STREAMLINED LCA COMPARISON: INJECTION MOLDING VS. LOW COST ADDITIVE MANUFACTURING FOR A NEW CONSUMER PRODUCT

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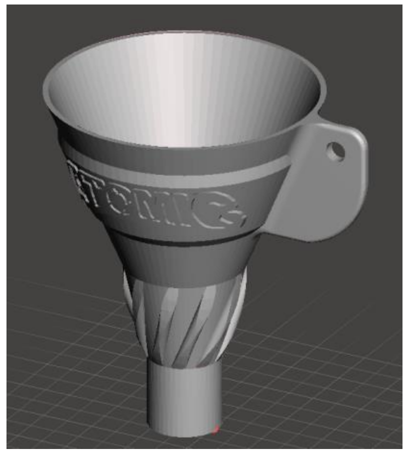
EXECUTIVE SUMMARY

This project involved a streamlined, comparative Life Cycle Assessment (LCA) of a consumer product that is to be either manufactured by the conventional process of plastic injection molding (IM) or by the use of low cost additive manufacturing (LCAM) equipment. The product is a simple plastic funnel with a customized logo and a side tab for easy gripping.



3D model of the project plastic funnel.

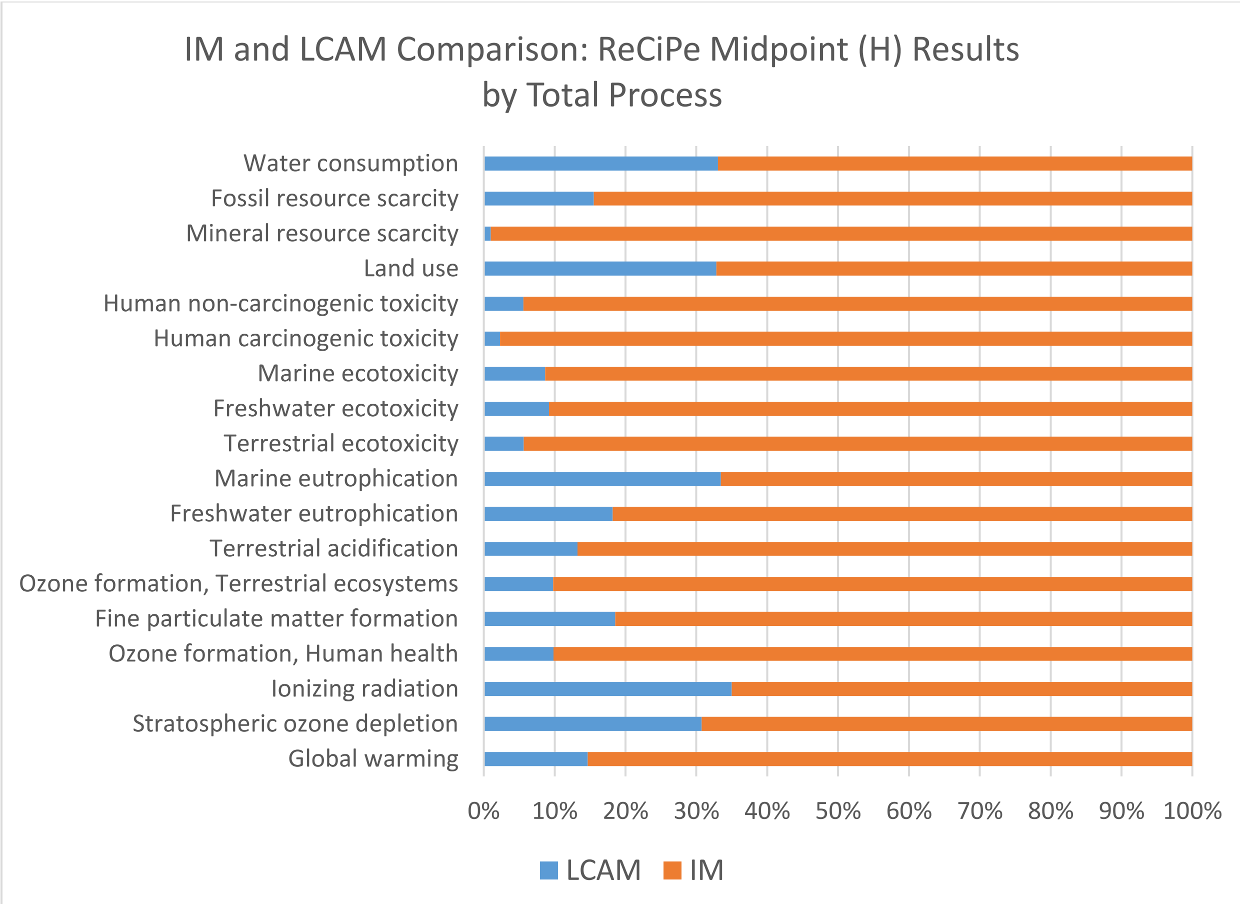
As the concept of using LCAM equipment for final production is a new approach, the intent of the project was to compare the two production processes with respect to their environmental impacts. The final goal was to determine if the additive manufacturing approach holds significant potential benefits that have thus far been unrealized within the manufacturing and small business realms.

The project functional unit was a single produced funnel, massing 14 grams, and composed of polylactic acid based plastic. The target product quantity was 500 units per manufacturing process.

The LCAM production process involved a single desktop 3D printer, a Prusa I3 Mk3, and the IM production process was assumed to be a double cavity steel mold, automated injection process. The impacts of the processes were based the life cycles of materials, manufacturing, transportation, and wastes. Any aspects of the product's life cycle that were identical regardless of the IM or LCAM production process, such as transportation to the consumer or consumer usage, were excluded from the study as being comparatively irrelevant.

Overall, the impact assessment demonstrated that the LCAM process was significantly superior to the IM process in terms of environmental benefits. With an exception of only a minor few impact sub categories studied, the LCAM process outperformed that IM process well beyond the typical 20% differential threshold for a valid comparative assertion. The primary reason of the LCAM's superiority is that it does not involve the fabrication of a steel mold that is required for the IM process.

However, the project showed that when the funnel quantity order approaches 10,000 units, the LCAM process impacts overtake the impacts associated with the IM process, and making the LCAM method no longer environmentally beneficial over the other. This is primarily the result of the LCAM electrical consumption per functional unit, though it was noted there were options to potentially lower the LCAM consumption rate with experimentation.



Comparative LCAM and IM broad spectrum proportional impacts.

This project represents a streamlined comparative LCA of the potential environmental impacts of the IM and LCAM methodologies. The work provided was performed in the most reasonably appropriate manner given the nature of the project and the limitations thereof. The work does reveal the relative potential of the LCAM production model in terms of more sustainable practices associated with lower quantity manufacturing orders in comparison to the conventional IM production model.

From the work, it is recommended that further review and research be performed toward the comparison of these two production technologies. It is also recommended that the manufacturing and small business industries in general turn more attention toward the LCAM methodology over the conventional injection molding processes as there are obviously environmental benefits to be realized. These benefits will likely become more obvious and possibly even more significant with the maturation of the LCAM equipment as well as the consumer acceptance of products fabricated by additive manufacturing.

This project does not meet the full requirements of ISO 14044, nor has it been critically reviewed, though it was performed in an appropriate manner reflective of some of the typical requirements of the ISO standard. This project is not intended for comparative assertions that will be disclosed to the public.

-End of Executive Summary-

1. GOAL AND SCOPE

1.A INTRODUCTION

This project represents a simplified Life Cycle Assessment (LCA) comparison of two manufacturing processes used to produce the same product. The processes being compared are conventional injection molding manufacturing and low cost additive manufacturing, also commonly referred to as 3D printing. The product to be produced by these two manufacturing processes is a plastic funnel approximately 65 mm wide by 70 mm tall with a tab on the perimeter useful for gripping and a logo of a weightlifting gym embedded on both sides of the funnel. The plastic material will be polylactic acid (PLA) for both manufacturing processes, though the injection molding (IM) process will use a granular form of PLA, while the low cost additive manufacturing (LCAM) process will use a filament form. The computer designed model of the funnel and physically produced version can be seen in Figures 2 and 3. The primary function of the funnel is that it is commonly used for pouring protein powders and workout supplements into typical 20 oz drinking bottles, while serving as a unique marketing tool for the Owner to advertise her business.

The scenario of this study is that the Owner of the gym desires to produce 500 units of the funnel for sales and marketing purposes. This study will compare the environmental impacts of utilizing a third party conventional injection molding manufacturing process versus the Owner using low cost additive manufacturing equipment to directly produce the funnels on site. For clarity, low cost AM equipment is considered to be less than a $5,000 purchase. This project will utilize Prusa i3 Mk3 units purchased from Prusa Research, as can be seen in Figure 1.

Figure 1: Prusa i3 Mk3 low cost 3D printer.

The overall goal of this study is to assess whether or not the availability of LCAM equipment now makes it possible for small business owners and entrepreneurs to produce some of their own plastic goods, with less potential impact on their environment. The general audience of this project will primarily be academic members, as the results will not be a publicly disclosed. However, it is likely that the information from this project may lead to decisions to pursue future, more thorough projects and serve as discussion points in the study of low cost AM and possible small business applications.

The study will be considered a comparative cradle-to-grave assessment in terms of the manufacturing processes involving the steel mold, but realistically a cradle-to-gate assessment in terms of the functional unit. This results from the fact that there will be several exclusions of processes due to the comparative nature of the project. These will be discussed more thoroughly later in the report.

