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Fused Filament Fabrication and Injection Moulding of Plastic Packaging: An Environmental and Financial Comparative Assessment

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Abstract: The drive towards smart and sustainable manufacturing is leading companies to opt for environmentally conscious technologies. This study assesses the environmental and financial feasibility of using additive manufacturing, in this case, fused filament fabrication (FFF), instead of injection moulding (IM) to mass-produce cosmetic plastic packaging. Using a life cycle assessment (LCA), the environmental impacts of the raw material production and manufacturing processes were assessed for both technologies. The results showed that using FFF creates a five times greater environmental impact, with printing energy consumption generating 80% of the impact. Using costing models, the cost per product produced using IM and FFF was evaluated, and the models showed that the raw material costs comprise the highest share in both cases. A net present value (NPV) model over twelve years indicated that the FFF NPV was seventeen times higher than that of IM. When testing for quality, the packages produced using IM were superior overall. This study concludes that FFF is more expensive and environmentally impactful when compared to IM.

Keywords: additive manufacturing; injection moulding; life cycle assessment; cost comparison; quality; sustainability

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1. Introduction

The plastic product manufacturing industry generated around 2.4 million tons of carbon dioxide emissions in the United Kingdom in 2020 [1]. The greenhouse gas emissions produced during the manufacturing processes pose a threat to the environment and human health. Moreover, a significant use of natural resources is required during the production of plastic packaging, which further contribute to the negative environmental impacts [2]. As awareness of the importance of environmental protection has increased, manufacturing companies are opting for processes that reduce their environmental burden.

Alternative production processes such as 3D printing have been introduced as a potential technology that can replace conventional manufacturing processes while reducing the negative environmental impacts associated with these processes, and 3D printing offers multiple advantages that could be applied to the cosmetic packaging industry. The technology allows for complex designs to be printed without any tool investments, providing complete design freedom. Furthermore, 3D printing also reduces the time-to-market of products due to flexibility, which is a useful advantage, especially in such a fast-changing industry. However, 3D printing is still emerging in industry and it has not yet been implemented in the mass production of packaging products.

Different 3D printing technologies exist and suit diverse production requirements. For this study, fused filament fabrication (FFF) was considered, which is a material extrusion process where material in filament form is heated and extruded through a nozzle. The material is deposited on a heated build platform in exact locations to create the part layer by layer [3].

The aim of this study is to analyse and compare the environmental and financial sustainability of implementing FFF instead of injection moulding (IM) to mass produce cosmetic plastic packaging, as well as compare the functional and aesthetic quality of components made using both technologies. Moreover, this study also aims to determine the production quantity up to which FFF would be more financially feasible to implement instead of IM. Currently, there are no studies that assess the sustainability of 3D printing and IM taking into consideration the impact on the environment, financial perspective, and quality. Moreover, no studies assess the feasibility of 3D printing for cosmetic packaging production. Separate studies exist comparing environmental impacts or costs incurred when using 3D printing to potentially replace conventional technologies, which are discussed further in Sections 1.1 and 1.2 [4–7].

The objectives of this study are in line with the United Nations' Sustainable Development Goals (SDGs), mainly affordable and clean energy (goal 7), industry, innovation, and infrastructure (goal 9), responsible consumption and production (goal 12), and climate action (goal 13). Analysing the potential benefits of implementing 3D printing to reduce the environmental burdens generated by injection moulding processes contributes to reducing the carbon footprint of manufacturing companies, while ensuring economic growth and innovative solutions that help tackle climate change.

1.1. Environmental Impacts of 3D Printing versus IM

Most studies that analyse the sustainability of 3D printing technologies assess the processes' environmental impacts compared to traditional technologies, including IM. The main advantage of 3D printing is the maximisation of material utilisation, which significantly reduces the material waste generated and increases resource efficiency [8]. The technology also offers geometric flexibility in design, where products can be manufactured using less material while printing complex parts, which would not be possible to replicate using conventional technologies [9].

However, an important consideration is the energy consumption during printing. Researchers' findings comparing printing's consumption with other technologies vary, since consumption is very case-specific. This leads to different results in environmental assessments comparing 3D printing with conventional technologies such as IM. One study found that the specific energy consumption of components made from FDM is three times greater when compared to using IM due to its high processing energy [10]. Moreover, when using IM, multiple parts can be produced per cycle with multi-cavity tooling, as opposed to FDM, where one part can be printed per cycle. Conversely, Mani et al. discuss how 3D-printed parts create less negative environmental impact throughout their life cycle compared to moulded parts due to a shorter supply chain [8]. All this being said, 3D printing could still potentially have a smaller overall carbon footprint when considering the potential to reduce the material usage and weight of the product, although the process requires high energy consumption. As discussed, the required electricity consumption during printing varies depending on the product being printed. With process parameter optimisation, the consumption could be decreased. The key parameters that increase consumption include layer thickness, process speed, and the volume being manufactured [11].

