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NEW WOOD DUST REINFORCED RECYCLED POLYPROPYLENE COMPOSITE FILAMENT AND TRADITIONAL POLYPROPYLENE FILAMENT FOR FDM APPLICATIONS: LIFE CYCLE ASSESSMENT STUDY

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Abstract: Life Cycle Assessment (LCA) is an effective method for determining the environmental impact of a composite material over its lifetime. Consequently, it is important to the composites sector, particularly for Fused Deposition Modelling (FDM) filament manufacturers as a material selection tool when determining the usability of recycled material utilised in component design phases. This article investigates the LCA framework of utilising wood dust as reinforced material and recycled polypropylene material in the production of composite filament for the FDM sector. Eco Audit, a feature of the CES Edupack programme, was utilised to evaluate the LCA from an environmental standpoint for product makers. Using recycled polypropylene containing an increasing weight percentage of wood dust to produce new types of composite filament materials reduces energy consumption (MJ) and lowers the carbon footprint (kg). This is because the quantity of energy required for recycling is far less than that required for initial manufacture. When compared to the new polypropylene material that is used to create filament, this study reveals a 56% and 37% reduction in energy consumption and CO2 emissions, respectively. This is a considerable improvement from an environmental point of view.

Keywords: Life cycle analysis, fused deposition modelling, recycled polypropylene, wood dust.

Introduction

Life Cycle Assessment Overview

Life Cycle Assessment (LCA) examines the environmental effects of products, processes or activities throughout their whole life cycle, generally from cradle to grave, using an internationally regulated scientific framework. This is accomplished for a product by summarising the relevant inputs and outputs of a number of processes, analysing the potential consequences of this list, and interpreting the results in light of the assessment's objective and scope (Tapper *et al.*, 2020; Muhamad *et al.*, 2022).

LCA is an effective decision-making tool that can discover environmental "pressure points," cost-saving opportunities, and process trade-offs. Along with a shift in public attitude toward environmental protection, these benefits have made LCA a recognised industry technique for evaluating and selecting novel materials and processes (Tapper *et al.*, 2020). It is witnessing increasing use in the construction, aerospace, and automotive industries. The LCA assessment criteria can provide important process simulation and quantitative analysis required to make well-informed modifications to achieve these goals. In contrast, the composites industry uses LCA to highlight the benefits of recycled or upcycled materials as alternatives to conventional materials (Ead *et al.*, 2021).

Methodology for Life Cycle Assessments (LCA)

LCA, which examines a product system's inputs, outputs and associated environmental implications, is a technique for analysing the environmental effects of a product system throughout its life cycle (International Organization for Standardization – ISO, 1997, International Organization for Standardization – ISO, 2006). Four categories make up an LCA: Goal and scope definition, analysis of the life cycle inventory, evaluation of the impact, and interpretation of the findings (Filimonau, 2015). The types of environmental effects will be outlined in the system's purpose and scope outline, along with any limitations or presumptions that were used throughout the assessment. It is crucial to establish the decision that will be influenced by the evaluation s up front. In the case of material selection, this involves comparing several systems for a reference unit, which can be a specified quantity of material or a single component (Tapper *et al.*, 2020).

The Life Cycle Inventory (LCI) involves locating and tallying all the pertinent unit process flows that are connected to the product system. Product systems for FDM filament comprise all of a product's connected unit operations, ranging from the extraction of raw materials to the processing of the product after it has reached the end of its useful life. The LCI (shown in Figure 1) is constructed from the fundamental stages of the life cycle of the functional unit, which are denoted by the system boundaries. The majority of product-focused LCAs cover the entire life cycle of a product, which covers the following stages: a) creation of raw materials; b) manufacture; c) usage; and d) end-of-life (EOL).