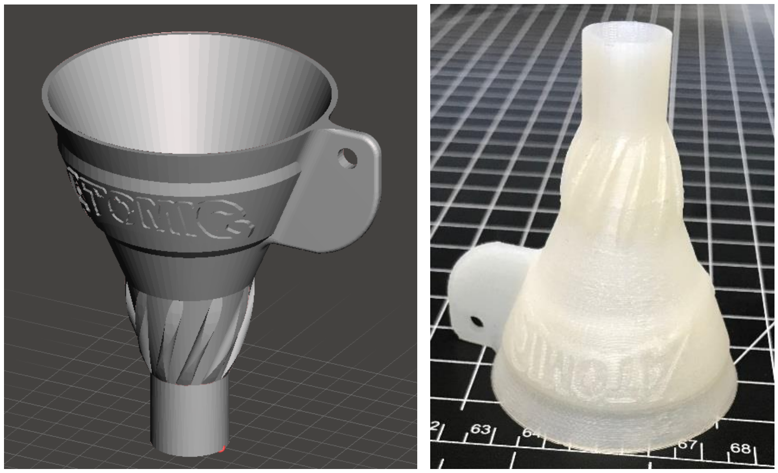


Figure 2 & 3: Atomic Gym funnel computer model (left).
Funnel produced by low cost AM equipment (right).

1.B FUNCTIONAL UNIT

The functional unit for this project will be a produced funnel unit or funnel part. Both manufacturing processes have the goal of producing the funnels, and the overall goal of the Owner is to sell funnels to customers. As mentioned, it will be assumed that the Owner will want a total of 500 funnels to sell to customers of the gym.

1.C COMPARATIVE ASPECT

This project will directly compare two manufacturing product systems that perform the same function, each producing the same design of a funnel that is identical in mass. Given the limited nature of time and resources of this project, the results will not be publically disclosed. As such, the project will clearly not meet all applicable ISO 14040 standards, however, all practical efforts will be made to ensure that the project is reasonably carried out in the most scientifically appropriate manner.

1.D SYSTEM DESCRIPTIONS

Injection Molding

The systems modeled in this project will include the metalworking processes associated with fabricating a steel mold to produce the funnels, the actual IM process to create the funnel, and the transportation of the funnel to the Owner for sales distribution. Eventually the steel mold will reach the end of its usefulness and will be transported to a recycling plant and recycled. Thus representing a cradle-to-grave process of the steel mold, whereas the funnel itself will comparatively only involve a cradle-to-gate approach.

Low Cost AM

This system will be modeled to include the transportation of plastic material to the Owner where on site manufacturing will occur, as well as the materials extraction process to obtain the base materials for the plastic, and the actual additive manufacturing (AM) production process to produce the funnel. This AM process specifically does not have a compatible process available in Simapro, therefore equipment will be utilized to estimate the amount of electricity necessary to produce the funnel. As the LCAM equipment does not involve any other inputs other than electricity and production material, the operating electrical input is all that is significantly necessary. Also, additional electricity will be needed to convert the granular plastic into plastic filament commonly used by LCAM equipment. Whereas IM simply loads the granular plastic in to a hopper, common desktop AM equipment using fused filament fabrication (FFF) requires that the pellets be converted into single strand of material. This strand appears very similar to the plastic wire found on outdoor weed trimmers and involves melting the granular plastic and then extruding them out as a continuous strand, approximately 1.75 mm in diameter. Although the actual equipment to do this conversion process is not available in the test lab for this project, there is some relative manufacturer's equipment data that can be utilized to determine the amount of electricity necessary to facilitate the conversion. As with the IM process, the funnel materials will only involve a cradle-to-gate approach.

1.E SYSTEM BOUNDARIES

Injection Molding

The system boundary for this element of the project can be seen in Figure 4. It can be seen to include the life cycle stages of material extraction, processing, manufacturing, transportation, wastes, and end of life (EOL). However, as can be seen, several elements such as certain transportation aspects and all aspects of product funnel EOL are excluded from the system boundary. Although the exclusions will be discussed more thoroughly later in this document, since the produced funnel is essentially identical for both IM and LCAM processes, there are no relevant comparative impacts of the funnel itself after production. It is to be noted that the wastes life cycle stage within the IM process is specifically relevant to the steel mold and any production wastes.

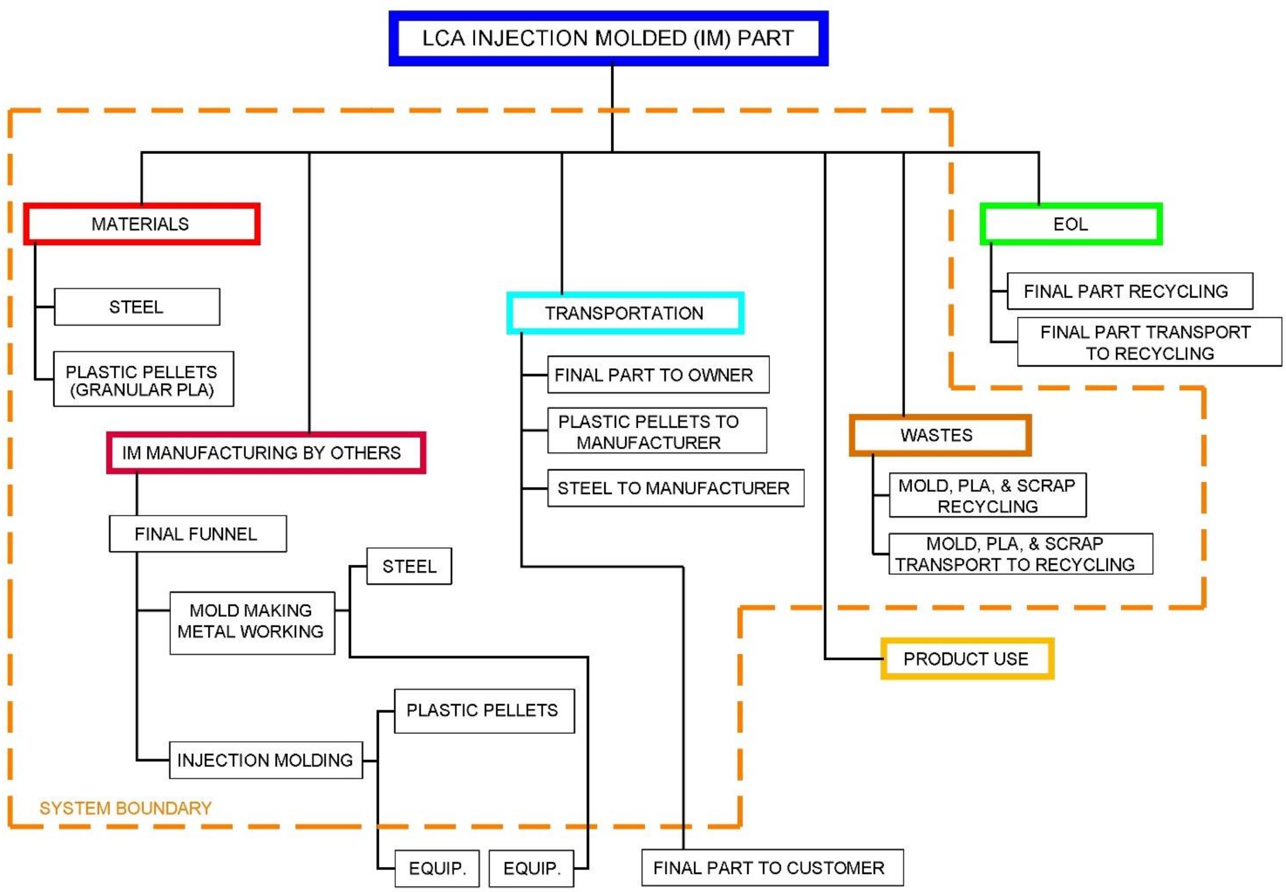


Figure 4: IM process flow diagram.

Low Cost Additive Manufacturing

The system boundary for this element of the project can be seen in Figure 5. It can be seen to include the life cycle stages of material extraction, material processing, manufacturing, wastes and transportation. However, as seen to be similar to the IM process, one sub process within the life cycle stage of transportation, and all of the funnel EOL are excluded from the system boundary. These exclusions as well as the assumptions for no actual manufacturing wastes will be discussed more thoroughly in the following section.