Currently, only few researchers have compared the environmental impacts of 3D printing and IM using an LCA approach. The results also vary greatly depending on the product printed, as well as the equipment being used [12]. One noteworthy study found that the global warming potential (GWP) of a 3D-printed part made from polylactic acid (PLA) generated around 30% less emissions compared to using acrylonitrile butadiene styrene (ABS). Furthermore, the use of 3D printing instead of IM led to a 10% increase in GWP [7]. Another study found that the printing process contributed 80% of the total global warming potential (GWP) value for FDM [4]. The life cycle impact of 3D-printed parts depends greatly on the specifications of each part, as discussed earlier. Therefore, concluding whether 3D printing is more environmentally friendly compared to other technologies has to be considered per product analysed.

1.2. Financial Impact of 3D Printing versus IM

To understand the sustainability of implementing 3D printing instead of IM, the economic perspective needs to be considered. In general, 3D printing is considered to be less cost-effective when compared to IM and is, in fact, mostly used for prototyping. However, cost benefits to using the technology include the fact that 3D printing does not require any tooling, reducing cost and increasing flexibility in the production process. The technology also offers the ability to produce complex geometries at minimal to no added cost [8].

The NPV approach is one of the most established methods to determine a project's profitability in the future by using the present value of future cashflows over a predetermined timeframe [13]. However, researchers have used other costing methods to determine the costs incurred when implementing 3D printing. Two studies have concluded that IM is, in general, more financially feasible compared to 3D printing the same product, while 3D printing is more profitable when used for small to medium production quantities, with the main cost driver being the material and printer costs [5,6].

2. Materials and Methods

Using LCA, the environmental impacts generated during the life cycle of FFF-printed and injection moulded parts were assessed. The financial feasibility was determined with an extensive costing exercise using costing models and the NPV method. Finally, the quality of the cosmetic packaging using both technologies was compared.

2.1. Life Cycle Assessment Methodology

The LCA software SimaPro 8.4 was used with the Ecoinvent 3 impact assessment database. The LCA methodology is a standardised method used to analyse the environmental impacts generated throughout the life cycle of products and allows comparison between different products. The LCA method comprises four stages, discussed hereunder [14].

2.1.1. Goal and Scope Definition

The goal of this LCA was to analyse the environmental impacts generated when mass-producing the cosmetic compact shown in Figure 1 using FFF and IM. The cosmetic packaging is manufactured by Toly Products Ltd. (Żejtun, Malta) in ABS and comprises a lid and base assembled using a pinned hinge. Hereafter, the term 'compact' is used to refer to the cosmetic packaging assembly including the lid and base only, while the term 'component' is used to indicate the individual lid or base that create the compact.

Figure 1. W0144 large round compact by Toly Products.

For this study, an empty compact was evaluated, taking into consideration only the manufacturing of the lid and base. For both technologies, ABS was used for a fair comparison. The life cycle stages included were the raw material extraction, processing, and manufacturing processes. The assembly, transportation, use, and end-of-life stages were excluded since it was assumed that the environmental impacts generated by these processes were identical for both technologies.

A functional unit is used in LCA to compare the environmental impacts of similar products [14]. Toly Products produce the compact at a volume of 1.5 million units per year using IM. For a fair comparison, the production of 1.5 million compacts using FFF was analysed, which allowed the understanding of the environmental impacts generated to meet the production volume required. The lifetime of an IM machine and FFF printer were taken as twelve and five years, respectively. For comparison, twelve years of production was used, which requires investing in printers every five years. Three investments of several printers would be required throughout the twelve years of production, which was thought to generate a substantial impact and hence was also included in the LCA. The functional unit was, therefore, defined as the production of 1.5 million compacts yearly for twelve years.

2.1.2. Life Cycle Inventory Analysis

The second stage involves identifying the data required to model the life cycle stages, in this case, the raw material production and manufacturing stages, summarised in Table 1.

Table 1. Life cycle inventory data.

Manufacturing Process	IM	FFF
Material	ABS	ABS
Mass of one compact (g)	29.87	22.41
Embodied energy, primary production of ABS (Wh/compact)	764	575
CO_2 footprint, primary production of ABS (g/compact)	102.75	77.09
Cycle time	7 s	5 h
Energy consumption (Wh/compact)	18	360
Machinery used and weight	ENGEL Victory IM Machine—13,700 kg	Prusa i3 Printer—7 kg

The first phase of the compact's life cycle is raw material production. In both processes, material extraction involves the raw material, energy consumption, and generated emissions. ABS granules were used for both technologies; however, the granules go through an additional process of extrusion to create filaments for FFF, which was included in the assessment. The mass of one compact includes the mass of the lid and base, as well as the runner system for IM. For FFF, no support material was required to print the components. The greater mass of ABS required generates a greater impact. Although the Ecoinvent database contains extensive information on the CO_2 footprint and embodied energy of raw material production, the extraction of data using SimaPro is sometimes complex. Therefore, Ansys GRANTA Edupack was used to obtain the relevant information on ABS production [15]. In Table 1, the embodied energy, which is the energy required to produce one kilogram of raw material, as well as the carbon dioxide produced and released to produce one kilogram of material can be found allocated to the production of the ABS compacts. Due to the greater amount of ABS required for the moulded compact, the embodied energy and CO_2 footprint for the IM compact are greater compared to using FFF. This indicates that the environmental impacts associated with the production of raw material for the FFF compacts should be lower, emphasizing the advantage of FFF in terms of the maximisation of material utilisation.