Fused Deposition Modelling Overview

One method for printing three-dimensional objects is fused deposition modelling (FDM). This method is one of the additive manufacturing engineering manufacturing processes that is becoming more and more popular among academics and the corporate world (Dey *et al.*, 2021). With the ability to manage materials efficiently and manufacture a variety of complex shapes and structures, additive manufacturing techniques are becoming ever more popular (Kristiawan *et al.*, 2021). This is because the technology produces less waste and has additional advantages over traditional production. In terms of manufacturing, the FDM procedure is equivalent to injection moulding. It comprises creating a series of customised products in order to maintain low prices while allowing each product to be distinctive. The core tenet of the FDM manufacturing process is the melting and moulding of the raw material into new forms. The substance is a filament coiled on a roll that is dragged by a driving wheel, heated to semiliquid state, and then fed through a temperature-controlled nozzle head. To construct structural pieces' layer by layer, the nozzle accurately extrudes and guides ultrathin layers of material. This follows the layer contours established by the application, which is frequently CAD, and integrated into the FDM work system (Wickramasinghe *et al.*, 2020). FDM working principle technology is shown in Figure 2.

A few processing parameters, including layer thickness, filament width, and orientation, have an impact on the mechanical properties of a 3D-printed component. The specific restrictions of FDM have made filament material development difficult. The thermoplasticity of the filament, which specifies its ability to bind layers during printing and solidify at room temperature after printing, is critical to the FDM process, since the shapes are built from

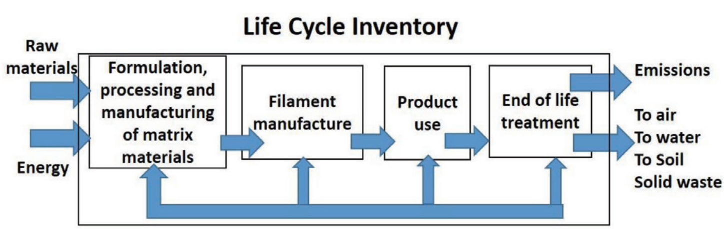


Figure 1: Schematic of a typical LCI for filament production

thin filament layers. Polymer-plastic filaments account for 51% of additive manufacturing production (Kristiawan *et al.*, 2021). FDM is more controllable and efficient since these materials meet the standards for usage and development. However, the viability of polymer-plastic filaments for a given application is not only determined by part complexity, manufacturing lead time, and cost. The environmental impact and financial cost of production rule them out in meeting industrial legislation or commercial standards. Recycling is one method for reducing this load because the energy required for recycling is frequently less than the energy required for initial manufacturing (Saosee *et al.*, 2020). The publication of several research studies and evaluations has increased interest in natural fibre composite FDM (Bryll *et al.*, 2018; Wickramasinghe *et al.*, 2020; Azali *et al.*, 2022) . Polymer and fibre material temperature and fluid flow properties are necessary for the construction of bespoke composites (Dey *et al.*, 2021).

Particularly for composite filaments, the use of LCA to assess the advantages of recycling is still in its infancy, and there is presently no methodology that is sufficiently thorough to capture the implications throughout several lifetimes. The methodologies that can be used to define and assess the advantages of a recycling process or utilizing recyclable material are examined in light of these findings.

Production of Filaments for FDM

Producing pure polymer filament for FDM products can be accomplished by extruding pellets or raw materials derived from polymers. In this process, extruders are utilised to force the material to be pushed or pressed through die-cut holes in order to generate the product in the form of an extruded product. In the interim, filaments can be made from polymer composites or by strengthening existing filaments. This is accomplished by combining the material just before the extrusion process and by preparing each composition in advance so that it can be joined to other compositions (Bryll *et al.*, 2018). The combination of the materials can be accomplished through a number of processes, the specifics of which are determined by the characteristics of the constituent parts. Either the dry mixing approach or combining the solution and then drying it before extraction can be used to complete it. (Wickramasinghe *et al.*, 2020). This technique is most frequently used to combine polymer filament material.

At the melting point of the polymer, a machine with rotating roller blades mixes a pure polymer. Then, following the compatibilizer technique, additives are added gradually in the required proportion. In order to assure uniformity, the molten substance is allowed to cool to room temperature. The mixture is then processed in an extruder to create little pieces of fabric or pellets.