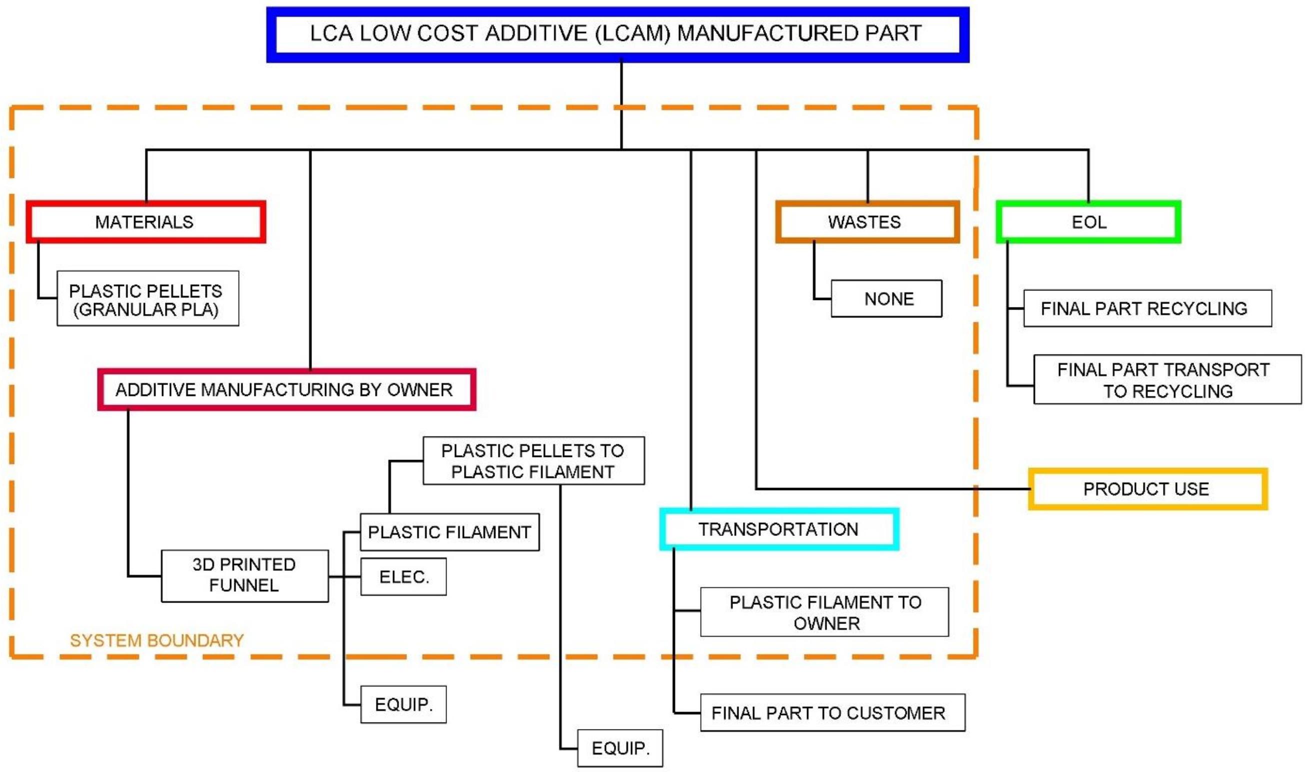


Figure 5: LCAM process flow diagram.

1.F EXCLUDED PROCESSES

As can be seen from the figures, several processes were excluded from this model, most of which were excluded because they were identical between the two manufacturing systems and therefore irrelevant to the study. Transportation impacts of the funnels moving from the Owner to the Customer were excluded from that model as they would be identical regardless of manufacturing methodology, and therefore comparatively irrelevant. The same is true for the funnel EOL stage, both in transportation from the Customer and the assumed recycling of the funnel given its single plastic material composition. The impact of the use life cycle stage of the funnel by the Customer would also be comparatively irrelevant to the project and therefore was also excluded.

For both manufacturing methods, all physical equipment, equipment idling, and facilities were excluded from the project models due the inability to realistically obtain such information and the reasonable acceptance of this practice within the LCA practitioner community.

1.G ASSUMPTIONS

Several assumptions were made in this project related to processes and results. The amount of plastic material necessary to make one funnel would be the same for each manufacturing method, and that the LCAM process would not utilize any support material due to the funnel's design. Therefore the LCAM process would have no waste from support material production. It is was also assumed given the relatively low order number of desired funnels and the simplicity of the design, that the LCAM process would not have any actual production failures nor calibrating production runs resulting in manufacturing wastes. It is assumed that due to the small nature of the design and only 2 funnels at most being produced within the mold, there would a maximum of 7% waste of plastic in the IM process.

It was also assumed that the injection molding manufacturer will fabricate their own molds. This is quite common among many machine-tooling and operations, in that they would be capable of both making the molds and utilizing them for production and therefore no intermediate travel would occur after the mold was fabricated. Regarding the fabrication process, it was also assumed that 20% of steel would be lost in the mold fabrication process based on expertise provided by mold fabricating technicians. Also, that this waste would be recycled at end of the steel mold's usefulness. This scrap recycling assumption was based on the fact that manufacturer would likely not make a special trip to the recycler after completion of the mold and would just add the scrap to the next trip to the recycler. Therefore, the mold and its equivalent amount of scrap could be assumed to eventually travel to the recycler at the same time.

The mold was also assumed to be a double cavity unit, meaning that 2 funnels would be produced during one production run or "shot." This assumption was based on the fact that a double cavity mold would be the most likely cost the Owner would be willing to spend for the project and could still result in a production of 500 units in roughly 3 to 4 regular working days. As mentioned, the mold at the end of its usefulness would also be assumed to be 100% recycled as the value of the steel is likely to still be high and molds typically do not contain any other materials that would cause issues in the recycling process.

For the most part, all transportation distances will all be estimated assumptions. For example, given the relative locale of recycling operations, it is fairly reasonable to assume that there will be recycling business within 150 km of the IM manufacturer. Likewise, suppliers of plastics are found to be stationed all across the United States, and typically can supply an order of filament or bulk granular plastic in less than 2 days if desired, therefore a distance of 160 km was selected for both manufacturing methods. General and assumed values for this project can be seen in Figure 6.

Simapro Data Inputs		
Mass of steel mold	56.82	kg
Mass of one funnel	0.014	kg
Quantity of desired funnels	500	units
Mass of tooling steel to make mold	68.18	kg
Mass of waste steel from tooling process	11.36	kg
Mass of wasted plastic to dial in LCAM process	0	kg (for sensitivity analysis only)
% of waste during injection molding process	7	% per funnel
Distance from IM to Owner	100	km
Distance from steel supplier to IM	160	km
Distance from plastic supplier to IM	160	km
Distance from plastic supplier to Owner	160	km
Distance from IM to recycling center	100	km
Electricity to convert pellets to filament	0.0075	kWh per funnel
Electricity to produce 1 funnel w/ low cost AM	0.099	kWh per funnel

Figure 6: General and assumed values.

1.H IMPACT ASSESMENT METHODS

The primary process database library for this project will be Ecoinvent 3-allocation, cut-off by classification – system. Several impact assessment methods will be utilized for this study including:

- IPCC 2013 Global Warming Potential (GWP) with a 100 year timeframe
- Cumulative Energy Demand
- ReCiPe 2016 Midpoint (H)

Two of these methods were selected as they represent fairly easy to understand environmental consequences and quantifications, noting that although this project is not going to be publically disclosed, it may still be the basis for future projects and discussion related to these comparative manufacturing technologies. The third will encompass a range of impacts to ensure that the study does not validate one process over the other as a result of a mere burden shift.

1.I SENSITIVITY ANALYSIS

The sensitivity analysis element of this project will include the quantity of desired funnels produced. This is the most logical related to the potentially comparative impacts, both economically and environmentally speaking. The number of funnels desired by the Owner will be increased to 5,000 and 10,000 units for impact evaluation. This comparison will help to reveal at what production quantity, if any, would be required to make one manufacturing process move from more of a hazard to the environment to less of a hazard when compared to the other. Another analysis will address the assumption that the LCAM process does not include any relevant waste. This will be addressed by allotting a lump sum value of 10 kg of equivalent wasted production funnels to account for initial production calibration and even possible production failures.

-End of Goal and Scope-

2. LCI DATA COLLECTION SUMMARY

2.A ASPECTS THAT ARE PRIMARY

The electrical energy utilized by the low cost additive equipment for the final funnel production. This data was directly collected utilizing a P3 P4400 Kill A Watt Electricity Usage Monitor while producing a sample allotment of funnels.

Information related to the funnel such as dimensions, mass, order quantity, and material composition was also primary data as the design and fabrication using low cost AM equipment was directly controlled as part of the project.

2.B ASPECTS THAT ARE SECONDARY

The remaining LCI data was secondary and obtained by utilizing Simapro with the library database Ecoinvent 3 – allocation, cut-off by classification system, converted 3.4 data, compiled April 2018.

Estimations of the data related to the IM processes were provided by an experienced professional technician in the molding fabrication industry including:

- Mass of the necessary steel mold to perform injection molding of the funnel
- Waste scrap of the mold making/metalworking process
- Waste percentage of plastic associated with the injection molding process

Estimations of data that were made up or assumed for the purpose of this study due to lack of sourcing information or actual equipment included:

- Transportation distances from material suppliers to the injection molding manufacturer
- Transportation distances from material suppliers to the Owner
- Transportation distances from the IM manufacturer to the Owner
- Transportation distances from the IM manufacturer to the recycler for waste disposal
- The maximum amount of electricity utilized to convert plastic granular material to plastic filament utilizing existing equipment. However, this estimate was based on the actual manufacturer's published data regarding the equipment's performance.
- Waste percentage of plastic associated with the AM process for sensitivity analysis
- Transportation distances from the Owner to the recycler for waste disposal for sensitivity analysis

2.C DATA COLLECTED PER LIFE CYCLE STAGE

Materials

As the end product was a single component plastic funnel, the project materials were modeled as low alloyed steel (GLO) and polylactide granulate (GLO). These project choices were fairly well aligned with reality as the mold would typically be composed of general tool steel and the end product of the funnel would in fact be composed of polylactic acid based plastic, also referred to as PLA, for both the IM and the AM production processes. The amount of steel needed for the project was estimated by the mold making technician as well as the percentage of IM waste. The mass of PLA represented for each funnel was determined from the computer design model and a digital scale, that being 14 grams.

Using the Simapro and Econvinet processes mentioned, these materials were modeled where applicable for both the AM and IM processes as materials/fuels inputs from technosphere. Noting that the AM process did not require any steel and would require a lesser amount of PLA plastic due to the fact that the AM process in this case resulted in no actual production waste.

Manufacturing

The IM manufacturing process

The modeled manufacturing processes were metalworking of steel and plastic injection molding. As mentioned, values of the mold steel mass, steel waste, and plastic waste from this approach were estimated by the machine tooling technician. The final steel mold being estimated to mass nearly 57 kg and requiring nearly a 68 kg steel blank from which to fabricate. The mass of the actual produced funnel was already determined.