The energy consumption to produce one compact using both FFF and IM was measured and provided by Toly Products. The printer consumption to produce one compact was twenty times greater than using IM due to the five-hour FFF cycle time compared to seven seconds. Hence, the environmental impact generated due to the consumption of electricity is expected to be much greater for FFF printing than for IM. For IM, the consumption includes the IM machines and chillers, while for FFF, the printing and filament extrusion consumption were considered. The filament extrusion process is not included in SimaPro databases; therefore, a filament extrusion line with an output of 0.46 kWh/kg was used as a reference [16].

The manufacturing phase includes processing the raw material into the components. The machinery production for the IM machinery and FFF printers were also included in the LCA. However, the FFF printer production and printing process were not found in the Ecoinvent database and had to be manually created using assumptions due to the complexity of creating an accurate process. A Prusa i3 printer was used as a benchmark and assumed to be made from wrought aluminium alloy using aluminium extrusion and sheet production [17]. Although an FFF printer comprises multiple components, the mass of the printer was divided between the aluminium frame and heating bed, with 75% of the printer's mass attributed to the frame and the rest to the heating bed.

Since the cycle time to print one compact is five hours, multiple printers are required to meet the 1.5 million compacts required per year. Assuming an 80% utilisation rate, with the hours worked per week being 120 h for 36 weeks to account for downtimes, one printer can produce 691 compacts yearly. Therefore, 2170 printers are needed to meet the yearly production volume, each having a five-year lifetime. Over the twelve years, 6510 FFF printers would be required, which corresponds to 45,570 kg of aluminium.

Two IM machines are required to produce the compacts; one to produce the base and another one for the lid of the compact. Toly use two IM machines running in parallel to allow for assembly after production, reducing lead times and the need for work-in-progress storage. Although the IM machine production and process are found in the Ecoinvent database, the IM machine production and moulding process were modelled in SimaPro in a similar manner to FFF. IM machines encompass several different components, and it would be very complex to accurately model the manufacturing of the machinery itself. Therefore, the IM machines were assumed to be made entirely of alloy steel [18]. This allowed for a fair comparison between the impacts generated during the production of the FFF printers and the IM machines, with both processes modelled using similar assumptions.

Two eight-cavity steel moulds are used to create the lid and base, with each mould weighing 1800 kg. The lifetime of one mould was taken as two years; hence, twelve moulds are required in total for twelve years of production. The manufacturing process to produce the IM machines and moulds was assumed to be milling. In a year, using the same assumptions as for FFF, 4.45 million compacts can be produced using two IM machines, meaning only a 34% utilisation rate is required for 1.5 million compacts yearly. Therefore, 34% of the production of IM machinery was allocated to the compact production. This means that only 34% of the IM machinery mass is allocated to the compact production, resulting in 9316 kg of steel for two IM machines.

2.1.3. Life Cycle Impact Assessment

The third phase of LCA involves translating the data gathered in the inventory analyses into environmental impacts. The ReCiPe 2016 methodology was used to convert the data into environmental impact scores using midpoint and endpoint indicators. Midpoint indicators include several categories that have an adverse effect on human health, ecosystems, and resource availability. In this study, the human health and ecosystem endpoints were taken into consideration, with relevant midpoint categories.

2.1.4. Life Cycle Interpretation

The results generated were then interpreted in stage four of the LCA, discussed in Section 3.1. A sensitivity analysis was also carried out to understand the impact of certain assumptions made on the LCA results generated, explained in Section 3.1.1.

2.2. Costing Methodology

The economic feasibility of implementing FFF to mass-produce cosmetic compacts instead of IM was assessed using two methods. Costing models adapted from Franchetti and Kress, and Hopkinson and Dickens, were used to assess and compare the cost per compact (CPC) using both technologies [5,6]. Similar to the LCA functional unit, the production of 1.5 million compacts per year was used for comparison. The costs considered for the FFF compacts were material, labour, machine, maintenance, and energy consumption. For IM, the CPC was calculated using material, mould, machine, labour, energy consumption, and maintenance costs. The costs were then added to obtain the total CPC using FFF and IM. Costs such as transportation, end-of-life treatment, administration, and factory overhead expenses were not included in this analysis since the aim of the study was to compare the cost to manufacture the cosmetic packaging using FFF and IM. However, it is important to note that due to the various printers required to meet the production quantity required, a print farm might be required, which would most probably take up more space than that required for two IM machines, which would ultimately increase costs.