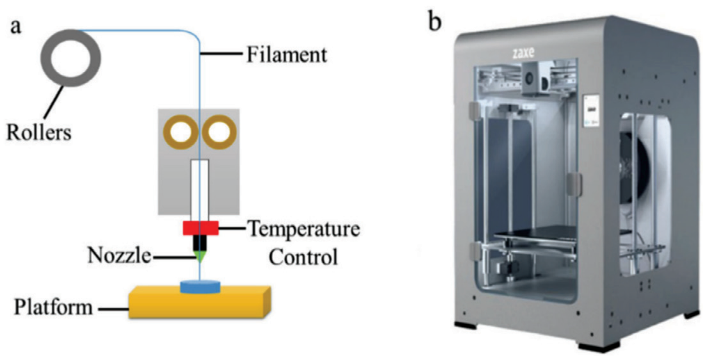


Figure 2: Schematic of the FDM (a) FDM fabrication process image (b) FDM - based 3D printer (Ulkir, 2023)

There are multiple phases involved in the production of filament when an extrusion machine is used. Extrusion starts from the nozzle die hole and continues until the filament is wrapped around the roller machine in the first stage. In this stage, the diameter of the filament that is going to be produced is determined, the extrusion parameters are set up, the material is inserted as a pellet, and the extrusion parameters are set. The process of generating filament is broken down into its component parts in Figure 3.

The pure polymer filaments that are already on the market can be utilised straight away as FDM material. However, because each reinforcement in a composite polymer will result in a unique set of properties, the process of developing composite filaments must first begin with careful study. This is due of the nature of the qualities that will be produced.

Previous Research on LCA of Filament for FDM Applications in the Literature

According to a study by Kumar *et al*., 2022, for filament made from PLA material, six out of eight indicators (climate change, fossil depletion, human toxicity, ozone depletion, terrestrial acidification, and particulate formation) indicate that the recycling phase has the greatest environmental impact (> 50%). Moreover, for PLA filament material, the raw material extraction phase has the highest contribution (65%) to fresh water ecotoxicity and water depletion, whereas its impact is relatively low for the other indicators. The negative impact of PLA's raw material extraction on water-related parameters is the greatest and most distinctive of the three materials. As PLA material is derived from sugarcane, maize and sugar beet, the cause may be related to the extraction process. This process is water intensive so PLA has high impacts on midpoint categories, such as water depletion and freshwater ecotoxicity, which harm freshwater species, and a high value for the endpoint category and ecosystem quality (Morao and Bie, 2019)

On the other hand, the assessment for ABS indicates that, among the three phases of LCA, the recycling phase has the maximum environmental impact (> 50%) for all eight indicators. This is due to the high specific heat of ABS, which causes it to utilize more energy in its recycling phase than in its other two phases. Except for freshwater toxicity, the basic material phase contributes the least to all other indicators. The manufacturing phase has an average relative impact of 15% across all indicators.

ABS material, which is derived from a petroleum-based plastic (Stanzione and Scala, 2016), has the highest environmental impacts of all categories, particularly during the manufacturing and recycling phases, due to its material properties, such as its high specific heat capacity. PETG has the lowest impact on the environment across all parameters. In terms of human health and resource parameters, the effects of PLA and PETG are comparable, with PETG having slightly less of an impact. However, PLA material has a high negative impact on ecosystem quality, only marginally lower than ABS material.

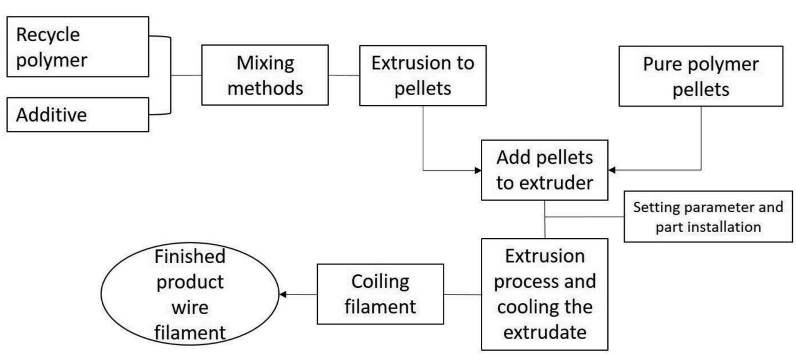


Figure 3: Filament manufacturing process flow (Kristiawan *et al.*, 2021)

KIMYA, a major participant in the industry, has also published an LCA for the 3D PETG filaments their company manufactures. The report concluded that recycled PETG filaments reduce CO_2 emissions by 35% compared to conventional PETG filaments. They are utilizing the LCA methodology to demonstrate their commitment to more sustainable production, as evidenced by the line of recycled filaments that will continue to grow to meet consumer demand.