The data collected from Simapro was based on the following inputs from technosphere:
Metal working, average for steel product manufacturing {GLO}| market for | Cut-off, S
Injection moulding {GLO}| market for | Cut-off, S

The AM manufacturing process

For the LCAM approach, the manufacturing processes were the conversion of PLA plastic pellets to PLA plastic filament and then the actual AM production of the funnel using the low cost equipment and the PLA filament. As previously mentioned the conversion of pellets to filament would not likely be part of the typical Owner's process as they would simply order filament instead of the PLA in granular form. However modeling the process as part of the manufacturing stage was considered relevant to capture the potential impact and account for the fact that the Owner may wish to reduce production costs by making their own filament.

The filament conversion process, which is simply melting down the granular PLA and extruding it as a 1.75 mm diameter continuous strand, was estimated by the data provided by the manufacturer of the pellet-to-filament converter, the Filabot EX2 Filament Extruder. Knowing the total number of desired funnels, their mass, the rate of PLA filament conversion, and the maximum wattage capable of being provided by its power supply during operation, a total amount of electricity needed per funnel was determined for the conversion. As this desktop device is a single-phase 110v unit, no power factor element was necessary in the calculation.

The data collected from Simapro was based on that electrical amount and the following inputs from technosphere:
Electricity, low voltage {US}| market group for | Cut-off, S

The AM production data was directly collected by producing a sample of funnels both in a batch of several funnels as well as the production of only one, and metering the cumulative amount of electricity utilized by the equipment with an electricity usage monitor. This amount was then divided by the number of the funnels in the batch to account for the amount of electricity consumed in the production of one funnel, that being 0.099 kWh per funnel.

The data collected from Simapro was based on that electrical amount and the following inputs from technosphere:
Electricity, low voltage {US}| market group for | Cut-off, S

Transportation

The IM manufacturing process

The transportation elements involved the shipping of the steel and the PLA granular materials to the IM manufacturer from separate suppliers, and the shipping of the final funnel products to the Owner. All actual distances for modeling were estimated, generally either 100 or 160 km. The transportation of any scrap or manufacturing waste elements to a recycling facility would be accounted for in the Wastes stage.

The data collection for all of the Transportation stage was through the use of Simapro with the following processes:
Transport, freight, light commercial vehicle {GLO}| market for | Cut-off, S

This process was selected as it was considered the best comparative evaluator given the low mass of the units being shipped, and the unlikelihood of a heavier freight carrier being utilized for any of the transportation.

The AM manufacturing process

The transportation elements involved the shipping of the PLA granular material to the Owner only. The transportation of any scrap or waste elements, which were assumed zero in the project model but were considered in the sensitivity analysis, to a recycling facility would be accounted for in the wastes stage.

The data collection for all of the Transportation stage was through the use of Simapro with the following processes:
Transport, freight, light commercial vehicle {GLO}| market for | Cut-off, S

Use

As mentioned previously there would be no use life cycle for this project as both IM and AM approaches would result in identical consumer use results and would be irrelevant for comparison.

EOL

As mentioned previously there would be no EOL life cycle element for the produced funnels as both IM and AM approaches would result in identical EOL recycling, being irrelevant for a comparison.

Wastes

The IM manufacturing process

Although not an EOL stage of the actual funnel, there would be wastes that would need to be addressed at the end of the usefulness of the funnel project, the most significant would be the steel mold used in the IM process, which would no longer have a use when the production of line of funnels ended. Therefore, a wastes stage was included that would address the mold, the steel scrap resulting from the manufacturing of the mold, and the wasted plastic associated with IM process, all of which would be considered fully recyclable. These components would also have to be transported to some other facility for such recycling. As such, the estimated transportation distance of the steel mold, the steel scrap, and the injection molding PLA scrap was also included.

The AM manufacturing process

The LCAM approach did not have any tooling elements or PLA plastic waste because of the optimized design of the funnel. The conversion of PLA granular material to PLA filament should also not result in any realistically measureable wasted plastic because the conversion process is very straight forward. Overall, there were no anticipated end of use waste considerations for the AM approach. However, for a sensitivity analysis an estimated amount of plastic waste would be associated with trial-and-error work to optimize the eventual AM production. This sensitivity analysis waste would also require an estimated transport distance to the recycler from the Owner's location.

The data collection for all of the wastes stage was through the use of Simapro with the following processes:
Transport, freight, light commercial vehicle {GLO}| market for | Cut-off, S
Steel and iron (waste treatment) {GLO}| recycling of steel and iron | Cut-off, S
PE (waste treatment) {GLO}| recycling of PE | Cut-off, S

It was noted that a recycling option for the actual funnel PLA material was not available, therefore, Polyethylene was utilized as a relatively similar substitution.

-End of LCI-

3. LICA RESULTS

Overall, as can be seen from Figure 7, the total LCAM process resulted in a significantly lower carbon footprint, also referred to as global warming potential (GWP), than the IM process by nearly a factor of 7. In terms of energy related impacts, the LCAM process was always less than the IM process, especially when considering non-renewable, fossil based energy sources, as can be seen in Figure 8. In fact, in every impact category analyzed in the course of this assessment, the LCAM process was superior to the IM process.

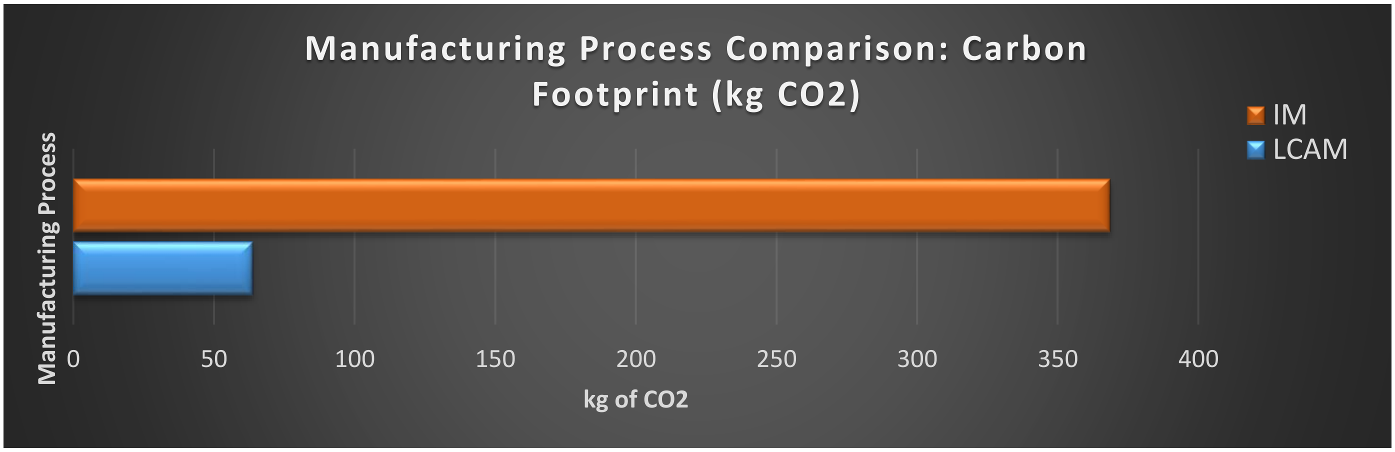


Figure 7: Carbon Footprint comparison.

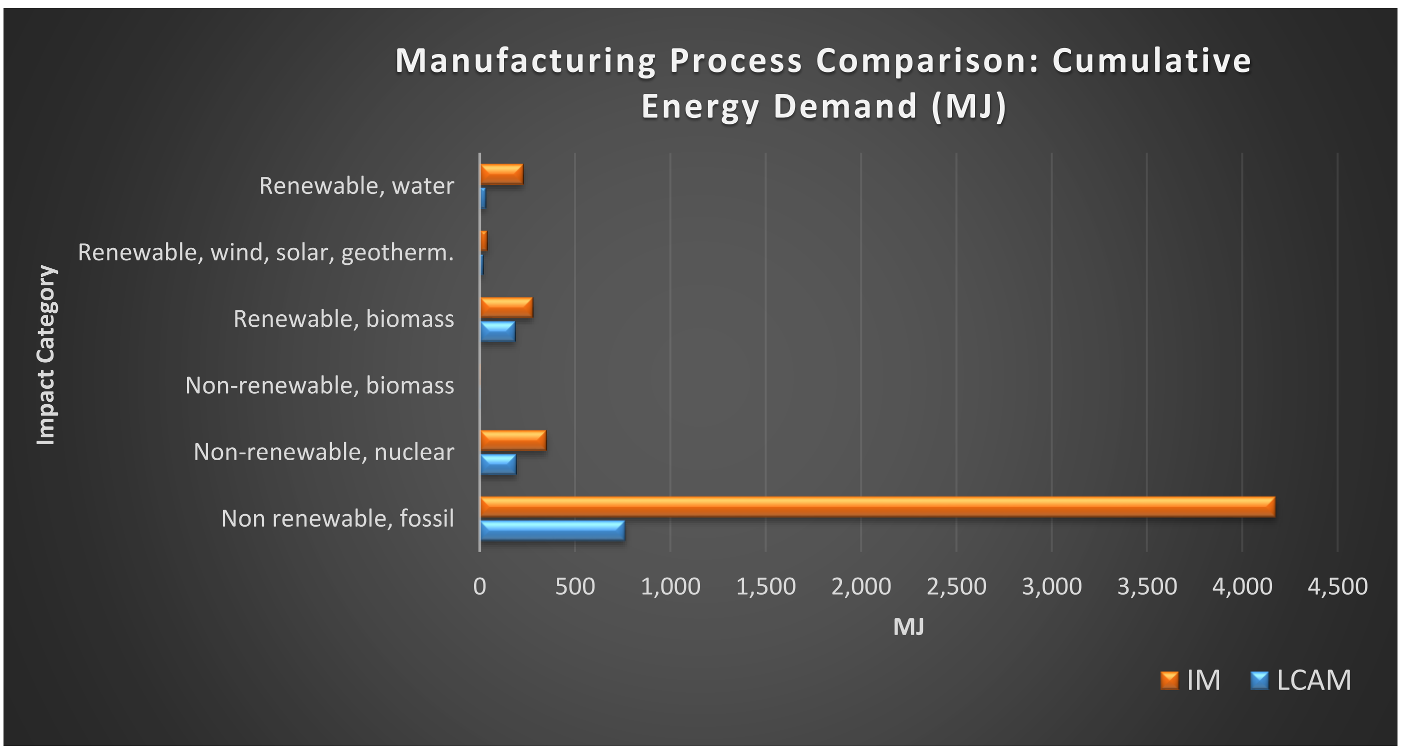


Figure 8: Cumulative Energy Demand comparison.