The costs used to calculate the CPC using both processes were provided by Toly Products in 2021. The printer cost was modelled after the Prusa i3 printer at EUR 800. Furthermore, one IM machine costs EUR 195,000 and EUR 40,000 per mould. The machinery costs were attributed to one compact using simple linear depreciation using the lifetime and utilisation rate of the machines, as explained in Section 2.1. The labour costs were modelled following 120 h a week for 36 weeks at an hourly rate of 12.50 EUR/h, with the IM machine requiring operators for 6% of the yearly working hours, as instructed by Toly Products. The printer set-up and part removal time per build was taken as five minutes, and four hours per machine are required to set up the IM machines. The material cost for ABS granules and filaments were 1.85 EUR/kg and 30 EUR/kg, respectively. Energy consumption costs were modelled using Band 9 for non-residential consumption tariff rates from Enemalta plc in Malta at 0.109 EUR/kWh [19]. The yearly maintenance fee per printer and IM machine is EUR 80 and EUR 2000, respectively, as advised by Toly Products.

The costing models have a limitation in that twelve years is too long to assume that costs remain fixed. The costing models assume a straight-line depreciation method for the IM and FFF machinery, which does not account for variation in the worth of money due to future inflation. Therefore, an NPV model was used to account for changes in the value of money over the twelve-year period. The costing models were used for determining the CPC obtained when using FFF and IM.

The NPV model considers the difference between the present value of a starting investment (I_o) compared to the present value of future annual cash flows (X_t) over a predetermined period (t), in this study taken as twelve years, as shown in Equation (1). The initial investment includes 2 IM machines and 2170 printers. The discount rate (i) is used to discount the future value of cash flows to obtain their present value and was taken to be 2%, corresponding to the inflation rate target of the European Central Bank [20]. The expenses of 2170 printers required every five years and 2 IM moulds every two years were discounted.

$$\mathrm{NPV} = -\mathrm{I_o} + \sum \frac{\mathrm{X_t}}{(1+\mathrm{i})^{\mathrm{t}}} \quad (1)$$

The cash flows used in the costing models were used in the NPV model as costs per year and discounted. Anticipated earnings were not considered, as the aim of the study was to compare the costs incurred to implement IM and FFF and manufacture the compacts. Therefore, a negative NPV value was obtained, with the process most expensive to implement having the greatest negative NPV value. Using a sensitivity analysis, parameters were varied to understand their impact on the total NPV for both IM and FFF. The production quantity per year was also varied to identify the quantity where FFF would be more financially feasible over IM for compact mass production.

2.3. Quality Testing Methodology

Cosmetic packaging needs to be aesthetically pleasing as well as functionally sound to be sold to and used by consumers. Manufacturers including Toly Products aim to have high-quality products with no defects. Therefore, compacts that potentially reduce environmental and economic impacts would be rendered futile if they are not of the same or superior quality to the currently used compacts. FFF and IM compacts made from ABS were compared to analyse the difference in quality when using different technologies and the same material to create the same product. The quality of the components was analysed under three quality aspects: visual, functional, and package integrity. A sample size of ten compacts per test was used.

For visual quality, the dimensions and maximum mismatch between the lid and base of the compacts were measured and compared with specifications and tolerances. The compacts were also inspected for visible defects and analysed for the quality of the surface finish, based on the experience and subjectivity of the author and the lab technicians at Toly Products. For functional quality, hinge breakage and clip opening force tests were performed to determine the force required to break the hinge and open the compact. The forces were recorded using a Mecmesin MultiTest 2.5dv force gauge, and the obtained values were compared to the tolerance range provided by Toly Products to determine whether they are satisfactory. The package integrity was determined using three tests. The first test was a stress cracking test, where the compacts were placed in an isopropyl alcohol bath for two hours and then placed in a temperature chamber at 45 °C for 24 h to determine the durability of the hinge and assess any resulting stresses. An open/close cyclic test was performed where the compacts were opened and closed 400 times to check whether any pins joining the lid and base at the hinge would move out and determine the durability of the hinge. Finally, a drop test was performed, where compacts were dropped from a height of 1 m to determine the durability during use.

3. Results

In this section, the results obtained from the environmental, economic, and functional assessments are reviewed, following the methodology discussed above. The LCA and costing results are presented according to the functional unit defined in Section 2.1.

3.1. Life Cycle Results Interpretation

The human health and ecosystem endpoints were used to understand the impacts when using FFF instead of IM to mass-produce eighteen million cosmetic compacts on human health and environmental categories, as shown in Figure 2. The impact on both endpoints when using FFF is five times greater than using IM. The human health impact is also much greater than the ecosystem endpoint for both technologies. This shows that both processes create a greater negative impact on impact categories related to human health than on the environment.

