Sustainability and environmental impact haven't been assessed in detail as this is a new technology. Focus with FDM in AM has been on efficiency, quality, cost.

Compared conventional manufacturing route
- One paper – glasses frames
- Another – insoles

3D Printing Influence Mostly:

Amount of material used & Electricity used during print run
- post-processing is done manually for this product
  - support material removal, surface treatment and colouring
- Electricity used for printing
  - Length of time for one product
- the production of the filament

For instance, to print the sample part in this paper, the life cycle energy is ranging from 0.008432 to 0.0144 kWh.

Aleisha's Thoughts

I tried to research these components but couldn't find any papers with existing work. There were some articles that kind of outlined the materials and process it takes to make cameras but nothing that was scientific enough (for example, Canon had an LCA done but it seemed bias and unreliable). Another thing to note was that the information found on cameras were for specific models, so I am not sure how to go about that if this is included in the report (should it be an approximation? what if that's not accurate enough as models vary in cost, materials, features).

This solution LCA was going to be coupled with a waste analysis to determine if putting the solution in place would offset the amount of material (PLA) waste produced. I think you called this comparison a "sensitivity analysis". I haven't found a ton of information on how much waste is made when failures go wrong but there are definitely some numbers I've come across and will continue this research.

This past week I've mostly found credible papers on using 3D printing as a manufacturing route instead of traditional or commercial manufacturing. For example, there are two papers that compare the process of manufacturing orthotics and glasses frames through 3D printing or plastic moulding. The papers talk about the environmental impact of both processes and conclude that the real environmental problems arise from the electricity required to run the 3D printing machines for hours on end.

There were some mentions about how the materials chosen also have an impact of their own, obviously. However, my concern is that since we're using PLA, which is a biodegradable material, there isn't much concern with the waste produced as it has the ability to decompose.

I think I'm just confused on what I should compare and contrast for the LCA. I think its interesting to compare or mention the differences in 3D printing manufacturing vs commercial manufacturing, but the LCA should probably focus on the solution portion, right? Instead of the use of the 3D printer.

Chad's Thoughts

Is there an indication that reducing material waste in FDM will have an impact on the environmental performance?

The idea would be to know whether this would be a good "selling point" for your technology or not — the answer can quite correctly be "No, this will have no impact on the environmental performance".

So, in this case the idea would be to provide a systematic analysis of the environmental impact of FDM printers which I guess you have already found in the literature and to carefully summarize this with their findings.

Then, you could perhaps look at variations away from this. You mention PLA below as a material- but it isn't the only material used in FDM printing - e.g. what if you used ABS how would that change the conclusion? Is energy consumption still dominant as the problem? But if energy consumption is the biggest problem, then shouldn't reducing waste reduce (wasted) energy consumption? In this way of thinking about the problem you don't actually consider the details of your design, rather you just look to make the case whether or not reducing waste in FDM would be a viable way to reduce impact and if so, under what conditions?

Product

- LESS WASTE compared to traditional manufacturing
    - Usually uses block material which is significantly more than what's required. Ratio of waste material to used material can be 19:1
- No more casting, forging and rough machining transportation and packaging
    - Shortened or eliminated in 3D printing
- no specialized tooling or fixtures
- capable to create on-demand spare parts reducing or eliminating inventory
- Recycling is easy
    - Products are made with a single raw material
    - Hard to recycle components of multiple materials
- By justifying that this is environmentally friendly compared to traditional manufacturing, we can justify that a failure prevention solution is necessary.

Energy use is a debate though

- Arguments that injection moulding uses less electrical energy
    - 50-100x more energy required for 3d vs injection for a part of the same weight
- Bulk forming uses less specific energy

Material Filament

- Powders emit harmful emissions (also health concerns)
- ABS and PLA cartridge will generate 1.61×10^{10} ea/min and $4.27–4.89 \times 10^{8}$ ea/min cartridge

Meeting Week 9 Minutes

LCA Update

A: Material waste is not the best approach, instead look into electricity use of the machine (energy consumption). Do systematic analysis of enviro impact of FDM by comparing material variation.
A: ABS bad for health is that in risk assessment.

