The value of iPhone sales taken as representative for the future years is 220 Million units. This is the mean value taken from 2015 to 2018 sales.

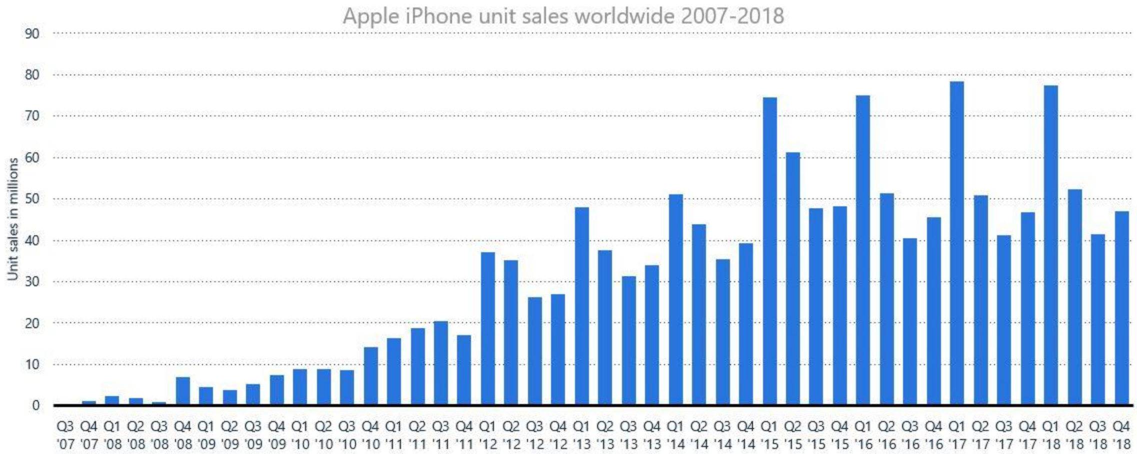

Figure 19 - Global Apple iPhone sales from 3rd quarter 2007 to 4th quarter 2018 (in million units)

It is assumed that not all iPhone consumers use a mobile cover, therefore the value is scaled down to 176 Million units (i.e., 80% of total sales). It must be mentioned that, although this is the value that has been considered in the research model, it is not correct to resemble sales of iPhone 5 model covers for the following reasons. First, it must be considered that the above graph is relative to all models of Apple iPhone sold, models that have different dimensions and, in most cases, do not share the same covers, therefore it would be wrong to assume that this value is relative to only one type of cover for a certain model. It has been determined that about 33% of the total sales in a year belong to the model that was launched in the same year, while the next year decreases to 15% and in the further 2/3 years the share of sales are mostly irrelevant [33]; Secondly, the value chosen is relative to the years where the iPhone 5, unit of research, was not anymore sold therefore making it not a correct representation. It was decided to bypass these problems as the aim of the research is principally to have an estimate of the trends over 20 years of the principal indicators of sustainability.

4.6.3. Coefficient of Innovation and Coefficient of Imitation

When time is measured in years, typical values of p and q are:

- the average value of p is around 0.03 and is often less than 0.1.
- the average value of q is around 0.38, and the typical range is between 0.3 and 05.

Once the model was built, the values were adjusted to reach the full market potential of 3D printed covers sales in about 20 years and the full potential of in-home recycling systems in 25 years. The graph in Figure 20 shows the demand variation for 3D printed covers and the amount of cover recycled every year for the next 20 years.

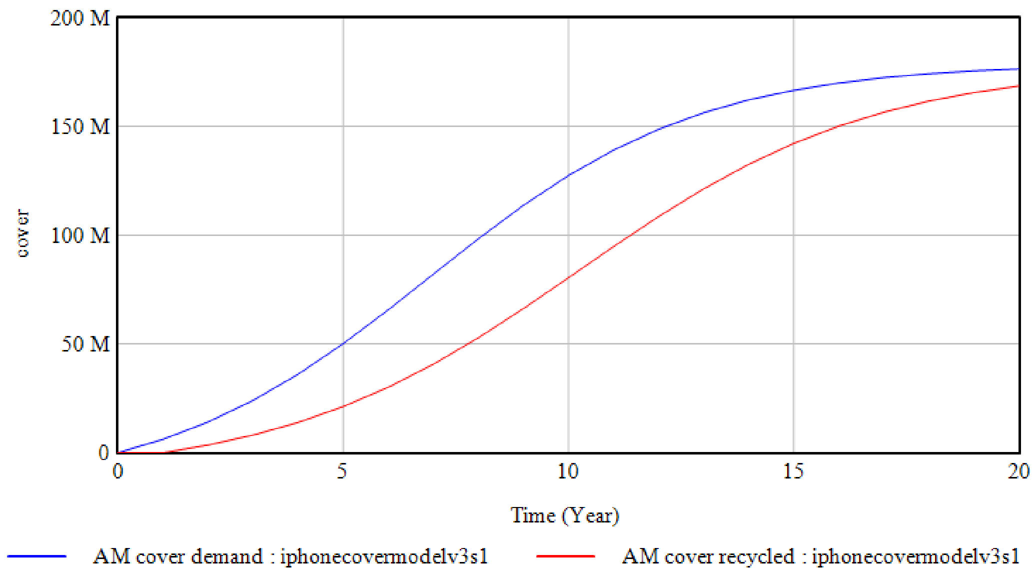

Figure 20 - 3DP cover demand and cover recycled trend

4.7. Waste Assessment

One of the major problems linked with the production of covers through conventional manufacturing is overproduction. Many more covers are produced than what is demanded. This is the main reason that moved this research. MTO manufacturing through AM avoids this issue as only the number of products needed are produced and coupling this technology with in-home recycling systems reduces, even more, the production of wastes. The effects of wastes on sustainability are accounted as landfill disposal of plastic (253 g CO2/kg [34]) when calculating CO2 emission. Figure 21 shows two curves referring to wastes produced by AM and by IM. IM covers' EOL is treated as usual plastic wastes and therefore not all of them pollute landfill but 9% are recycled [35]. The IM waste curve is therefore equal to the IM cover produced minus 9%. The AM wastes curve is instead obtained by subtracting the demand and the recycling curve (Figure 20).

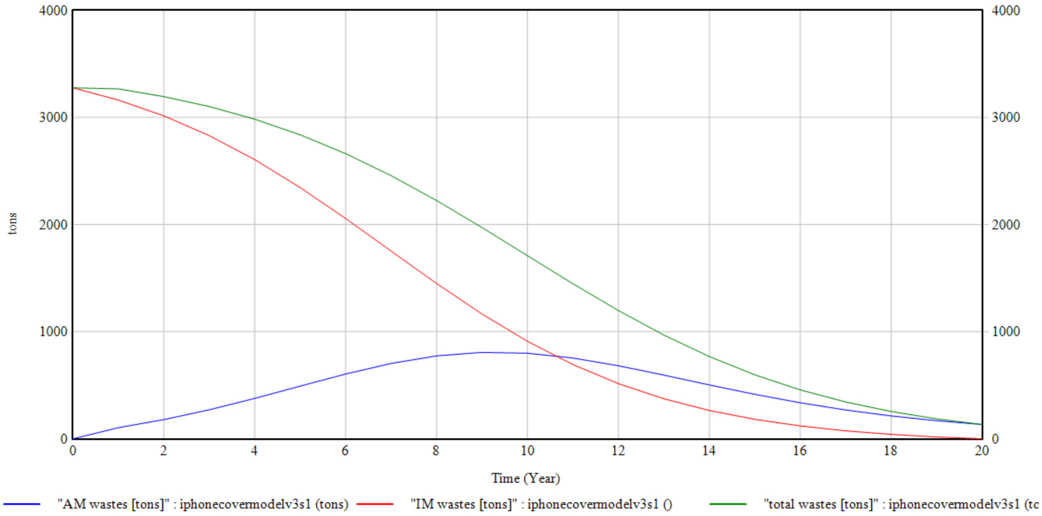

Figure 21 - Injection Moulding and Additive Manufacturing cover wastes

4.8. Energy Assessment

In the following chapter, the energy consumption for each process is calculated. All the components of energy for each process are explained in detail. Most energy values were taken from the CES EduPack [30] [28] whose values are referred to as oil equivalent. This means that the value of embodied energies of the materials is calculated by dividing the final energy consumed by 0.38 (i.e., the conversion efficiency from fossil fuel to electricity) and therefore obtaining the primary energy value. This is because is usual when comparing energies to relate them to primary energy sources from which are drawn most commonly, fossil fuel. However, as this research compares two processes, that take place in different parts of the world, where conversion efficiencies are different between each other, it was preferred to make, at first, a comparison on the final energy consumed by the two processes and then, based on the regions' energy mix, the primary energy is calculated for each one of them and then compared. For this reason, the embodied energy values from EduPack are brought back at first to their original values, i.e., final energy, and then adjusted by the conversion efficiency of the region in which the cover is produced.