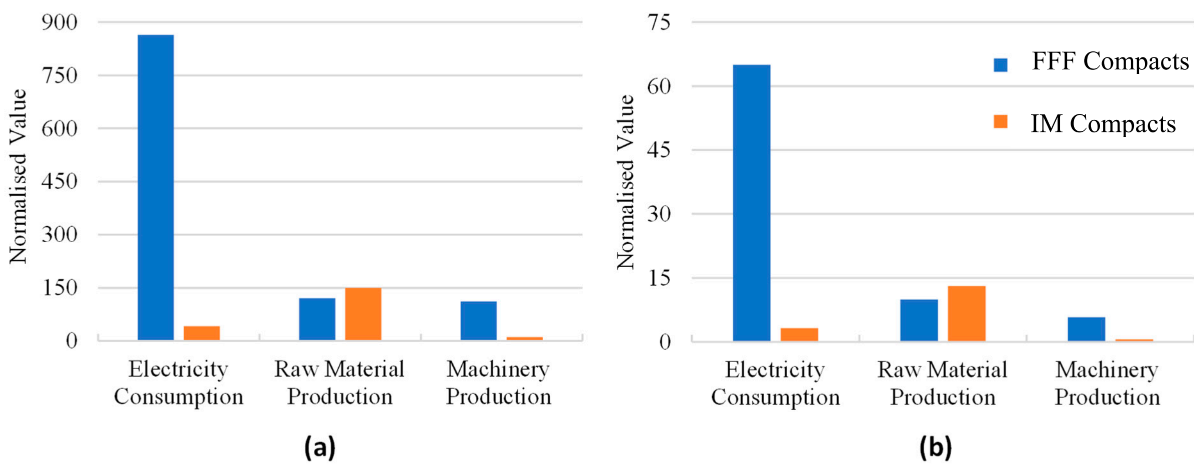

Figure 2. (**a**) Human health and (**b**) ecosystem endpoint for FFF and IM.

Analysing the generated impact on the endpoints per process, it is evident that the electricity consumption to print the compacts generates the greatest impact. The printing energy consumption impact is twenty times greater than IM consumption impact on both endpoints, which was expected since the energy consumption during printing was much greater than for moulding due to the five-hour cycle time. The raw material production for IM has a 24% and 32% greater impact on human health and ecosystem endpoint, respectively, than the FFF compacts. This was attributed to the greater amount of material required for IM, as explained previously. The production of the printers creates a ten times greater impact on both endpoints compared to the IM machine and mould production. This was attributed to the use of aluminium, which generates a greater environmental impact compared to the use of steel. Moreover, the amount of aluminium by weight in kilograms required for the 6510 printers over twelve years is around five times more than the steel required for 2 IM machines and moulds.

Each endpoint was analysed further to understand the midpoint categories that were most affected. Using Pareto analysis, the impact categories that had the largest contribution to the human health and ecosystem endpoints were further analysed, using the 80/20 rule. For the human health endpoint, global warming and fine particulate matter formation generated more than 90% of the total endpoint impact for both FFF and IM. For the ecosystem endpoint, global warming and terrestrial acidification contributed to 85% of the total impact for both technologies. Figure 3 shows a detailed breakdown of the midpoint impacts specified per process. The impact on the selected categories generated by the FFF compacts was greater than when IM was used, which was expected since FFF had a five times greater impact on the endpoints. The printing electricity consumption is responsible for the significant difference in impacts compared to using IM.

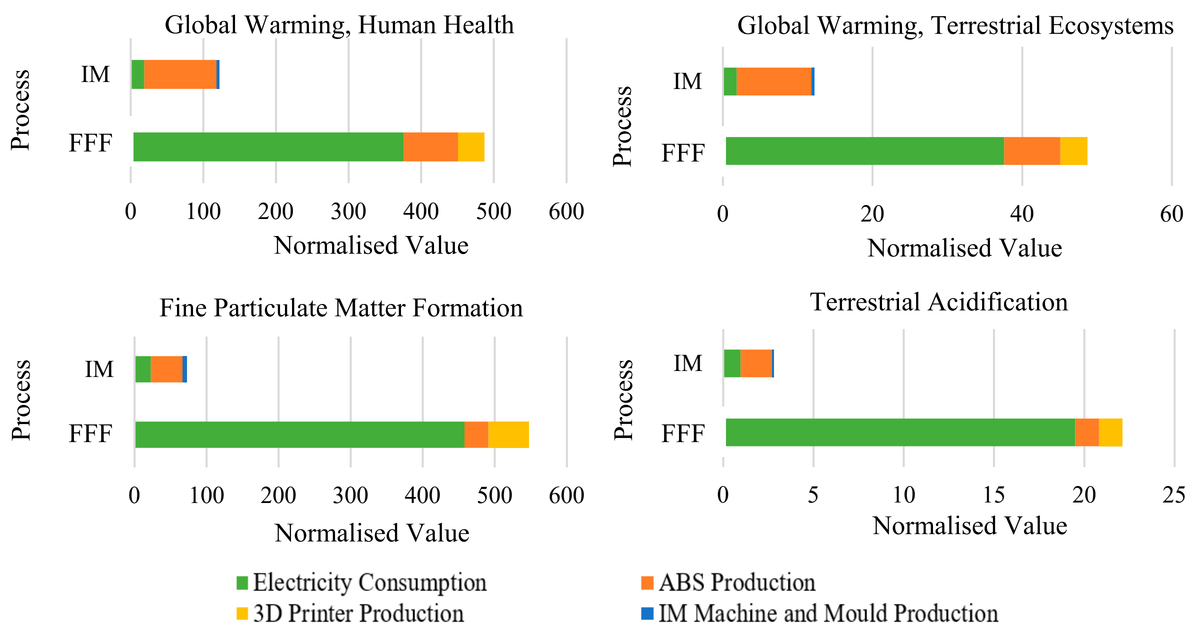

Figure 3. Selected human health and ecosystem impact categories.