Chad: that would go into impact factors normally but that is too complex for us. So talk about the impacts (health) give supporting evidence as to if they are large or small impacts. If there is a lot of info don't worry about the health.

Chad: Start from perspective of mtrl waste is bad in 3D prints, question from Enviro is:

Is contribution of waste material a significant portion of the energy footprint of the process?
How much impact does 34% have in terms of 3D print energy consumption?
Reduce waste = reduced energy consumption. Then factor in the recycling process which also requires energy.

For materials: are biodegradable polymers benign (no additional impact because it will degrade… but will it)? Compostable bags actually do not work any better than regular ones. Compare PLA to ABS maybe. Need specific temperature and humidity to degrade it.

Look at it from energy point of view- reducing waste would reduce enviro impact of 3D printer? And what happens to the waste material- is waste from PLA that much better than that of ABS.

A: Analyse commercial vs manufacturing uses?
Chad: There is waste in 3D printing: scaffolding, rejected parts… Thermo casting wastes less than 3D printing.

Chad: Start with answering: how much less environmental impact is there if you reduce waste?
Is there significant impact- define it yourself… Significant impact relative to total energy used in 3D printing. What does the impact look like: linear or other relation? Leave 3D printer out of it, think about just operating it. Imagine we are comparing the same printer, same part, same rates. Change the amount of waste and see what the reduction (?) of energy is… then go into materials and other if not enough information.

Filament Impact: ABS VS PLA
Waste Analysis – Which is more environmentally friendly?

PLA	ABS
Polylactic Acid Thermoplastic (liquify in response to heat) Biodegradable	Acrylonitrile Butadiene Styrene Thermoplastic (liquify in response to heat) Ex. Lego
Advantages	
• Made from corn starch • Ease of use • Not as sensitive to temperature changes • Therefore, you do not need a heated bed to print • Low melting point: 180C • Very stiff, robust material • Parts have great surface quality and decent strength • In a straight strength test, PLA can handle more weight before breaking • More forgiving with complex features • Can print complex overhangs compared to ABS • Can breakdown in landfill • Less warping issues	• Generally, ABS can withstand more heat, pressure, and stress better than PLA, therefore it is a more suitable plastic for wear and tear applications • Printing temperature is a little higher, therefore requires more energy ~220C • Therefore, heated bed is required • Different mechanical properties: more flexibility, softer to print with • Finishes easy - Sanding, priming and painting is easily
Disadvantages	

• Not suitable for parts that will undergo a lot of wear and tear or be exposed to the elements for a long time • More brittle and will break under stress more easily • Weakness: because of low melting point, ease of extrusion and ease of printing, the part could droop or melt (ie. during hot summer day) •	• Tricky to print with • More sensitive to temperature changes in the environment • ABS needs to cool slowly, otherwise the print can crack along layer lines • Cannot break down in landfill • More susceptible to curling or warping during the printing process • Will distort and bend before breaking

LCA Developments

- *LCA of PLA* http://www.designlife-cycle.com/3d-printers-makerbot-pla-filament
    - *75% will go to landfill*
- *LCA of ABS* https://pubs.acs.org/doi/abs/10.1021/sc400093k
- Printing with both – using different sources of electricity
    - How much more environmentally friendly is it to use PV
- https://pubs.acs.org/doi/abs/10.1021/sc400093k
- https://www.oecd-ilibrary.org/sites/9789264271036-9-en/index.html?itemId=/content/component/9789264271036-9-en
- https://www.greenbiz.com/blog/2013/07/19/3d-printing-environmental-win
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LCA OUTLINE (FINAL)

Intro

3D printing has a reputation of being more environmentally friendly compared to conventional additive manufacturing routes. Traditional AM processes include injection moulding or machining for consumer goods. There is a misconception that FDM printing is waste-free as rapid prototyping is eliminated. In traditional product development, many iterations of the same product are produced to check functionality, surface finish, and dimensions. In FDM printing, there is no need to create multiple iterations of the product as the 3D digital model can be edited and adjusted, and when the user is satisfied with the model, the print can be made.