It was noted that the materials and manufacturing life cycle stages contributed to the most significant GWP for both processes. And it was also these stages where the most significant impact differences between the processes could be observed. As can been seen in Figure 9 with regards to the GWP, the LCAM process was nearly a factor of 4 and 8 times less than the IM process in the life cycle stages of Manufacturing and Materials respectively. This can directly be contributed to the simple fact that the IM process involved the processing and production of the steel mold. As both the IM and LCAM process share roughly the same amount of PLA plastic, the impacts from that component would be expected to be similar. However, the steel mold making process is what truly creates the differential in these two manufacturing approaches.

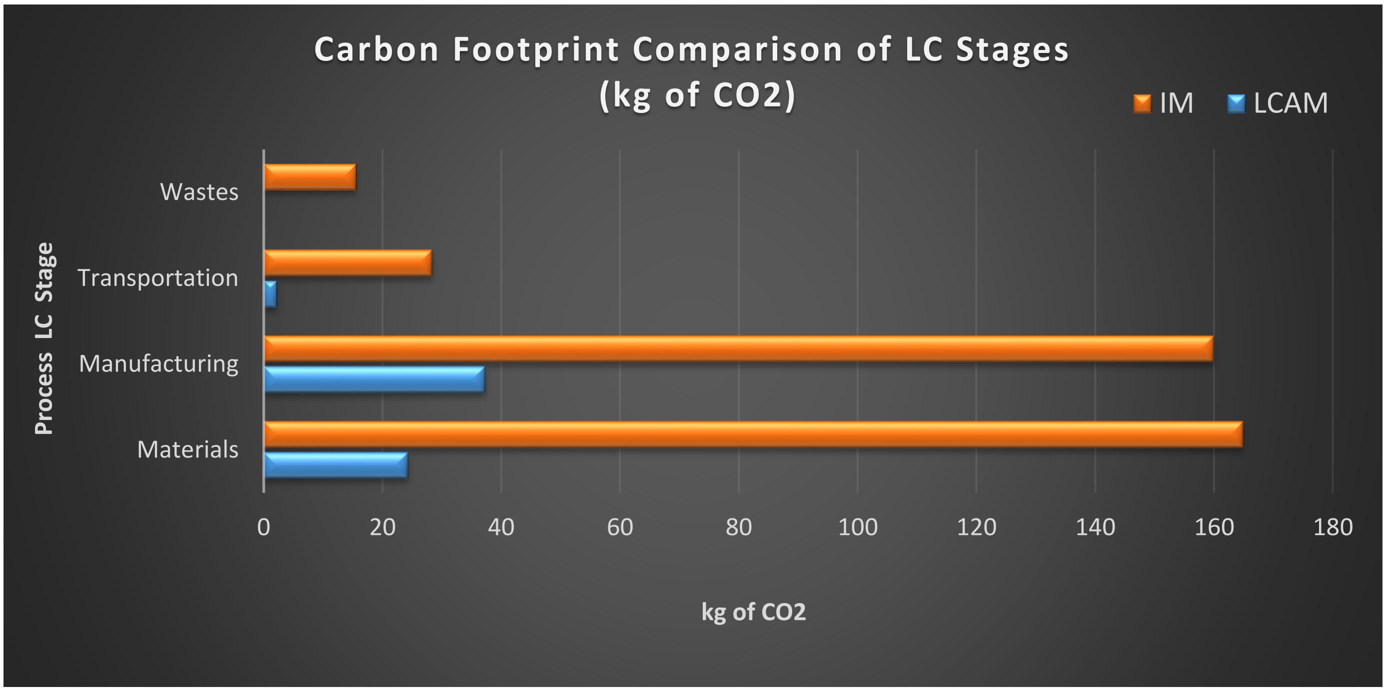


Figure 9: Carbon Footprint comparison by life cycle stage

From a broad spectrum impact perspective, the ReCiPe 2016 Midpoint (H) analysis for both systems, seen in Figures 10 and 11, demonstrated that both the wastes and transportation stages within each process had predominately minor impacts when compared to the materials and manufacturing stages. Especially for the LCAM process, where there were no actual wastes associated with that system. Also for the LCAM process, it can be visually noted that the manufacturing stage was the slightly more impact significant stage, whereas for the IM process, the materials stage was the more significant.

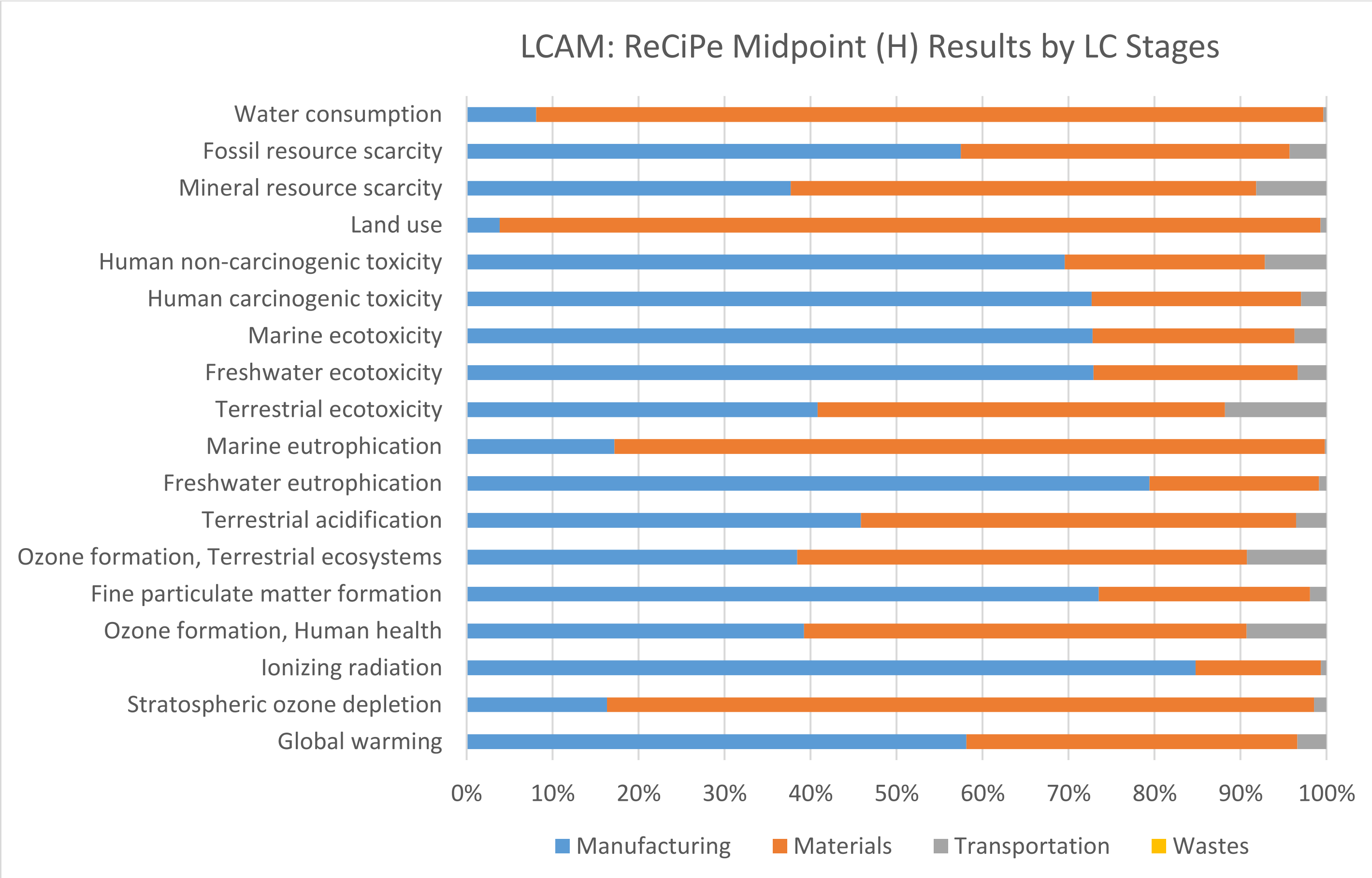


Figure 10: LCAM broad spectrum proportional impacts by life cycle stage.