The results show that greenhouse gas emissions, which impact human health and ecosystems, are mostly generated during printing for FFF compacts. Analysing the emissions during electricity consumption (MT mix), it was found that around 50% of the total global warming impact on both endpoints was caused by CO_2 emissions. Moreover, interestingly, fine particulate matter emissions had the greatest impact on human health for FFF compacts, where fine particulate matter was generated as a result of chemical reactions from other pollutants such as sulphur dioxide and nitrogen oxides, which are emitted during electricity consumption. On the other hand, IM energy consumption contributes around 15% of the total impact on global warming for human health. This further proves that the longer cycle time of printing creates much greater negative impacts when compared to IM.

For IM compacts, the production of ABS granules had the greatest impact on all categories. Greenhouse gases and fine particulate emissions were generated during the production of ABS, which contributed to the total impacts on both endpoints. In fact, analysing the emissions generated during the material production, CO_2 emissions accounted for around 50% of the total impact on both endpoints, while sulphur dioxide emissions accounted for around 23%, contributing to global warming and fine particular matter impacts, respectively. Terrestrial acidification was mostly affected by printer consumption and ABS granule production, since sulphur dioxide and nitrogen oxides are also acidifying pollutants that are emitted during these processes. Moreover, machinery production creates a small but still significant impact on human health, with minor impacts on ecosystem midpoints. Printer production generates greater total emissions compared to that of IM machinery.

Comparing the obtained results to the literature, various similarities were noted. FFF maximises material utilisation, which was highlighted in the greater impacts generated by IM raw material production when compared to filament production. Furthermore, as explained previously, the results from energy consumption studies vary significantly. The results obtained in this study show that the consumption of FFF is twenty times greater than using IM, which agrees with findings from Kurman and Lipson, and Yoon et al. [10,21]. Carrying out optimisation of process parameters would lead to a reduction in energy consumption during printing, which would reduce the associated environmental impacts [11].

3.1.1. Sensitivity Analysis Results

One of the assumptions made to model the LCA data was that the FFF printer is made entirely from aluminium. This assumption was made since the production of 3D printers was not included as a process in the Ecoinvent database. For a fair comparison, the IM machinery was modelled as being made entirely from steel. Since the production of the IM machinery is included in the moulding process found in the Ecoinvent database, the created IM process was compared to the database process to determine the difference in results. The total impact of the latter led to a 2% increase in both endpoint results when compared to the simple modelled process. This very small variation shows that the assumptions made to model the IM process led to very close results, especially taking into consideration the substantial impact of the FFF process compared to IM.

For the FFF process, since a more accurate representation was not available in the Ecoinvent database, the mass of aluminium used was varied by 50%, where the sensitivity of the human health and ecosystem endpoints resulted in an 11% and 7% difference, respectively. This variation is relatively minor considering that the manufacturing of the printer was around 10% of the total impact for both endpoints. Hence, it was concluded that the assumptions made do not greatly affect the results.

3.1.2. Life Cycle Assessment Results Conclusion

The results obtained from the LCA show that implementing FFF for the mass production of the compacts led to a five times greater environmental impact compared to using IM, which is in line with various studies. Therefore, it can be concluded that using IM to mass-produce the compacts leads to a lesser impact on the environment as opposed to using FFF. This also holds for one compact, since utilisation factors were used.

3.2. Costing Results

The results obtained from the costing models and NPV methods explained previously are analysed in this section.

3.2.1. Costing Model Results

The total cost per compact (CPC) using FFF was EUR 1.58, which is a 17 times greater cost compared to the EUR 0.09 obtained using IM. This drastic increase in cost per part was obtained due to various factors. The CPC breakdown is shown in Figure 4. The greatest cost for FFF was the material cost, which is twelve times greater compared to the ABS granule cost for IM. Considering that 1.5 million compacts per year are required, meaning 3 million components, the greater material cost generates a substantial annual expense. The labour cost was the second greatest cost for FFF, due to the set-up and part removal time required after every build. Contrastingly, the labour CPC for IM is almost insignificant. The FFF machinery CPC is 33 times greater than the IM machine CPC due to the multiple printers required. Moreover, it should be kept in mind that since the utilisation of the IM machinery to reach the annual production volume required was 34%, only 34% of the IM machine cost was considered in this comparison. The high printing energy consumption generates a cost that is twenty times greater than the IM consumption cost. The maintenance CPCs for the printers and IM machines were significantly different due to the greater number of printers requiring maintenance yearly.