4.8.1. Injection Moudling

Figure 22 shows the graphical interface on the Vensim Model of final energy consumption calculation for IM covers. The energy consumed to produce an IM cover comes from four phases: production of raw ABS material (D1), injection moulding (D4), decoration (D2), and manufacturing and disposal of mould (D3).

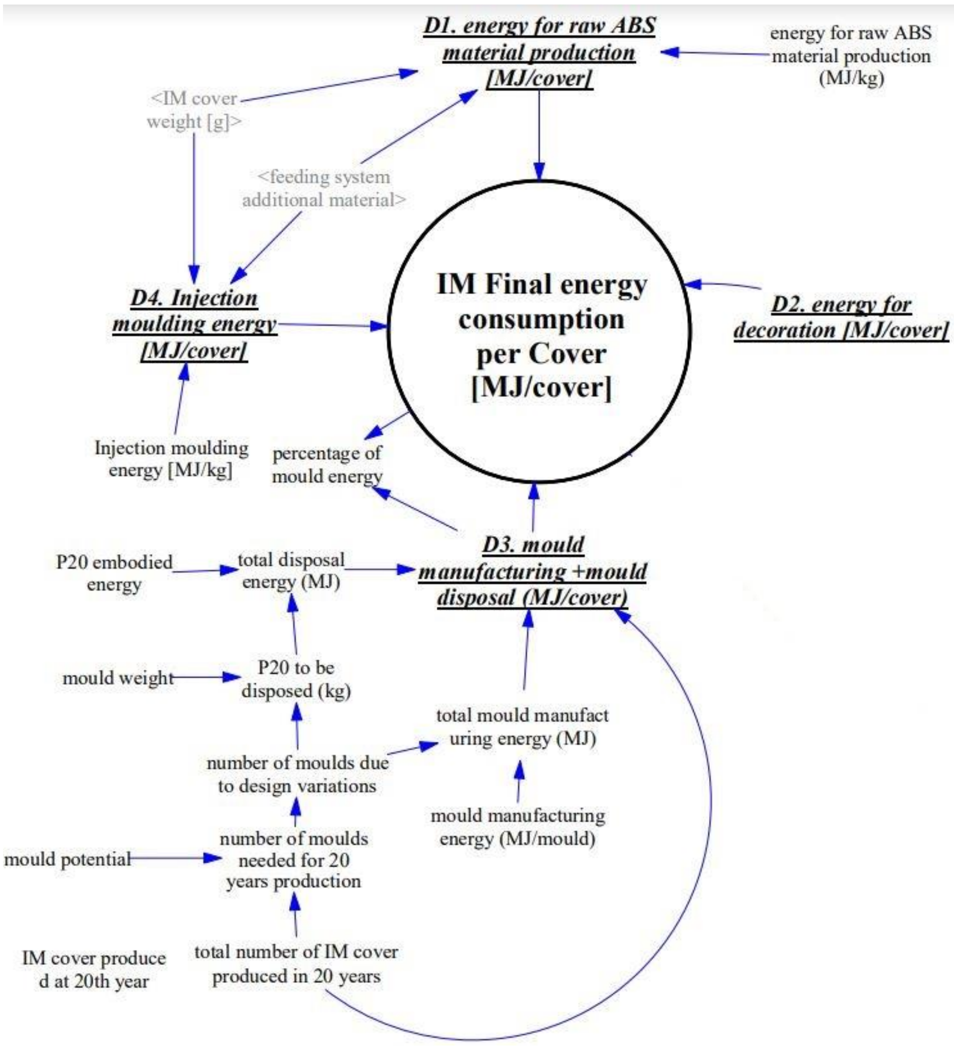

Figure 22 - Vensim graphical interface: Injection Moulding Final energy consumption

The raw material for injection moulding is pellets of ABS and to produce it requires approximately 95.25 MJ/kg [30], while the average for injection moulding of ABS material is approximately 18.55 MJ/kg [30]. Therefore, considering that a cover weighs 17 grams plus 10% additional material for the feeding system, which becomes 18.7 grams, the energy expense for raw material production and injection moulding part is respectively 1.784 MJ and 0.347 MJ per cover [28]. While the calculation of D1 and D4 was straightforward, the other two take some further steps.

Mould Manufacturing and Disposal

The Injection Moulding process requires a mould whose cavity is the inverse shape of the product, but slightly oversized to consider the material shrinkage that occurs during processing. For simplicity, it is assumed that all the plates are made of P20 steel, whose alternative coding is 2311. The iPhone 5 cover dimensions are 127.8 mm x 62.9 x 10.8 mm. Including additional space for the feeding system and other standard elements, it is assumed that the mould plates have a standard size of 346 mm x 446 mm. Table 3 shows all the parts of the mould and their dimension [28].

Element	Dimensions (in mm)		
	Width	Length	Thickness
Top Clamp plate	396	446	36
Cavity plate	346	446	76
Core plate	346	446	96
Space plate (right)	62	446	96
Space plate (left)	62	446	96
Ejector top plate	218	446	17
Ejector bottom plate	218	446	22
Bottom clamp plate	396	446	36

Table 3 - Plates of the injection mould

The plates account for a volume of 0.048 cubic meters, considering 7850 kg/m^3 for the P20 steel, the mould weights about 380 kg. Knowing the weight, it is possible to evaluate the energy required for each manufacturing step. Table 4 shows the energy consumption for mould fabrication.

Manufacturing step	Specific energy (MJ/kg)	P20 steel weight (kg)	Energy (MJ)
Primary production	25.65	417.6	10711.5
Casting	11.50	417.6	4802.4
Coarse machining	1.78	33.4	59.6
Fine machining	13.35	6.3	83.6
Grinding operation	26.20	2.0	54.7
		Total energy	15711.8

Table 4 - Energy consumption for mould fabrication

The energy required for the fabrication of the mould accounts for 15711.8 MJ. For what concerns, the mould disposal, the embodied energy of P20 steel when recycled is 7.51 MJ/kg, i.e., 2853.8 MJ for a single mould [28].

Assuming three 8-hour shifts per day along 365 days with 85% utilization, the mould productivity is 1.34 million case cover per year. Considering that a good quality mould achieves 5 years of utilization, with a 20 second cycle time for the mobile case cover production, it produces 6,700,000 case covers. The energy expense for this part is 0.0028 MJ per cover [28].

Decoration

There are several processes used for the finishing part of the cover, the most widely used is a process of in-mould decoration. It requires printing of a decorative pattern on a label of thin sheet polycarbonate (PC) material. The embodied energy for PC production is 108.5 MJ/kg [30], for extrusion is 6.085 MJ/kg [30], and the thermoforming operation takes about 10 seconds using a machine with a power of 20 kW. Therefore, the total energy consumed is about 0.935 MJ per cover [28].

All the energy values listed above are primary energy consumption, therefore as mentioned before, they must be converted to final energies by a factor of 0.38.