Theoretically, there should be a negligible amount of waste from a print. The user designs exactly what they want to print, with set parameters (ie. colour, dimensions, size) and they print the exact model.

Even if a print is completely successful, there is still physical waste attached to it.

However, failures hinder this idea.
Until technological advances in printers are made,

As this project's aim is to assess whether or not there is a need for a defect detection system in FDM printing, a comparison between

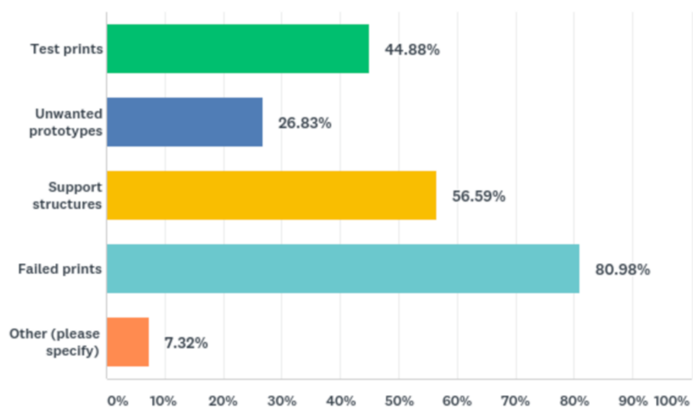
From the get-go, people assume this because
Environmental impact comes from operating the 3D printer itself.

BENEFITS

- 3D printing – new technology that seems to be more environmentally friendly than traditional manufacturing.
    - No rapid prototyping – all those iterations are eliminated
    - No overseas transportation required – things can be made locally

CONS

- But people forget about when printers fail. As this technology is relatively new, failures may occur, where the desired print doesn't match up to what is actually printed.
-
    - Left with unusable parts / excess material



    - How much filament is used?
- Support structures? Are we including that? Cause they I would need to explain further, what is it, materials, how much waste is involved for every print
    - Purpose: prevent warping
- Once the part/product is worn out, it is replaced with a fresh new one. How much waste does that cause?
- Not easy to recycle materials because of contamination (only 9% of all plastics are actually recycled)
    - Only solution is you recycle it yourself
        - A plastic processing unit that granulates plastics down to a particle size
        - An extruder machine to turn the plastic particles or granules into filament
        - A spooler to coil the filament for use in a 3D printer

Electricity consumption to operate

- Prints could run overnight (12 hours)
- Print quality/resolution translates to more time which translates to electricity

Material used has a huge impact on environmental impact
Each material is better suited for a different purpose

- ABS
    - Needs more electricity to heat at higher temps, susceptible to warping
    - Distorts/bends before failure
    - Better for larger parts that will undergo lots of wear and tear
- PLA
    - Biodegradable, lower melting point decent mechanical properties
    - Better for complex parts
    - Brittle
- PETG
    - Copolyester (CPE) - combination of ABS and PLA's properties
    - PET with glycol which makes It have a lower melting temperature (230), and allows it to be translucent

- PET easily recyclable
- PLA compostable in specialised facilities
- ABS somewhat toxic and not recycled
- Typical acrylonitrile butadiene styrene (ABS), polylactide (PLA), nylon, polyethylene terephthalate glycol-modified (PETG)

Question:

- Does reducing material waste have a positive impact environmentally?
- If so, this proves that there a **need** for a defect detection method. (ie. more investment into this project)
- What's the largest contributor environmentally?
    - Toss-up between Materials and Energy Consumption