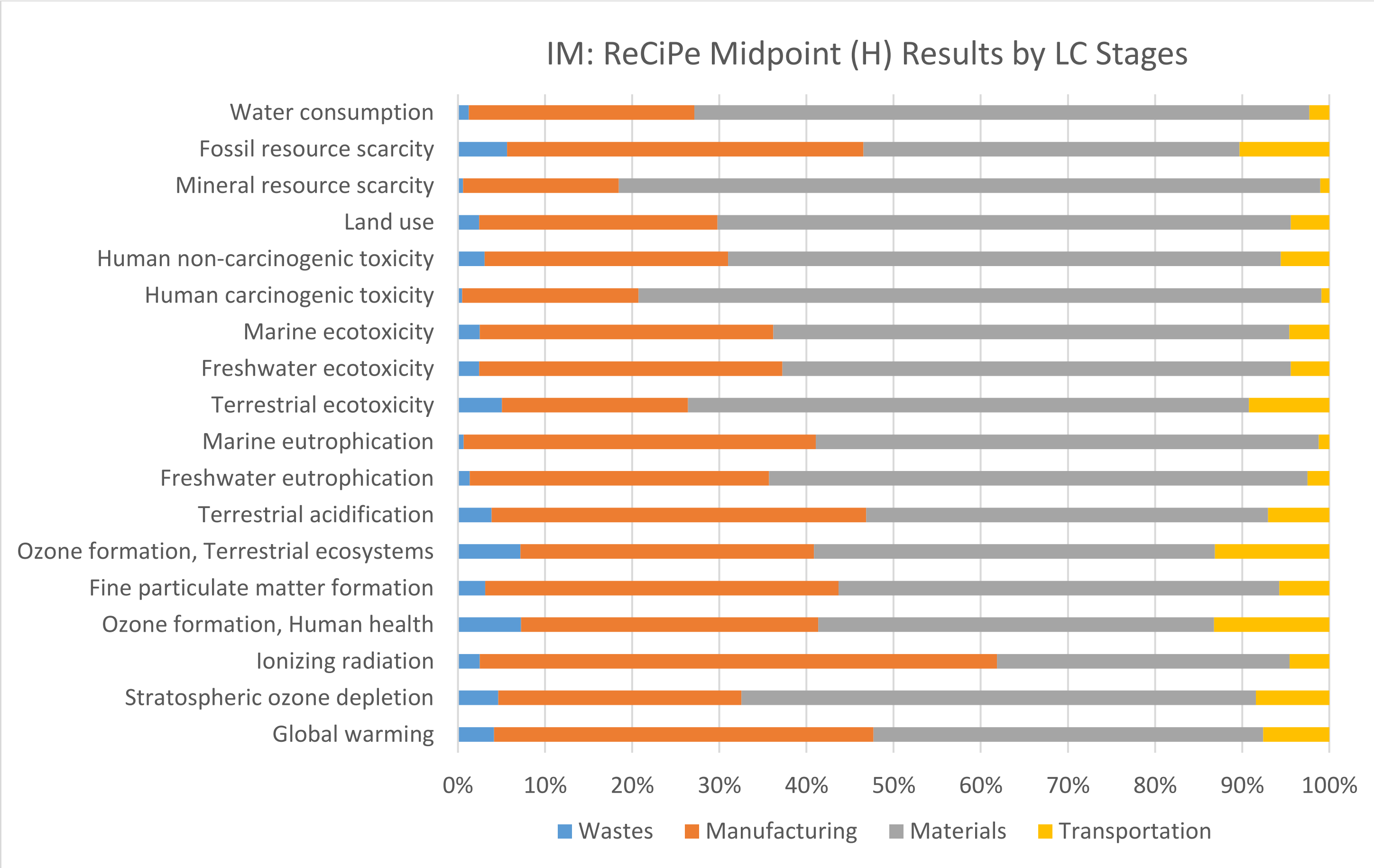


Figure 11: IM broad spectrum proportional impacts by life cycle stage.

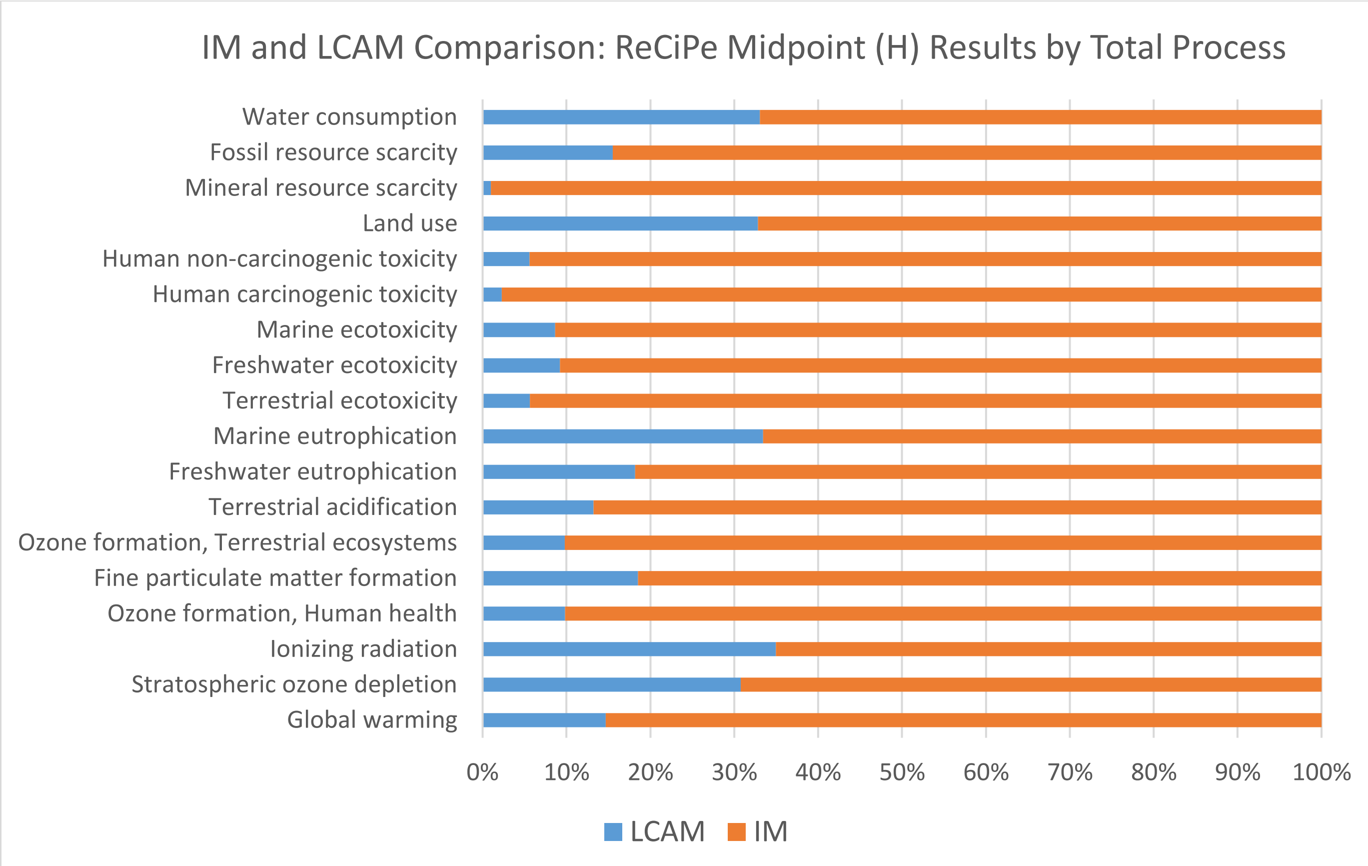


Figure 12: Comparative LCAM and IM broad spectrum proportional impacts.

As shown in Figure 12, the broad spectrum impacts of the LCAM process continuously made up less than 40% of the total IM process impacts per category. And in the majority of the impact categories, made up less than 20% of the total impact.