4.8.2. 3D Printing

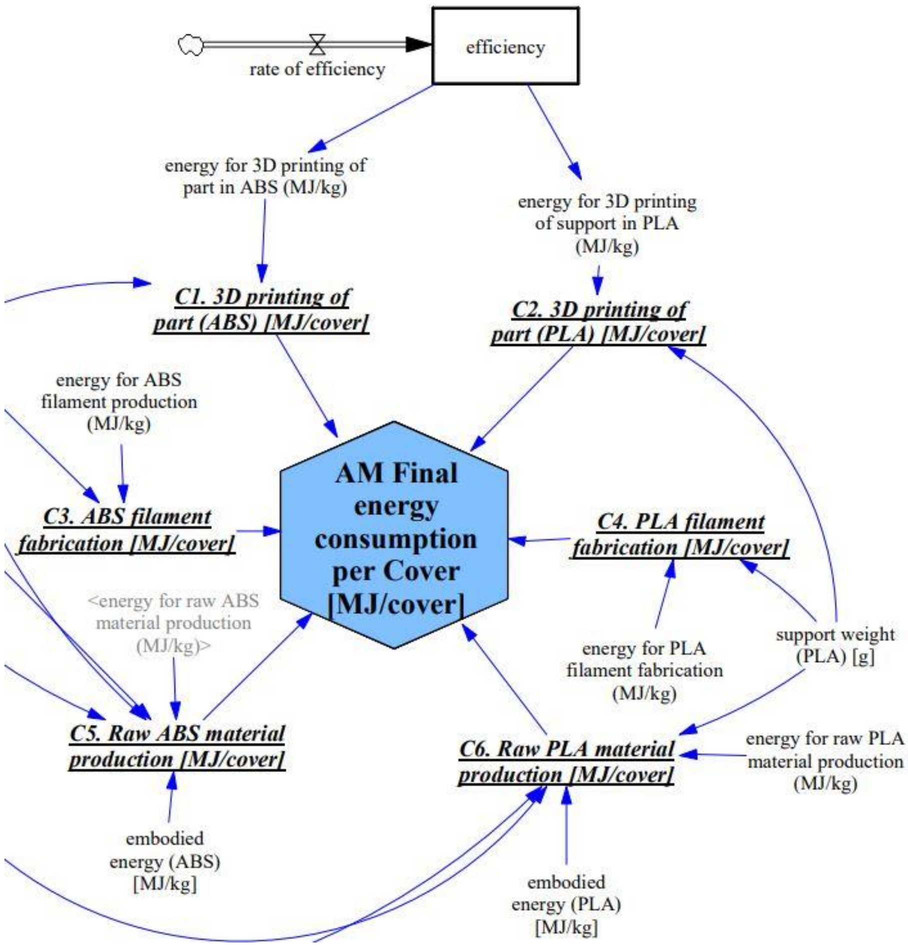

Figure 23 - Vensim graphical interface: 3D Printing cover energy consumption

The desktop 3D printer used for this study is the Makerbot Replicator 5th Generation. While the case cover is produced from ABS material, supports are fabricated from PLA. The amount of material required for the support structures of the overhangs and the raft at the base is approximately 16.5 grams.

The energy embodied in the primary production of the PLA material is 51.70 MJ/kg [30] while ABS, as already said before, is 95.25 MJ/kg. The extrusion of PLA requires 5.94 MJ/kg, while 6.08 MJ/kg is used for extruding ABS filament. The average consumption for a Makerbot is about 0.11 kW for the ABS and 0.08 kW for the PLA material. Therefore, to produce one cover it is required 1.619 MJ to produce ABS pellets, 0.103 MJ to extrude ABS filament, and 0.223 to print the cover. In terms of PLA, the production of the pellet requires 0.853 MJ, the extrusion 0.098 MJ, and the printing of support accounts for 0.158 MJ [28].

In future years, new covers will be made from recycled old covers if people possess an in-home recycling system. This embodied energy to recycle ABS is 33 MJ/kg while for PLA is 17.5 MJ/kg. These values are much lower compared to the production of the raw material, is easy to understand that as more recycled material is used to build the cover, the lower it is the energy required. For simplicity, the model is built in a way that the recycled material only comes from old covers.

The box "efficiency", in Figure 23, is used to build further scenarios that consider the eventual effect of using more efficient 3D printers.

4.8.3. Results

The graphs below are obtained by the Vensim run. The analysis is done over the next 20 years and explores the effects of recycling on the final energy consumption of 3D printing. Figure 24 shows the trend of the final energy required to build a 3D-printed cover. As it was expected, energy decreases. In-home recycling system technology grows, more covers are expected to be recycled and, as it was previously mentioned, being the energy required to produce raw ABS from recycled material less than if it was from new material, the total energy required decreases by about 29% in 20 years.

Although 3D printing benefits from recycling, the energy drop does not reach the IM cover low energy consumption levels (Figure 25).