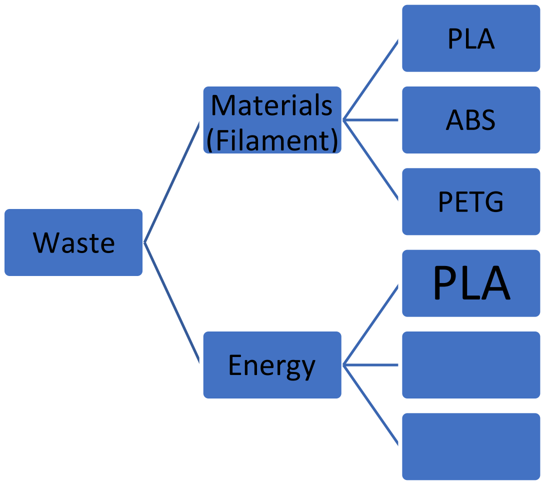
Questions for chad:

It's hard to get real studies done for accurate quantitative values
Ie. would this be accurate?

34% material waste

Return on investment
How long would it take to pay it off based on solution?

Is wasted parts environmentally bad?



MIDTERM REPORT

Methodology

Consequently, as an entirely new, physical component is introduced, additional environmental concerns are also introduced. A full life cycle assessment will be performed on the chosen solution, the laser line projection. As mentioned in previous sections, three components are involved, an optical camera, a laser line scanning device and a filter. As these pieces are all available for purchase individually, a separate LCA will be performed for each component. The impact will be added together to give a total environmental analysis of the project solution. It is important to note that a computer is also required to analyze the data of the laser deviations captured by the camera. As a computer is required to FDM print anyways, an assumption that the laser analysis can be done on the same computer is made. Therefore, a computer will not be included in the LCA of the solution.

It is clear that introducing a defect detection system will present a definite environmental impact. With this system in place, however, there is a possibility that if it is successful in detecting a defect, stopping the machine automatically, PLA material will be saved. This is an important assessment to include as the savings in PLA, could offset the environmental impacts required to implement the detection system. The 34% material waste statistic that was discussed in earlier sections from printing failures, could be reduced further, possibly making the laser line projection solution environmentally friendly [3].

Economics

Evidently, PLA is the most common material used in polymer-fed FDM printers. It is a biodegradable thermoplastic polymer, with a variety of applications in different industries (such as medical, food packaging and automotive parts) [29]. Rising environmental concerns have made the biodegradable polymer industry one of the most competitive, with prices per kg of material increasing each year [29]. Savings in PLA filament could make a huge impact, economically for users. As such, an economic analysis will be performed comparing costs incurred because of PLA waste, without the defection detection system in place, versus, having it in place and avoiding PLA material waste

Life Cycle Assessment

Arguably, Climate Change has become one of the most pressing global issues humanity faces today. As a product of urgency, the concept of having sustainable designs in practice is emphasized greatly in the marketplace. Industrial manufacturing systems, that is the process of transforming raw material into usable products, are responsible for a large portion of global greenhouse gas (GHG) emissions, such as carbon dioxide (CO_2) into the atmosphere as well material waste [A13]. The process of how an item is produced, or the materials chosen can have a severe impact on how environmentally sustainable it may be in the long term, and as a result, affects if the process or material is implemented [AC1].

To measure these impacts, a life cycle assessment (LCA) can be performed using various programs. Each stage of a products life in terms of energy use, water use, production of harmful by-products and impacts on land are measured [AC2]. A single life cycle is broken down into separate stages of a products life, this is schematically shown in **Figure x.** Specifically, from its raw material acquisition, to manufacturing the product, to transporting the final product, to use of the product and finally, disposal or recycling of the product [AC2].

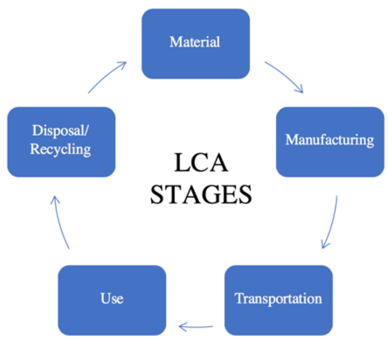


Figure x: Life Cycle Stages of a Product/Technology [27]

In FDM, an average of 35% of material waste (by weight) is produced when printing [GEORGIA]. 55% of that is directly from defects that lead to printing failures, generating unusable or rejected parts [GEORGIA]. The remaining 45% of material waste comes from using support material during printing, however this will not be discussed as the focus of this report is on reducing material waste that stems from printing failures only [GEORGIA].