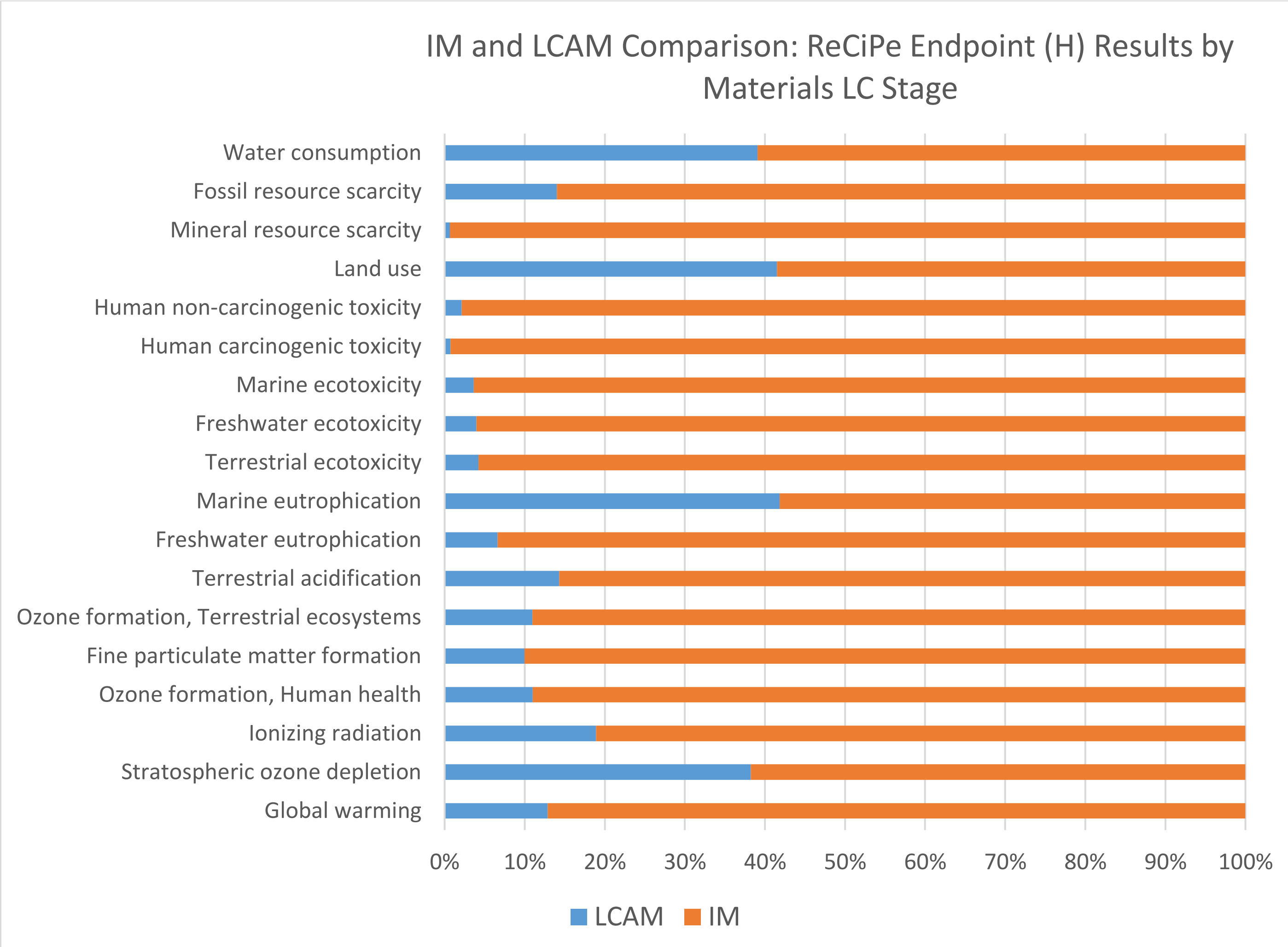


Figure 13: Comparative broad spectrum proportional impacts by materials stage only.

Given the fact that the only major difference between the materials life cycle stage of the LCAM and the IM process was the presence of the steel necessary to produce the mold, Figure 13 helps to isolate and show the significance the steel represents in terms of comparative impact. The majority of the LCAM impacts made up less than 20% of the total IM impacts per category simply because there was no steel extraction and processing necessary for its production methodology.

The LCIA element of this project clearly revealed that for the target production of 500 funnel units, the LCAM production process would be the preferred method over the IM process in terms of minimizing environmental impacts. The overall differential being well beyond the recommended 20% threshold for a comparative project.

-End of LICA-

4. INTERPRETATION

4.A KEY OBSERVATIONS

It was clear from this project that for both the LCAM and the IM processes the materials and manufacturing life cycle stages were the most significant impact stages by far. And the LCAM process was far below the IM in terms of those environmental impacts. It was also obvious that the primary impact driver of the IM process was the steel mold. Even though the mold was fully recyclable and required less than 70 kg of steel to fabricate, its use in the overall process was detrimental to its environmental performance when compared to the LCAM process.

With the steel mold being the obvious IM process hotspot, potential solutions for consideration to reduce the IM impact would be to reduce the mold capacity from a double cavity mold to a single cavity mold. This would approximately reduce the necessary steel and metal working processes by half, which should greatly reduce the overall environmental burden. Though this would double the necessary IM part production time, there is little likelihood of a burden shift from that action.

Another more unorthodox approach to reducing the IM impact of the steel would be to potentially use metal powder based additive manufacturing techniques to produce the mold itself. Although, there is no data available at this time to even test this concept, it is known that metal additive manufacturing can be used to produce steel molds at a lower steel density and with less metal working process involvement. Thus potentially reducing the overall impact of the mold.

A related option would be to use photosensitive resin based additive manufacturing techniques to produce a mold for the IM process that would not be made of steel but rather a polymer. Again, there are no opportunities for testing this theory given the scope of this project, but this technology has shown to be capable of producing high temperature resistant polymer molds useful for short run productions. And given the desired unit quantity of this project, this could be a viable alternative, especially given that the funnel material is PLA plastic, a very low temperature thermoplastic. However, this concept could involve a burden shift because photosensitive resins, especially those with exotic additives to enhance certain properties, would likely have a more toxic impact within a variety of environmental and human help categories. Additionally, it is unknown if such a polymer based mold would be recyclable at the end of its usefulness. It is unlikely though that these burden shifts would be as significant as the conventional approach of using a steel mold.

It was noted that because of the recyclability of the steel and PLA plastic, the wastes life cycle stage was the most insignificant for the IM process and obviously resulted in zero impacts for the IM process. Had there been a need for a different mold stock material other than steel or a less recyclable plastic for funnel production, the IM process impacts would likely have increased. As they were, the IM wastes life cycle stage barely exceeded the project cutoff of 3%.

The transportation impact from IM process was slightly higher than expected. This is of interest because all the transportation distances were estimated. Although the values were considered reasonable, it is likely that they could be less or more. A reduction of estimated distances however, would not dramatically improve the IM process. On the other hand, considering the number of current U.S. companies that outsource their injection molding needs to suppliers in China for economic savings, it is very likely that a real world application of this project would result in a much higher transportation life cycle impact for the IM process.

For the LCAM process, it was clearly observed that the actual additive manufacturing production of the funnel was the largest hotspot for the process. Requiring nearly 0.10 kWh per funnel for final production versus the 0.0075 kWh per funnel necessary to convert the granular PLA to usable filament, the impacts were clearly within the final production of the funnel. This approximate 0.1 kWh per funnel electrical consumption was primarily due to the heated build plate component of the desktop 3D printer. The heated build plate being a much larger area compared to the very small filament heater block, draws much more electrical power to maintain its target temperature for optimum first layer adhesion. During production runs, it was observed that the larger number of funnels per batch, or production run of the printer, the lower the kWh value per funnel. For example, a single funnel production run was 0.16 kWh, whereas a production run of 7 funnels resulted in the 0.099 kWh per funnel value used for the LCI.

Although it was unable to be tested due the limitations of the electrical metering equipment, a production run of 14 funnels is quite easily achieved. And by plotting the kWh data that was recorded, a trend line equation predicted that 14 funnels per batch would result in less than 0.05 kWh per funnel, possibly as low as 0.04 kWh per funnel. Such a reduction of kWh per funnel unit could cut the majority of the LCAM impacts by roughly a third.

Therefore, since the heated build plate was the hotspot for the process, it too could be improved upon by placing an insulated containment unit around the device, thus reducing the electrical consumption necessary to maintain the heated build plate temperature. Lowering the equipment build plate target temperature 5°C would also improve the process. However, the best solution would likely be operating the equipment without heating the build plate. This would likely require a slightly altered PLA plastic material, specialized toward limited residual thermal stress incursion, but such material is available and could possibly be applied to the process. However, it is likely there would be more LCAM production failures due to lack of good first layer adhesion associated with non-heated build plates.

Another key consideration associated with the LCAM process is the fact that there was no data collection involving nanoparticles emitted during the LCAM manufacturing process. It is well documented that LCAM equipment such as the one used in this project does release nanoparticles into the environment. However, the current research notes where PLA filaments are used, the hazards are much lower than other thermoplastics such as Nylon or ABS. Therefore, since there was no data collected during the LCAM process related to this issue, there could be other environmental or health impacts that were not represented during the course of this study.

From a comparison standpoint of the data available, it was clear that the LCAM process was the superior production methodology over the IM process in terms of the environmental impacts considered. Overall, the LCAM positively outperformed the IM process well beyond the recommended threshold of a 20% differential. Though is project is not a true comparative LCA and in no way is in full compliance with ISO 14040 standards for such a project, it does provide preliminary insights toward such a comparison. It also warrants further investigation of the utilization of the LCAM process over the IM process for certain product manufacturing situations such as those represented in this project.

4.B SENSITIVITY ANALYSES

To address the assumption that LCAM process would result in virtually zero production wastes and therefore not have a wastes life cycle stage comparable to the IM process, a test involving 10 kg of PLA waste was introduced into the model. This 10 kg was considered a very high and unrealistic estimate of waste as it equated to nearly 714 wasted or failed production funnels in addition to the actual 500 produced for the project, plus the wasted material transportation to the recycling center. As can be seen in Figure 14 this effectively more than doubled the impact of LCAM carbon footprint, but was still less than half that of the IM process with no failures.

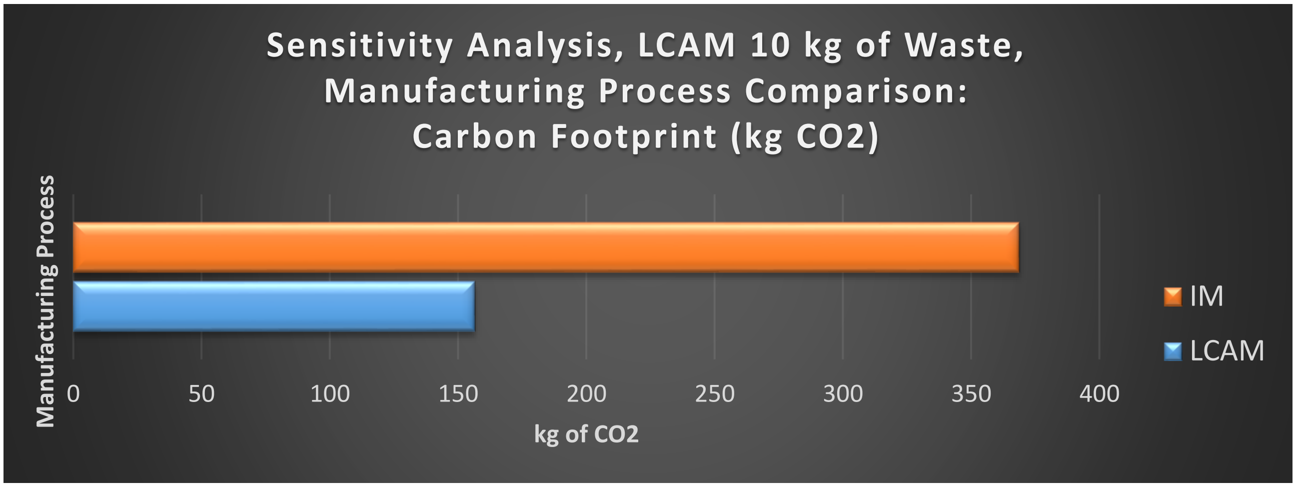


Figure 14: Sensitivity Analysis, LCAM 10 kg of waste.