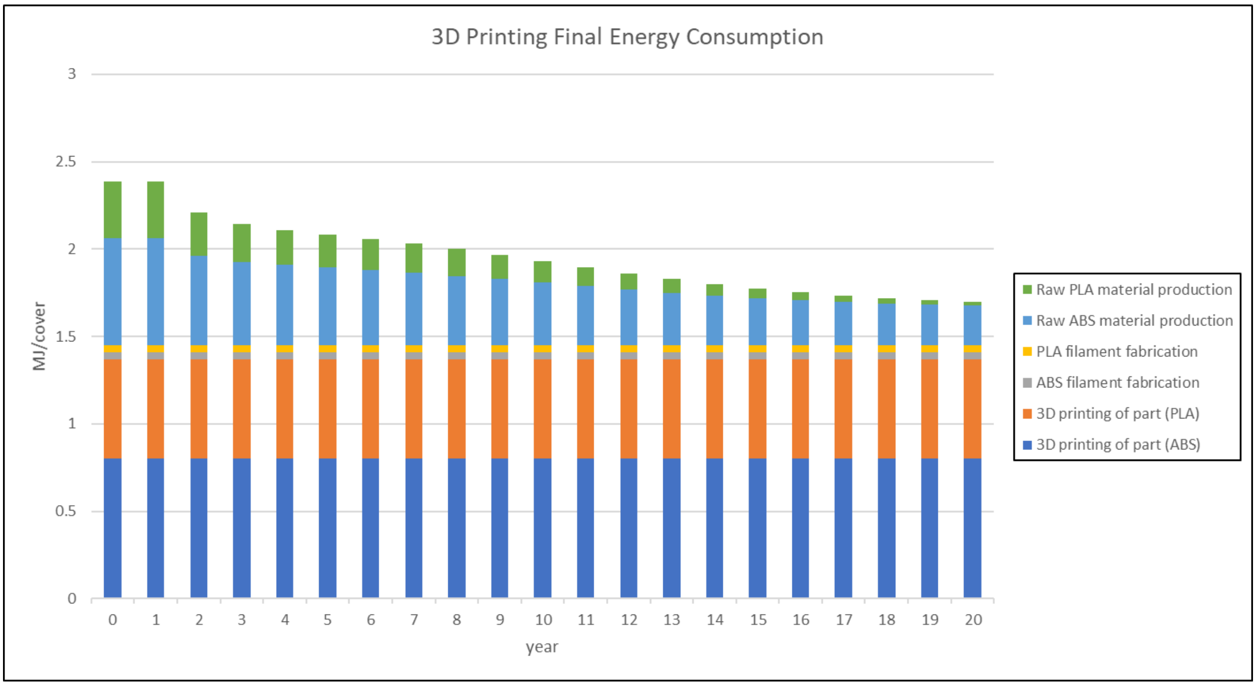

Figure 24 - 3D printing final energy consumption

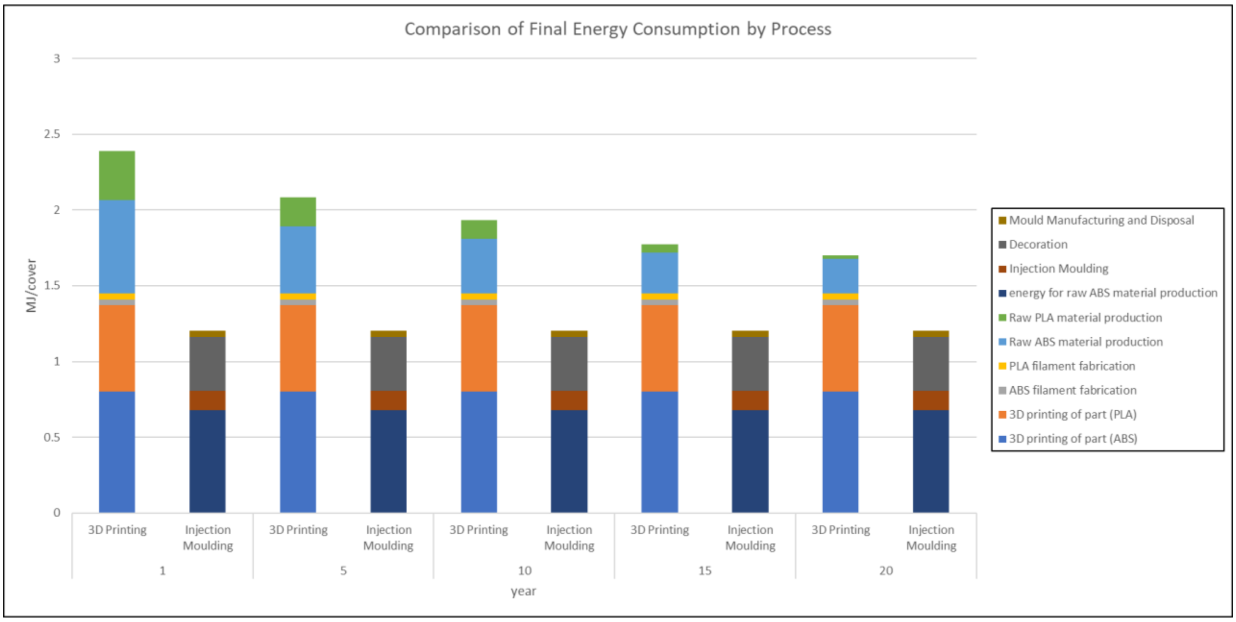

Figure 25 - Final energy comparison between 3D printing and injection moulding

4.9. Cost Assessment

4.9.1. Injection Moulding

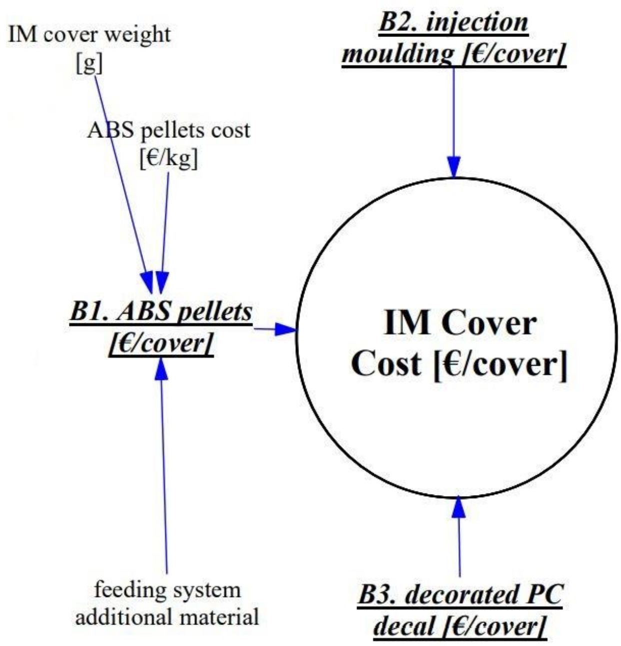

Figure 26 - Vensim graphical interface: IM cover cost

The above visual interface of the Vensim model shows the three components of IM cover cost. The cost of a single cover is the sum of the cost for pellets of ABS, injection moulding cost, and cost for decoration. The pellets cost approximately 2.70 €/kg, injection moulding cost is about 0.26 € per part, and cost for decoration is 0.10 €. The calculation of the cost for injection moulding was determined using the Energy Consumption Calculator for 18.7 grams, 20 second cycle time, the average European electricity cost (0.114 €/kWh), and 7446 production hours per year. The cost of production for an Injection Mouding cover is 0.41 €.

4.9.2. 3D Printing

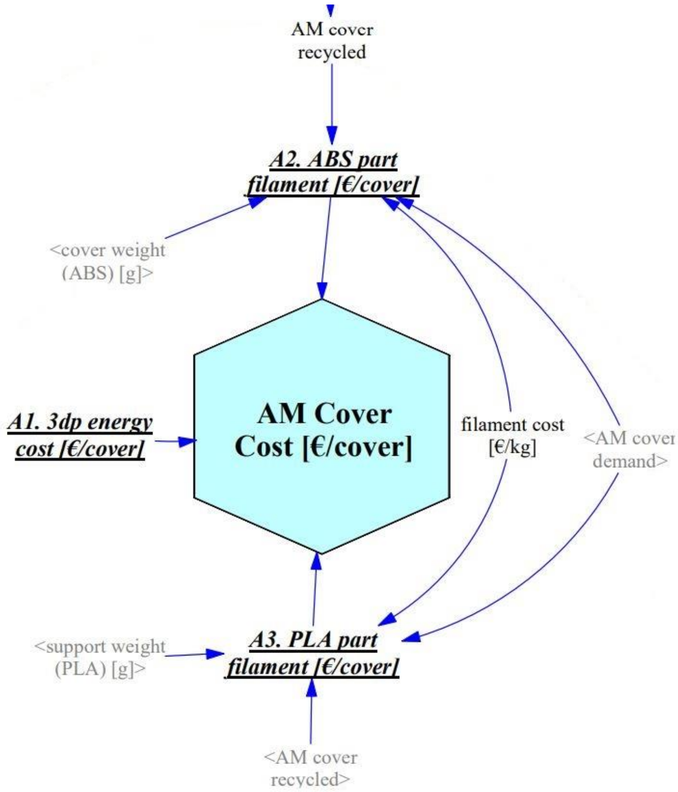

Figure 27 - Vensim graphical interface: 3D Printing cost

The cost of both ABS and PLA filaments is about 25 €/kg for a good quality filament, making the cost for ABS and PLA for a single cover respectively equal to 0.43€ and 0.41€, while the energy consumption during 3D printing costs 0.04 €.

Here again, recycling has a great impact. The more is recycled, the less filament must be bought to produce the cover. Filament costs are expensive and represent the greatest share of the total cost, it is therefore expected that a lower need for new filaments will lead to a fall in costs.

4.9.3. Results

Figure 28 shows the cost variation over the next 20 years. Between the 1st and last year, there is a fall of about 91%. In the 7th year, the cost to produce a 3D printed cover falls below the cost to produce an IM cover (Figure 29).