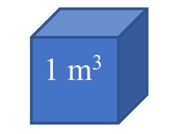
The goal of this section is to determine how significant the problem of wasted material parts are for the environment, and where that impact derives from. An LCA will be performed to examine the types of environmental contributors associated with 3D printing to determine whether or not having a defect detection system is worth it. If defects are detected and the print stops immediately, avoiding printing the entire object, then filament material can be conserved as well as energy (electricity) to operate the machine. Analyzing the effects that these two factors have on the environment and eventually on the economics side, can help in confirming whether or not there is a need for a defect detection system, and whether or not this idea should be invested in further.

Material Filament

As part of the overall LCA of an FDM printer, the materials used to print can also have a significant impact on the environment from producing the filament itself. To determine how much of an impact, an

LCA of the top three printing filament materials were analyzed. The three materials include, polylactic acid (PLA), which is a biodegradable polymer made from corn starch [AC7], acrylonitrile butadiene styrene (ABS), and a copolymer called polyethylene terephthalate glycol-modified (PETG) [AC8]. They are all types of thermoplastic polymers, meaning that they liquify in response to heat, and will solidify when cooled [AC7].

To determine if material choice has a significant role in the sustainability of FDM printing, Cambridge Engineering Selector (CES) Software was employed using the Level 3 database. For an accurate comparison of the environmental impact that each material has from production, a 1m^3 cube was used for measurement. The average densities of each material were obtained from the CES database and the mass of each cube was calculated and input into CES to obtain the corresponding LCAs of each material.



	ABS	PLA	PETG
Density (kg/m^3)	1.02e3 – 1.08e3	1.28e3 – 1.42e3	1.26e3 - 1.28e3
Volume (m^3)	1	1	1
Mass (kg)	1.05e3	1.35e3	1.27e3

Despite the fact that PLA is a biodegradable polymer, which means that it has the ability to naturally decompose, this can only be done in specialized facilities which aren't available in all regions [AC5]. Additionally, only 9% of all plastics are actually recycled globally [AC9]. Therefore, it was assumed that all three materials (ABS, PLA and PETG) were thrown out and sent to landfill after its use, with no possible end of life potential. Each object was assumed to have a life span of 2 years before natural wear and tear occurred, as well as were polymer extruded as the manufacturing method. Additionally, it can be assumed that each part has the same transportation method which in turn doesn't contribute to any significant differences between the 3 materials in this category, allowing for emphasis to be placed on how each material is produced.

The LCA performed on the three materials looked at two important parameters, the first is the CO_2 footprint which is the amount of CO_2 (in kg) emitted into the atmosphere upon creating 1 unit of the product [AC2]. The second parameter is the embodied energy which is the fossil-fuel energy (in MJ) consumed in making one unit of product. Intrinsic energy, which is energy stored in the material that may be recovered or stored into other forms, is also included [AC2]. The results from each material are shown in **Figure x.**