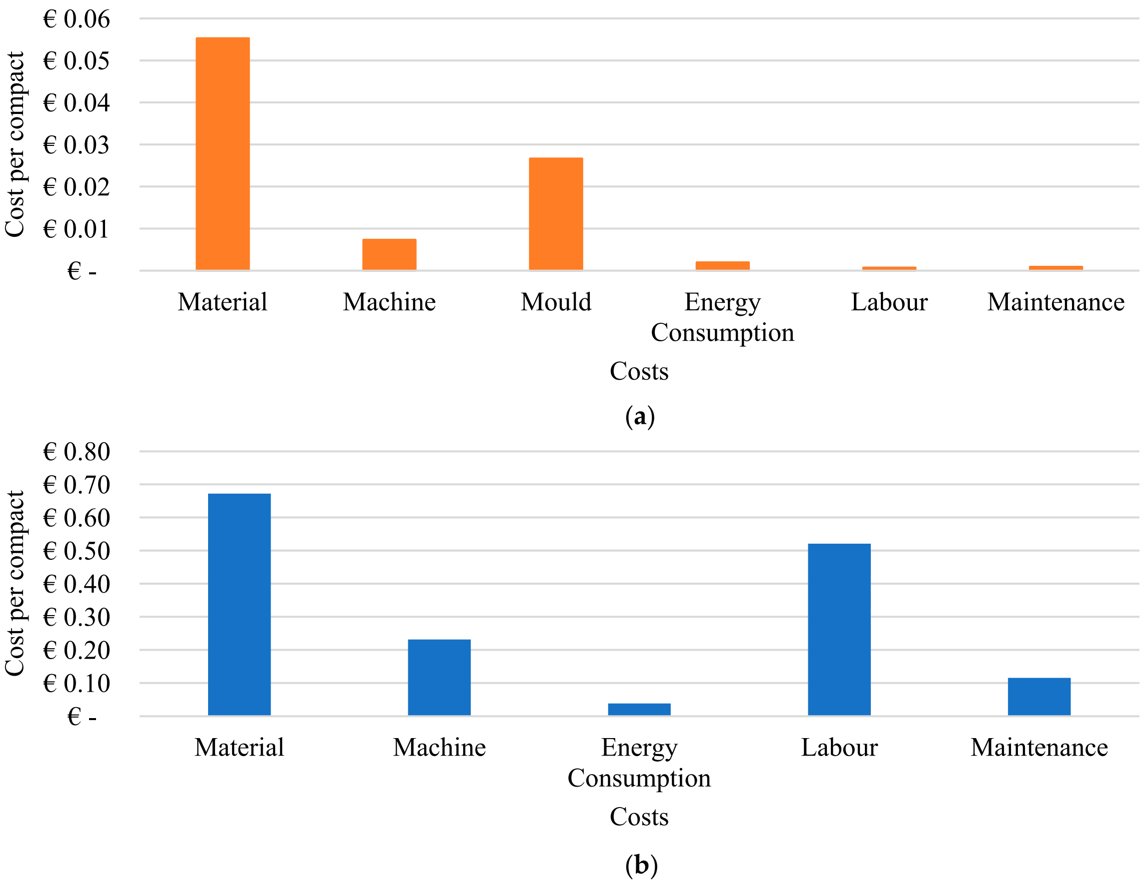

Figure 4. (**a**) IM and (**b**) FFF cost per compact breakdown.

3.2.2. Net Present Value Model Results

The total NPV for IM and FFF after twelve years of production was EUR −1,493,837 and EUR −26,043,761, respectively. As previously explained, the NPV values are negative since only expenses were considered to understand the cost incurred to produce the compacts using both technologies. Similar to the CPC, the NPV for FFF is 17 times greater than for IM. The required investment for 2170 printers every five years due to the lifetime of the printers led to much greater costs incurred over twelve years as opposed to the initial investment in IM machines and expenditure of 2 moulds every two years. Moreover, since the IM machine utilisation to produce the required quantity was 34%, the costs were considered accordingly. Therefore, although FFF does not require tooling, the total NPV for IM is not greatly affected by the two moulds required every two years due to discounting. Significantly greater expenses are generated when using FFF, with the capital investment and material costs being 36 and 12 times greater than expenses for IM, respectively. This is due to the number of printers required and the greater cost for ABS filaments compared to granules.

3.2.3. Life Cycle Costing Sensitivity Analysis

A sensitivity analysis was carried out to analyse the effect of certain costs on the total NPV for both technologies over twelve years. The material and printer costs were decreased by 90% due to their great contribution to the overall NPV for both FFF and IM to understand their impact on the total NPV. For FFF, the total NPV was 41% and 18% sensitive to changes in material and printer cost, respectively, while the total IM NPV was 59% sensitive to variation in material cost since more material is required to mould the compacts. The production quantity was also decreased by 90% to identify the effect of the quantity on the resulting NPV. The total NPV for FFF and IM was found to be 100% and 61% sensitive to quantity variation, respectively. Hence, the yearly production quantity had the greatest effect on the total NPV.

The production quantity was varied to identify where FFF would be more financially feasible to implement instead of IM. This point was obtained at circa 20,000 compacts yearly, which is only 1.3% of the total required yearly production. At this point, the total NPV over twelve years was EUR −347,250 for FFF and EUR −443,351 for IM, where the greatest cost contributor for IM was the mould costs, since two moulds are still required to produce the compact. Hence, at 20,000 or fewer compacts yearly, FFF would be more financially feasible than IM due to the tooling costs required.