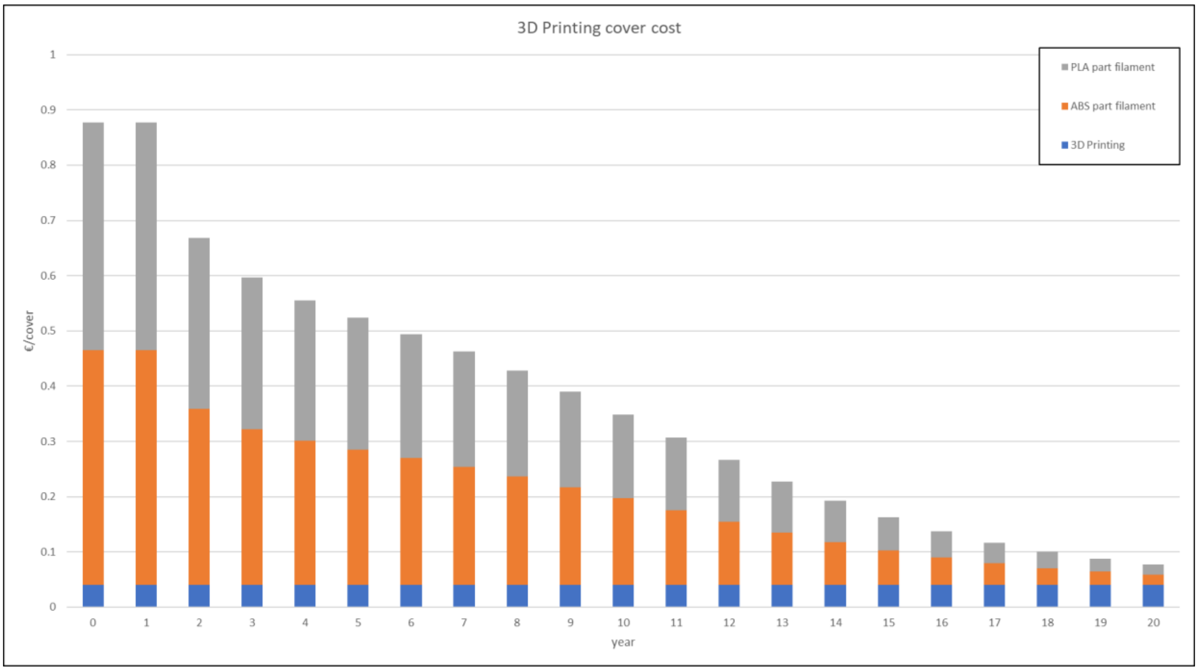

Figure 28 - 3D Printing cover cost

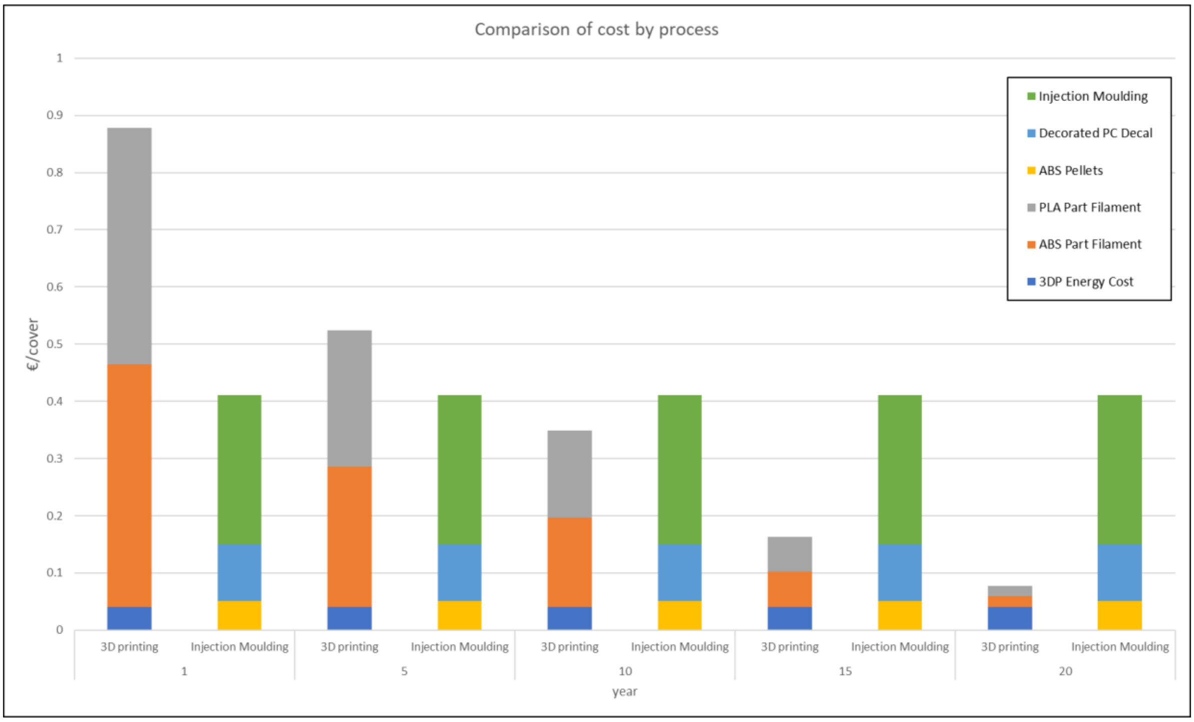

Figure 29 - Cost Comparison between 3DP and IM cover

4.10. Emissions Assessment

The environmental analysis is perhaps the most relevant part of this study. It gives a direct vision of what is the impact that a certain product has on the environment. The only indicator used to account for such impact is CO2 emissions, which are calculated for every region where covers are demanded. The carbon footprint, the amount of CO2 emitted during a product's lifecycle, is one of the most used indicators when assessing sustainability. Carbon dioxide emissions are emissions stemming from the burning of fossil fuels, produced during the consumption of liquid, solid, and gas fuels.

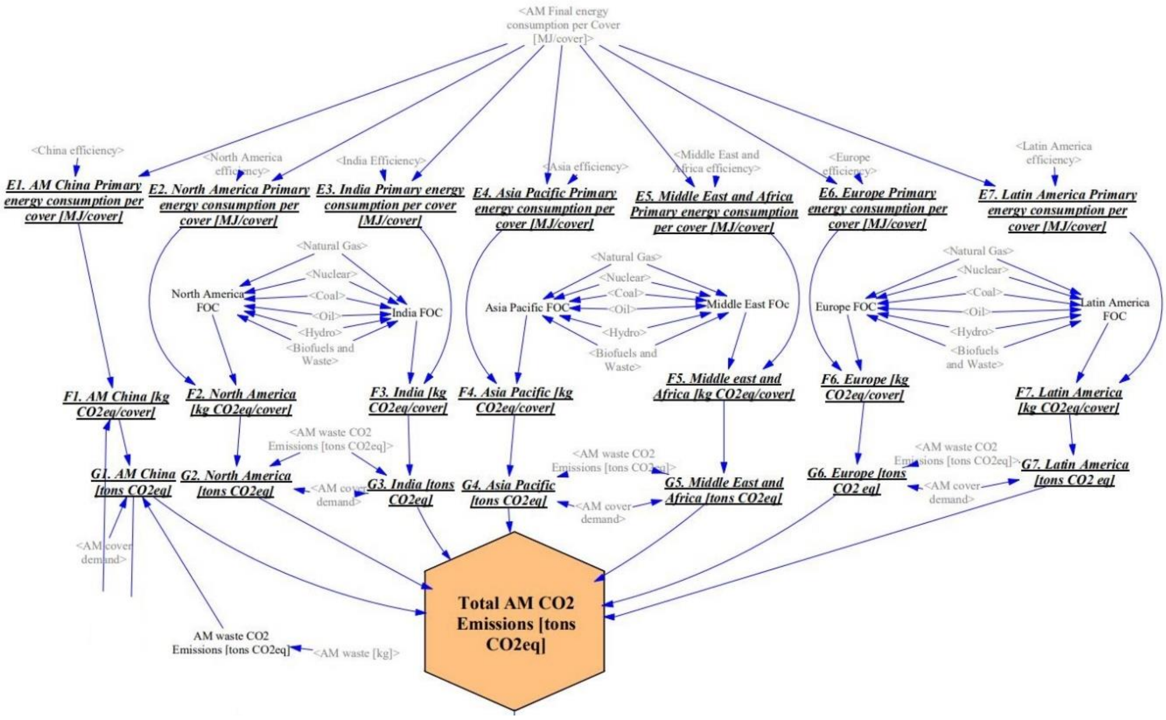

Figure 30 - AM CO2 emissions

Figure 30 displays the graphical view on the Vensim model of the emissions calculation for AM covers. The following chapters explain step-by-step how this calculation occurred. The first step is to calculate the quantity of primary energy consumed in every region. It follows the calculation of CO2 emissions per cover for every region due to the primary energy required, the wastes produced, and, for IM covers, transportation. Finally, total emissions are calculated for every region.

4.10.1. Calculation of Primary Energy Consumption per Cover in every Region

In the 'Energy Assessment' chapter, the final energy for the cover production has been calculated. This is the energy consumed by the end-user, such as households or industry. This energy was obtained by primary sources. Primary energy is the energy found in nature that has not been subjected to a conversion process. To make a precise comparison between the two production processes, as they take place in different regions of the world, it is correct to compare the primary energy

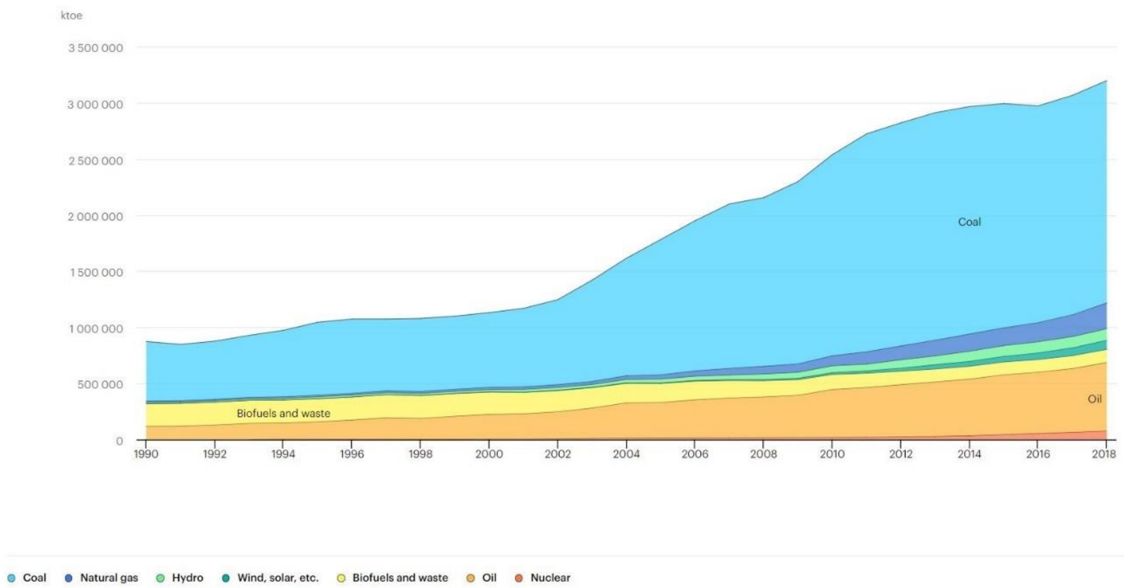

Figure 31 - China energy mix

consumption. The amount of primary energy consumed differs between every region as it depends on their energy mix and the efficiency of conversion of the energy sources. The energy mix is the group of different primary energy sources from which secondary energy for direct use is produced. The energy mix of every region was obtained by the U.S. Energy Information Administration (EIA) [36]. Figure 31 shows China's energy mix from 1990 to 2018.