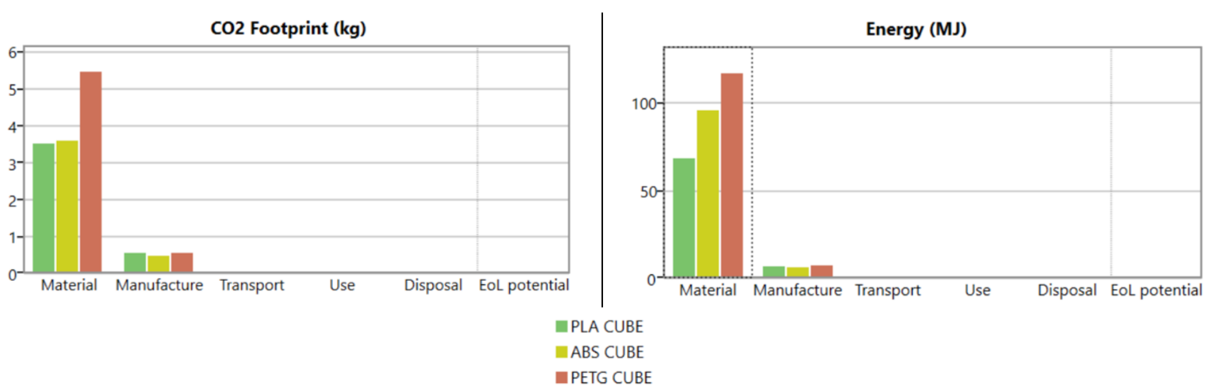


Figure x. (a) The CO_2 footprint (kg) and (b) Embodied energy (MJ) for each material.

When looking at how FDM affects the environment based on materials alone, it is clear that PLA has the least environmental impact regarding both its CO_2 footprint and the energy involved to produce the raw material. ABS is the second least contributing, followed by PETG. The material properties of each polymer can help to explain these results.

As PLA is a type of bioplastic derived from agricultural sources such as corn starch, instead of fossil fuels, the embodied energy is significantly less than both ABS and PETG [AC5]. PLA also has the lowest melting point of 160°C [AC12], compared to the other two materials, meaning that during processing, it takes less heat, or energy rather, to extrude the material into its desired shape [AC5]. As PETG and ABS have melting points of 250°C and 200°C, respectively, more energy is necessary to melt and shape the material [AC10] [AC11]. This causes both the CO_2 footprint and the embodied energy of the material to increase considerably.

Energy Consumption

Although material waste and in turn, material choice can contribute to how sustainable FDM printing is, there is evidence that depicts energy consumption as the largest contributor. Energy consumption simply considers the electricity use as a resource which is essential to operate and run an FDM printer and can therefore be classified as the manufacturing-related energy [AC7].

A 6-month long case study done in Compiegne, France printed a plastic orthotic insole using FDM techniques to determine which part of 3D printing has the largest environmental impact [AC3]. As discussed, the two major impactors surround the material polymeric filaments used to print and the energy consumption required to operate the printer. The results from the case study were compared to orthotic insoles that were made by traditional handmade manufacturing practices [AC3]. An LCA approach was taken, to analyze the effects that producing and distributing 3D printed objects have in 4 distinct damage categories (human health impact, ecosystem quality, climate change and resources), however for the relevance of this report, only the resources category was analyzed.

The results are shown schematically in **Figure x.** Within the resource category, the production phase of the process was the largest contributor, of 70%, where 95.9% was directly from electricity consumption [AC3]. This holds significant value, as it confirms that acquiring the raw materials, distributing the product, product usage and it's end of life phase are negligible compared to actually operating the machine to print the orthotic insoles.

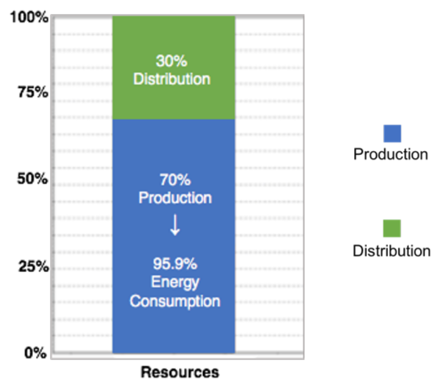


Figure x. Life Cycle Assessment of the resources required to produce and distribute a 3D printed insole.

The study finished with a sensitivity analysis which analysed what the outcome would be if the printing time was reduced by 2 hours. It was found that 30% of resources would be cut, confirming that printing time can have a significant impact on the environment [AC3].

In a separate study comparing the LCA's of 3D printing versus injection moulding, inkjet printing and CNC (computer numerical control) milling, Jeremy Faludi, a professor at UC Berkeley and TU Delft, also showed that electricity is the largest resource used in FDM printing, rather than material waste [AC4]. As electricity use is a function of time, it is important to reduce the amount of time spent running the machine which will inherently reduce environmental impacts.