3.2.4. Life Cycle Costing Results Conclusion

From the financial analysis carried out, IM was found to be more financially feasible than FFF for 1.5 million compacts produced yearly for twelve years. However, for small production quantities lower than 20,000 compacts, FFF is more feasible. This obtained result agrees with the conclusions of Franchetti and Kress, as well as Hopkinson and Dickens [5,6]. The breakeven point obtained by researchers varied between 200 and 20,000 parts and was dependent on the size and complexity of the printed part. Additionally, with economies of scale, the machine and material cost would be reduced with the increased use of 3D printers, potentially making the technology a more viable option [6].

3.3. Quality Testing Results

For visual quality, the average dimensions of ten IM compacts were all within the specified limits, while the dimensions of the FFF compacts were not within the acceptable limit due to thin walls, which create a challenge during printing. Moreover, the lid and base mismatch for all compacts was within the acceptable limits. Multiple visual defects were observed for the 3D-printed parts. Rough surface finishes were obtained due to the stepping effect caused by the printed layer thickness, as can be seen in Figure 5. Stringing was also noticed, where thin filaments were left on the compact by the extruder nozzle. Conversely, and as expected, the IM compacts were of superior visual and aesthetic quality, with a smooth and glossy finish and no visible defects. To obtain better surface finish for the printed parts, additional post-processing would be required to reduce the appearance and texture of the layer lines. However, this would continue to increase costs.

For package integrity, the IM and FFF compacts passed the stress cracking tests with no visible damage to the compacts. From the open/close cyclic test, the pins in the printed compacts started to come out after 200 cycles. This occurred since cylindrical holes are difficult to produce using FFF, especially since the holes could not be aligned with the z-axis and internal support structures were printed. Therefore, the pin was fitting tightly in the holes, which led to the pins moving out due to the repeated motion. From the drop test, three out of ten FFF compacts failed due to a broken hinge upon impact. The hinge is created from a thin wall that is prone to damage due to the reduced strength and delamination of the printed layers. The IM compacts passed all integrity testing.

From a functional quality perspective, the hinge breakage test showed that the printed compacts endured lower forces than the minimum specification of 27 N before breaking, unlike the IM compacts, which passed the test. This was due to minimal yielding of the hinge of the FFF compacts before failing under the applied force, where a clean brittle fracture occurred at the hinge. The force applied was perpendicular to the hinge, which led to delamination of the layers, causing minimal to no yielding before brittle fracture. Moreover, the force required to open the FFF compacts was smaller than the allowable 1.96 N limit since the clip did not print properly due to its very small size.

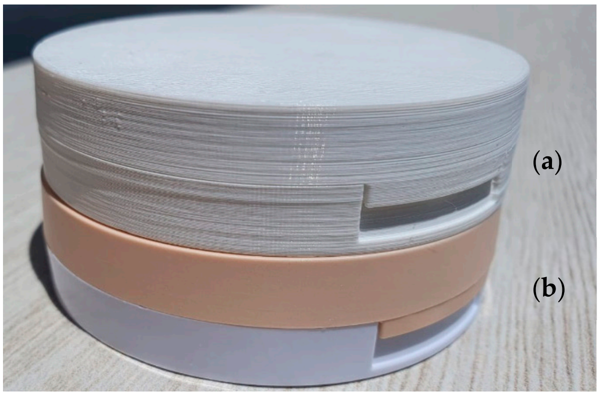

Figure 5. Surface finish comparison of (**a**) FFF and (**b**) IM compact.

Quality Testing Results Conclusion

From the quality testing results obtained, it is clear that the IM compacts are of superior functional and aesthetic quality compared to those created using FFF. Compacts produced using IM have greater strength due to their high uniformity as opposed to defects in the printed compact due to the layer-by-layer addition of material. However, with better parameter selection, the strength and quality of the compacts could be improved.

4. Conclusions

From the environmental assessment, using FFF generated a five times greater negative environmental impact when compared to using IM, mainly due to the higher energy consumption during the printing process. Moreover, FFF is not yet financially feasible for the mass production of parts due to the cost incurred being 17 times greater than if IM is used, with the greatest cost contributor being material costs. However, it was shown that for quantities below 20,000, FFF was more financially feasible than IM. Additionally, printed compacts have inferior functional and aesthetic quality compared to their IM counterparts, predominantly due to the layer-by-layer addition of material during printing. Therefore, replacing IM with FFF is not yet a feasible alternative for the mass production of cosmetic packaging. However, it is not excluded that future improvements would lead to the process being more suitable.

Areas for future research include investigating different 3D printing processes that have a shorter cycle time, which would, in turn, decrease printing time and running costs, as well as ultimately the negative environmental impacts resulting from the energy consumption. Selective laser sintering (SLS) could be a potential alternative, since multiple parts can be produced at the same time, leading to better build efficiency and shorter cycle times. Furthermore, the use of more environmentally friendly materials such as biodegradable or biobased alternatives that would be less energy-intensive could reduce the overall environmental burden generated by these products. Another area for further research would be redesigning the compact for additive manufacturing, since the case study used was designed specifically for injection moulding. Designing for FFF would result in a better functional performance and would be more comparable with the current injection moulded compact.

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