For this work, the latest values were used, therefore the 2018's ones. China's energy, for example, is characterized by a mix of 58 % coming from coal, 7% from natural gases, 2% from nuclear, 3% from hydro, 3% from biofuels, and 18% from oil. Table 5 shows the energy mix of the other regions.

Regions	Energy Sources						
	Coal	Natural Gas	Nuclear	Hydro	Renewable	Biofuels and Waste	Oil
North America	13%	32%	9%	2%	2%	5%	36%
Latin America	5%	22%	1%	10%	2%	22%	40%
Europe	16%	25%	12%	3%	4%	9%	31%
Middle East and Asia	7%	35%	0%	1%	0%	24%	32%
Asia Pacific	48%	11%	2%	3%	2%	8%	25%
India	43%	5%	1%	1%	1%	19%	24%
China	58%	7%	2%	3%	2%	3%	18%

Table 5 - Energy Mix of Regions of the world

Each primary energy source is characterized by an efficiency of conversion and it differs from region to region, however, for simplicity, they were considered all the same. Table 6 shows the conversion paths for all the energy sources. These values were taken from Ashby [37]

Energy Conversion Path	Efficiency, Direct Conversion (%)
Gas to electric	37-40
Oil to electric	36-38
Coal to electric	33-35
Hydro to Electric	75-85
Nuclear to electric	32-34
Biofuels	23-26

Table 6 - Efficiency of conversion of energy sources

With the energy mix of every region and the efficiencies, it is now possible to calculate the conversion efficiency from primary to final energy for all regions. To do so, the percentages of energy sources used in a particular country are multiplied by their efficiency and then added together. The energy mix is the weight of the function used to calculate the region's efficiency. For example, the calculation of Europe's efficiency is:

$$Europe\ eff = 34 * 0.16 + 38 * 0.25 + 33 * 0.12 + 80 * 0.03 + 25 * 0.09 + 37 * 0.31$$

Table 7 shows all regions' efficiencies:

Regions	Efficiency (%)
North America	37
Latin America	40
Europe	37
Middle East and Asia	36
Asia Pacific	36
India	32
China	33

Table 7 - Regions' energy conversion efficiencies

It is now possible to calculate the amount of primary energy needed to produce a single cover in every region (Figure 32).

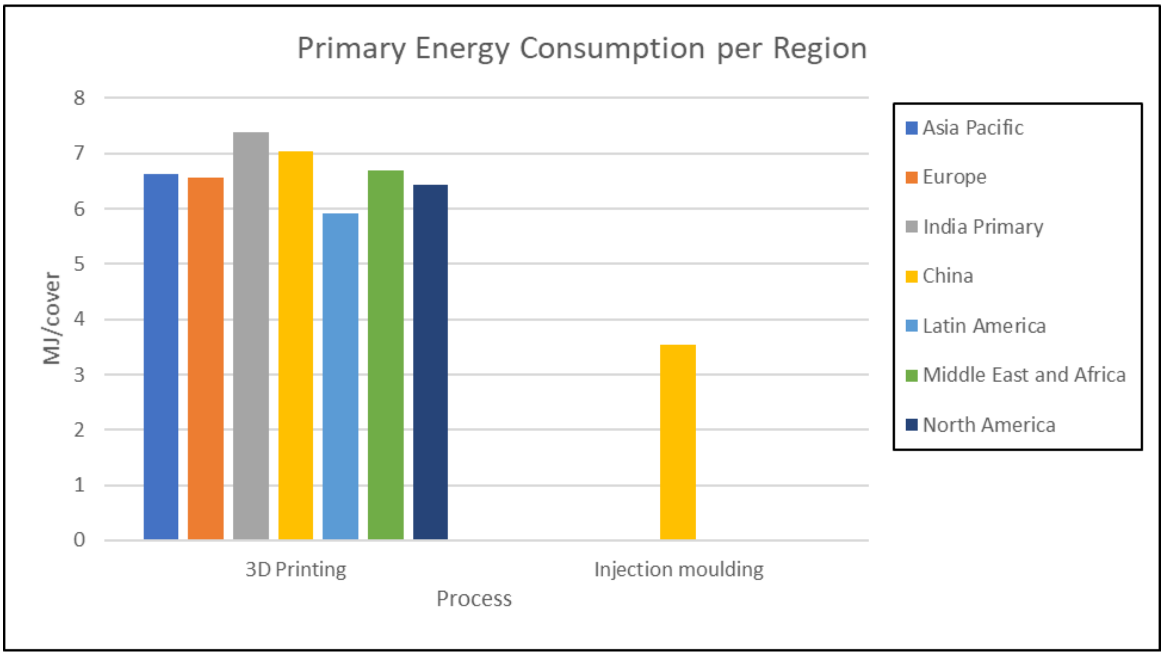

Figure 32 - Primary Energy Consumption per region

The values of the above graph refer to the 1st year, therefore at the highest values of energy consumption for 3D printing, used only to show the differences between the regions' differences of energy consumption.

4.10.2. Calculation of CO2 Emissions per Cover in every Region

The calculation of CO2 emissions is quite straightforward at this point. Once the primary energy is calculated for every region, it must be multiplied by the region's factor of conversion (kg CO2 eq/MJ). The calculation of the conversion factor follows a similar process to the regions' efficiencies calculation. A weighted average is done for every region, where the energy mix of the region acts as the weight. Table 8 shows the conversion factor of the energy sources and Table 9 shows the conversion factors of all the regions.

Energy Conversion Path	Associated Carbon kg CO2eq/MJ
Gas to electric	136
Oil to electric	74
Coal to electric	227
Hydro to Electric	6.7
Nuclear to electric	3.3
Biofuels	63

Table 8 - Factor of Conversion from MJ to CO2 emissions [11]

Regions	Factor of Conversion [g CO2eq/MJ]
North America	103
Latin America	85
Europe	99
Middle East and Asia	102
Asia Pacific	147
India	134
China	157

Table 9 - Conversion Factor of every region

China has the highest conversion. This means that for the same energy consumption, China consumes the most. Through a distributed manufacturing of covers through 3D printing, it is expected that global CO2 emissions diminish, however it must be considered that 3D printing requires more energy compared to injection moulding, this could balance out the advantage of distributed manufacturing.

The bar graph below shows the CO2 Emissions per cover for every region.

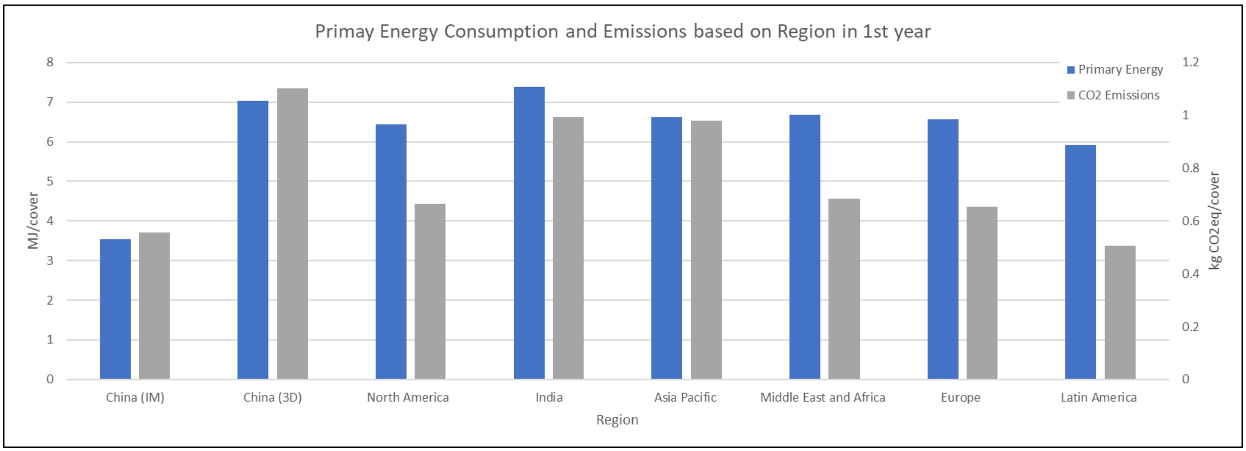

Figure 33 - Energy consumption and relative emissions of a single cover in every region