Energy and Cost Analysis

Energy Consumption

The case study presented that 13.9 kWh (2309 W running for 6 hours per print) was required to 3D print one single insole [AC3]. In Canada, specifically in British Columbia, this translates to $1.58 CAD in electricity alone, to print one insole.

Evidently, 35% of material produced from 3D printing is wasted. 55% of that is directly because of defects that lead to printing failures [GEORGIA]. This means that if 100 kg of insoles were 3D printed, then 35 kg would be wasted. Of those 35kg, 19.25kg would be from printing failures alone.

As the goal of this project is to create a system that will eliminate 19.25 kg of material from being sent to landfill, a sensitivity analysis was performed to see what the savings in energy are for producing material filament versus the energy needed to print one insole.

If 100 kg of insoles are produced and one insole (size 10) weighs 0.08788 kg (3.1 ounces) [AC15], then a total of 1138 single insoles are made. Due to printing failures only, 219 insoles would be sent to landfill. This is tabulated in **Table x**, below.

Amount of Material	Weight (kg)	Amount of Insoles
100% Material Used to Print	100 kg	1138 insoles
35% Total Material Waste (by weight)	35 kg	398 insoles
55% of Material Waste from Print Failures Alone	19.25 kg	219 insoles

Table x. Summary of how many PLA printed insoles are sent to landfill based on printing failures.

Finally, if the study concluded that it requires 13.856 kWh, and takes 6 hours to print one insole. Therefore, to print 219 failed insoles, then 1314 hours (55 days) and 3034 kWh are needed. Using the BC Hydro Smart Energy calculator, it costs $346.02 CAD to print 219 failed insoles, and a total of 19.25 kg of materials are sent to landfill [AC6].

Material Filament

A similar analysis can be conducted based on the embodied energy needed to produce PLA filament material. From the LCA shown in **Figure x (b)**, 64.0 MJ or 17.8 kWh of energy is needed to produce 1m^3 (or about 1000 kg) of PLA filament. Therefore, to produce only 1 kg of filament, it requires 0.0169 kWh. If one 3D printed insole (size 10) weighs approximately 0.0878 kg (3.1 ounces) [AC15], then only 0.00149 kWh are needed to produce the PLA needed for one insole. Using the same BC Hydro calculator, this cost is only $13.14.

A comparison summary of the loss in energy and capital for both producing the amount of PLA required for insole, and the energy consumption to print one insole are shown in **Table x.**

If 219 insoles are sent to landfill:	
Material Filament	Energy Consumption
0.3285 kWh in losses	3034 kWh in losses
$13.14 CAD in losses	$346.02 CAD in losses

Table x. Energy and Cost losses comparing material filament and energy consumption.

Therefore, it is clear that the environmental impacts associated with printing 3D parts are more dominant with the energy consumption to operate an FDM printer, rather than the embodied energy of the material itself, as 99.99% more energy is required.

Conclusion

The International Journal of Mechanical and Mechatronics Engineering released a paper confirming that production, specifically energy consumption, was in fact the largest contributor to the environment compared to every other category including, material acquisition, transportation/distribution, product use, disposal and end of use potential [AC7].

Finally, through an LCA analysis of both the PLA material filament and energy needed to 3D print one insole, it was found that environmental impacts are strongly connected to the electricity used during printing. 99.99% more energy is needed to print a part, then to produce the material for the part, translating in higher costs in electricity. Therefore, investment for more efficient printing technologies or technologies that will stop the machine from running, ideally turning it off, when a print goes awry is recommended. Specifically, if a defect detection system of around $350 is implemented and a percentage of defects

Material Waste Reduced By	Energy Saved (kWh)	Savings ($ CAD)	Savings in landfill (No of insoles)	Savings in landfill (kg)
20%				
40%				
60%				
80%				
100%				

Resources

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