A second and third sensitivity test were performed to address considerations related to the actual production quantity of the funnels. This was to evaluate whether or not there would be a comparative improvement of the IM process over the LCAM process if a large enough order of funnels were required. This was considered quite plausible in the event that the Owner successfully expanded their operations and would require more funnels for more franchise locations. The unit quantities of 5,000 and 10,000 were modeled and the GWP results can be seen in Figures 15 and 16. As can be seen, the differential between the two manufacturing processes decreases significantly at the 5,000 unit production level, and the GWP of the LCAM process exceeds the IM process at the 10,000 unit production level.

This demonstrates that the environmental advantage of the LCAM process has its limitations in terms of scale, if all remaining conditions of the production remain static. Such as the potential need of the IM process to eventually require a steel mold replacement, though such a replacement is not expected for production runs of less than 15,000 units.

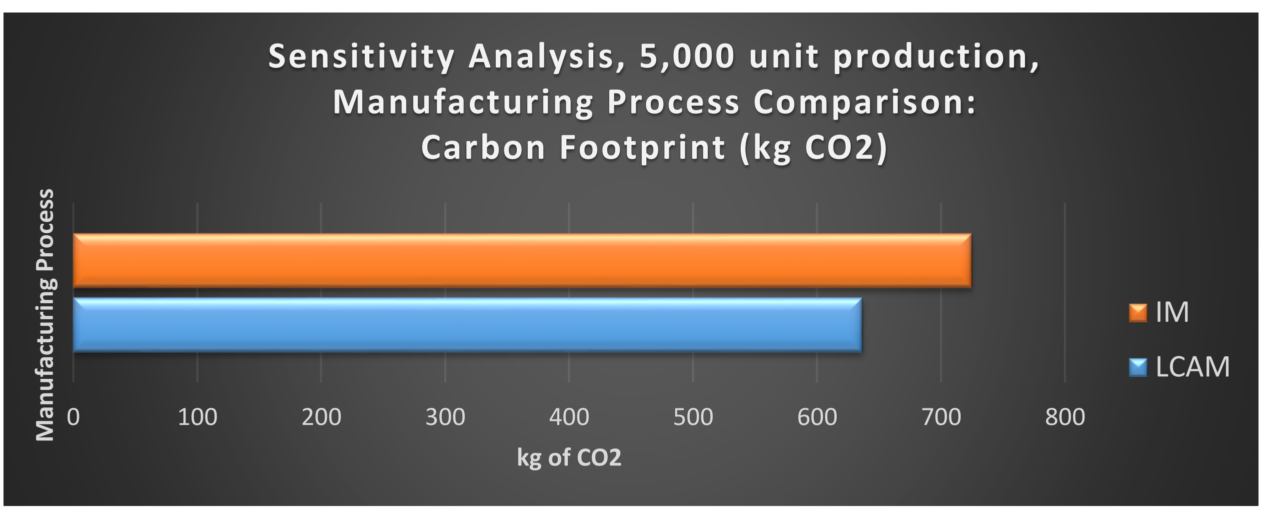


Figure 15: Sensitivity Analysis, 5,000 unit production run.

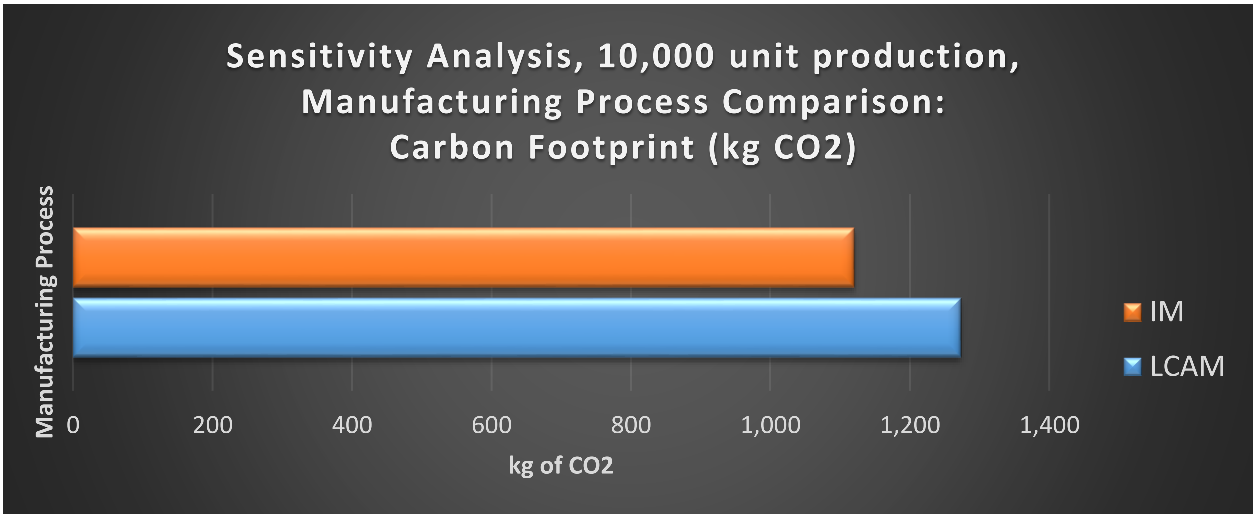


Figure 16: Sensitivity Analysis, 10,000 unit production run.

4.C COMMENTS ON DATA QUALITY

Data quality for the IM process was secondary data and directly from Simapro utilizing Ecoinvent databases. Quantities of materials were based on fairly good estimates by machine tool practitioners and actual production dimensional information.

LCAM production data was fairly high quality as the actual funnel production was directly performed and measured. Filament production was estimated but the kWh value per unit was fairly reasonable and resulted in a very low impact overall.

As mentioned, no collection of airborne nanoparticles and toxicity was collected for the LCAM process. On the other hand, the IM process through the Ecoinvent database, did include emissions to air impacts. Therefore, this project does have a comparative weakness and a lack of data quality regarding such impacts.

The funnels produced by the IM process versus the LCAM are inherently different by the production process, and would not necessarily look exactly the same, IM would be smoother and better finish. It could be possible that to meet customer expectations, the Owner may have to do an addition finishing process to each funnel as part of the LCAM process to smooth the surfaces. This would result in an additional process that was not accounted for in this project, and if implemented would possibly involve another process that would be difficult in which to collect primary or even secondary data.

Also, the LCAM layer to layer bonding process results in a different product in terms of structural performance when compared to one that is injection molded. If in actual consumer use, the LCAM funnel version was found to require more structural performance, the LCAM process modeled in this project would have to be modified. Often times to increase layer to layer bonding strength, the production layer height is reduced, resulting in a stronger layer, but an increased production time per unit. This would of course increase the LCAM kWh value per funnel and increase its overall impacts. Therefore, this possibility also demonstrates a potential weakness in this project's collected data.

4.D COMMENTS ON PROJECT COMPLETENESS CHECKS

In terms of project completeness, for both processes there were not that many flows to necessitate a higher percentage of cutoff, such as 10%, being used for a benefit of clarity or complexity reduction. And for this project, the cutoff percentages of flows were 3% and 0% for the IM and LCAM processes respectively. However, the implication of the LCAM process being that thorough is not realistic as the data available for its LCI and resulting LCIA was limited to essentially the electricity consumption and the use of the granular PLA plastic material. Therefore, omitting certain flows to reduce project complexity was not necessary. Although the LCAM process in some sense does not require that many inputs, it is still important to note that collection of available information was limited. However, the LCAM impacts were so low that proportionally, it would require a 4% cutoff for essentially any flow to be excluded.

The IM process cutoff was set in Simapro such that flows from the wastes life cycle stage would be included, those being approximately 4% of the total impact contributors. Below this cutoff the flows were deemed negligible to the impacts of the project as they generally only included impacts from the recycling process and an extremely small amount of impact flow from the transportation of the granular PLA and the funnels to the Owner. Excluding these minor impacts did not appear to result in any form of data skewing.

-End of Interpretation-

5. CONCLUSIONS AND RECOMMENDATIONS

Overall, this project represents a streamlined comparative LCA of the potential environmental impacts of the IM and LCAM methodologies. The work provided was performed in the most reasonably appropriate manner given the nature of the project and the limitations thereof. The work does reveal the relative potential of the LCAM production model in terms of more sustainable practices associated with lower quantity manufacturing orders in comparison to the conventional IM production model.

From the work, it is recommended that further review and research be performed toward the comparison of these two production technologies. However, it is also recommended from this work, that the manufacturing and small business industries in general turn more attention toward the LCAM methodology over the conventional injection molding processes as there are obviously environmental benefits to be realized. These benefits will likely become more obvious and possibly even more significant with the maturation of the LCAM equipment as well as the consumer acceptance of products fabricated by additive manufacturing.

-End of Project-