4.10.3. Waste and Transportation Pollution

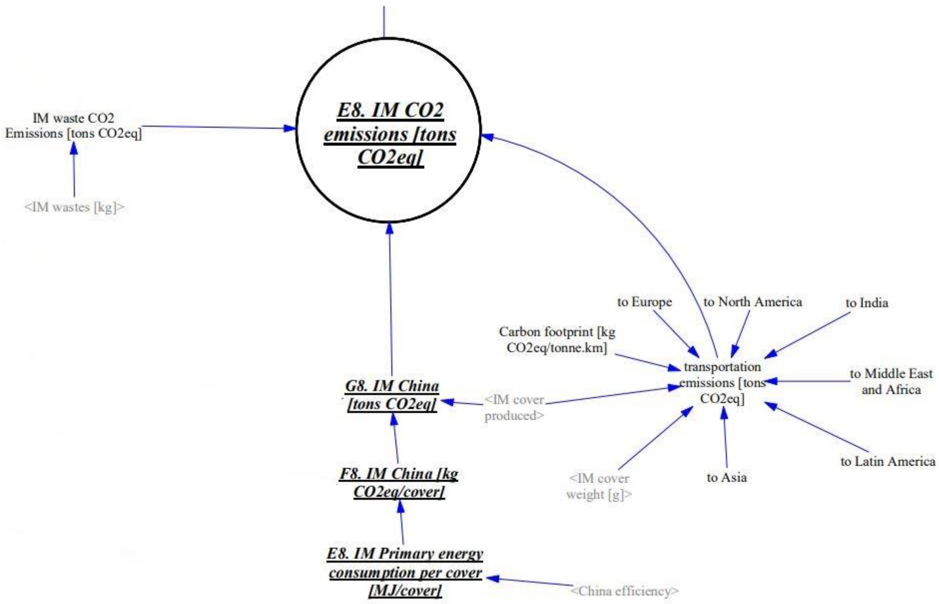

Figure 34 - IM CO2 Emissions

Figure 34 displays the graphical view on the Vensim model of emissions calculation of the IM process. Apart from the emissions coming from the cover production, other shares of pollution must be calculated. These come from wastes created by overproduction and not recycled covers, and sea freight of IM covers from China to the consumer countries.

The EOL of not recycled covers is landfill. To account for the impact of plastic wastes that end in landfills, the amount of plastic wastes is multiplied by 253 (CO_2eq/kg).

In this research, it was supposed that all IM covers are produced in China. Being this region a leader pole in the production of most cheap short lifecycle product, with good approximation, this hypothesis is valid. Moreover, searching on several e-commerce websites that sell covers, most of them are produced in China

Transportation pollution must be accounted for. The transportation takes place by ocean shipping which is generally very cheap. The carbon footprint of ocean shipping is 0.015 kg CO_2eq/tonne.km [37]. The distances traveled were calculated on the website 'searates' [38].

Both wastes and transportation effects must be calculated, however overall, their share of impact appears merely irrelevant. Indeed, together they represent less than 1% of the total emissions.

4.10.4. Results: Global CO2 Emissions

After the evaluation of the previous efficiencies and factor of conversion, it is now possible to evaluate the amount of CO_2 globally emitted by all regions. To precisely calculate the regions' share of pollution, is important to understand how to split the total demand for covers, approximated through the Bass diffusion model, between the different regions. No relevant information was found referring to mobile case covers' market, while there is enough referred to smartphones. Being the two

Regions	Smartphone Sales (%)
North America	9
Latin America	9
Europe	17
Middle East and Asia	13
Asia Pacific	15
India	11
China	27

Table 10 - Smartphone sales around the world

markets strictly correlated, with good approximation it can be said that they are the same. Table 10 shows the share of smartphone sales in every region (and therefore the share of covers sales in every region) [39].

Based on this share it is now possible to calculate the number of covers demanded in every region as well as the total amount of emissions due to energy consumption. Adding the latter to the emissions due to wastes, the following graph (Figure 35) shows how emissions due to covers production would vary around the world if the production process would shift from conventional manufacturing that takes place in China, to distributed manufacturing through 3D printing that takes place in the consumer countries.

It appears from the graph that after 20 years there is less than 8% decrease in the total CO2 emissions. It is not a substantial decrease over such a long period. The higher energy consumption of 3D printers balanced out the advantage of a distributed manufacturing that moved production toward less pollutant regions. This, however, still guarantees for China, from a societal impact point of view, a great advantage. Indeed, this region sees its local emissions decrease by 60% in 20 years.

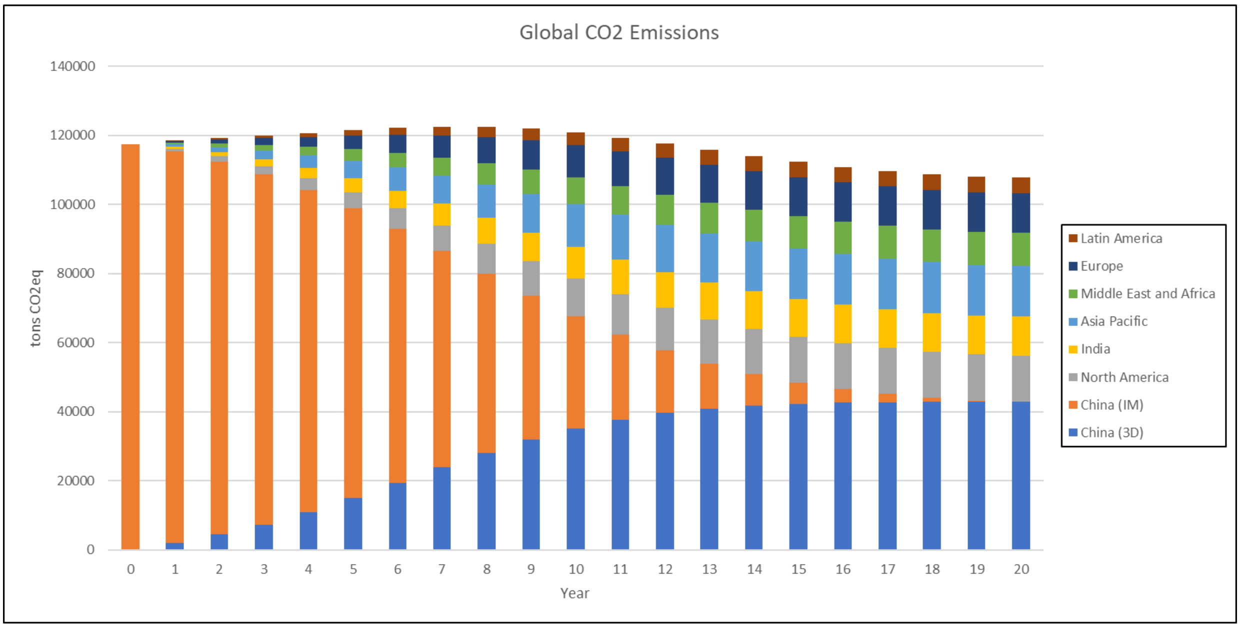

Figure 35 - Global CO2 Emissions

4.11. Exploiting 3D Printing Technology growth

It must also be considered that no variation in 3D printers' efficiency has been accounted for over the entire time of analysis, which is quite unrealistic. AM technologies have been growing, in the last decade, exponentially, and there is no reason why this technological growth should stop. Considering that nowadays 3D printers remain unchanged in 20 years is quite a conservative hypothesis. For this reason, further studies are approached to analyze and exploit the effects of an eventual (and probable) increase in 3D printers' efficiencies over the next decades.

It was considered that printers efficiency increased by 2% every year, reaching a 40% increase after 20 years, being therefore almost as twice as better compared to nowadays printers. Figure 36 shows the energy assessment and comparison with IM. Compared to the previous model, this time the final energy required to produce a 3D printer cover falls below the level of energy needed to produce an IM one. Indeed, Figure 37 shows that such a decrease has quite a relevant effect on CO2 emissions. About 33% less CO2 emissions are produced in the 20th year, compared to the 1st year.

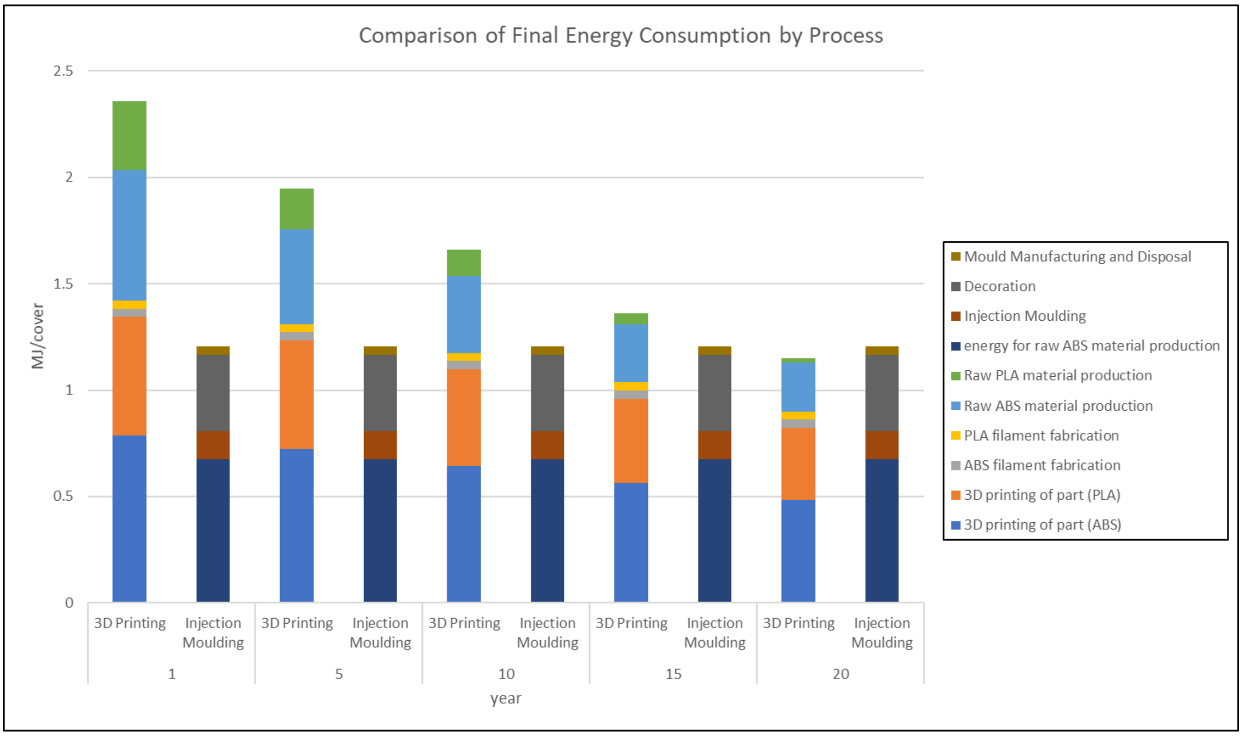

Figure 36 - Energy Assessment of 3D printers' efficiency increase

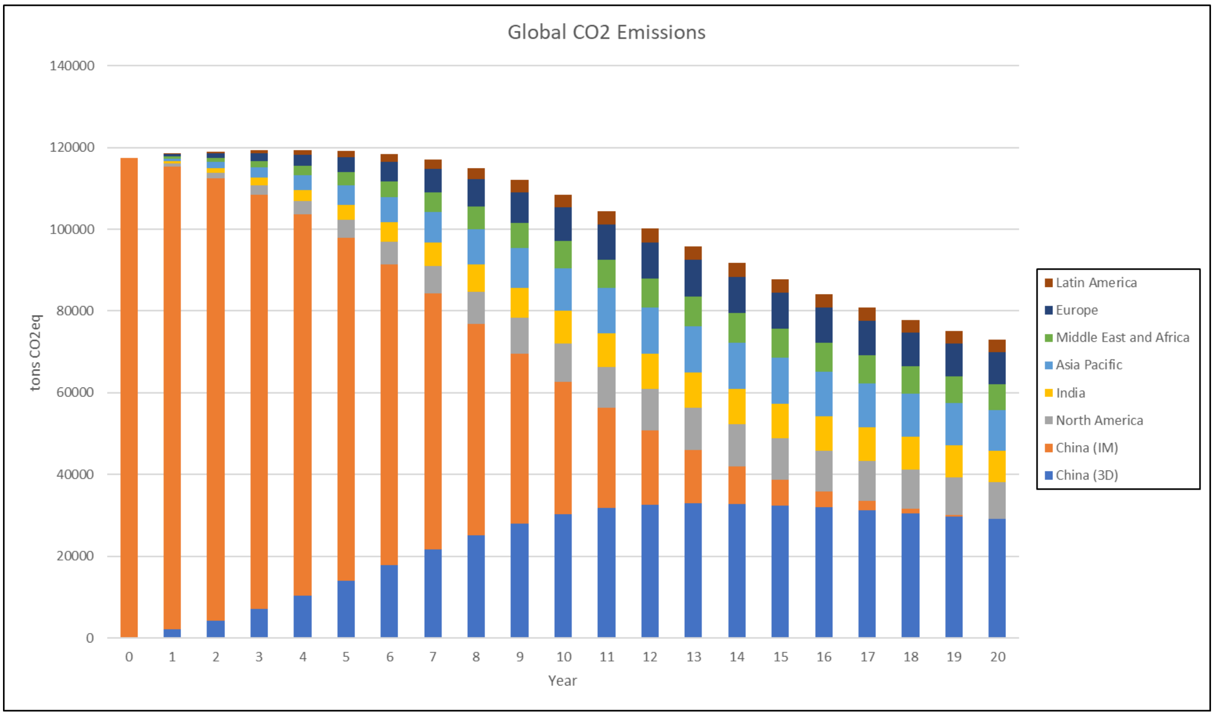

Figure 37 - Emission Assessment of 3D printers' efficiency increase

5. Conclusions

Nowadays excessive consumption of short lifecycle products is leading to large volumes of plastic wastes that burden the environment. The research tried to find a solution in 3D Printing technology and studied the eventual shift from conventional manufacturing to Additive Manufacturing of mobile case covers. The adoption of AM moved production towards consumer countries and stimulated an MTO philosophy, unlike conventional manufacturing. This avoided overproduction as no prediction on future demand is needed. Moreover, the eventual coupling of 3D printers with in-home recycling systems is applied to incentivize prosumers to recycle their old covers to make new ones.

The Vensim Software was used to perform the analysis on sustainability over the next 20 years as the shift between the two production processes occurred. The analysis looked at the covers' costs, energy consumption, and CO2 emissions to draw its conclusions. It emerged that implementing in-home recycling systems led to a fall in costs and waste production as was expected; the energy required to produce 3D printed covers did not reach the low energy levels needed for the injection moulding process, although it decreased. For what concerns CO2 emissions, it appeared that just a relatively small decline occurred on a global scale, however, emissions were redistributed towards consumer countries and therefore China saw its emissions fall by 60%.

It was expected that shifting to distributed manufacturing in less polluted countries would bring higher benefits in terms of total emission, but it turned out that the higher energy consumption level balanced out this eventual benefit. For this reason, a further analysis was carried out to exploit the benefits of the eventual increase in 3D Printing efficiency and as was expected it showed promising results. Assuming a 2% annual efficiency increase led to a 33% fall of total emissions by the end of the 20th year, compared to the first case which saw just an 8% decrease.

This research deepened a study conducted by Professor Minetola and Eyer [28] providing new results as well as new opportunities for further studies. Although a detailed analysis was conducted, the work gives a qualitative view of the trends as it is based on assertions and hypotheses on future behaviors, especially demand behavior, that must be confirmed. Many parameters have been considered constant while it is reasonable that they would vary in the next 20 years. To refine the work, the functional unit of assessment should be upgraded to new phone models' covers which are almost twice as big as the iPhone 5 case cover used for this research. Moreover, the analysis should be extended to other AM processes used in industrial applications with a high productivity rate such as Selective Laser Sintering (SLS) or Multi Jet Fusion (MJF). These technologies do not require supports and unused powder could be recovered at the end of the process.

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