The literature review demonstrates that utilizing recycled materials for the production of 3D printing filament offers numerous environmental and economic benefits. LCA research demonstrates that one of the benefits is environmental sustainability. Using recycled materials for filament production reduces the demand for virgin resources, such as polymers derived from petroleum. In addition, diverting waste from landfills and reusing it contributes to a more sustainable and circular economy.

Recycling materials for the production of 3D printing filament reduces pollution and promotes the principles of reduce, reuse, and recycle. The plastic detritus can be transformed into useful filament, thereby extending the materials' life cycle. In addition, the production of recycled filament typically requires less energy than the production of filament from virgin materials. This energy savings is a result of the decreased need for new raw material extraction, refining, and processing. The objective of this study is to determine the life cycle performance of Polypropylene (PP) polymer material types as traditional filament types versus recycled PP material reinforced with natural fiber obtained from Kapur wood dust for use in the construction of composite FDM. This study will focus on the environmental impact and energy consumption of new material added to recycled material, as well as the use of natural fiber as a reinforcing material.

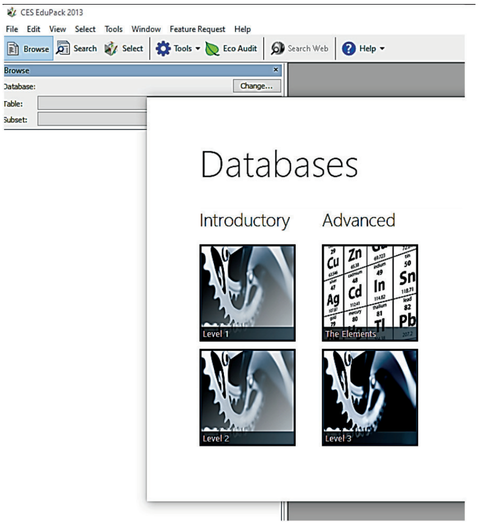
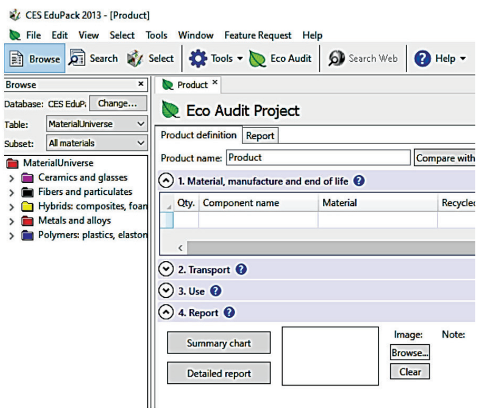
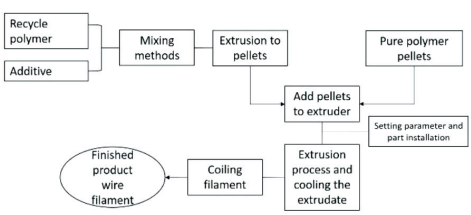
Materials and Methods

LCA for this study utilises CES-EduPack Software from Ansys Granta Design to undertake environmental and human impact analysis in order to achieve this study's purpose. The accessible Eco Audit Tool in the software provides extensive data on eco-properties and an estimate of product costs. The software also improves material processing and end-of-life considerations (Wong Chun Yip, Yusliza Yusuf, 2021). It is a method for minimising environmental effects. In the interim, it enables quick identification of the domain life phases. Using the Eco Audit Tool, a comparison of the substantial influence of various materials will be shown in this study. Before receiving a report from the Eco Audit Tool, it is necessary to prepare the types of materials, manufacturing and end of life, transport, and filament usage. Table 1 demonstrates the overall steps required when utilizing the ECO Audit Tool by CES EduPack software.

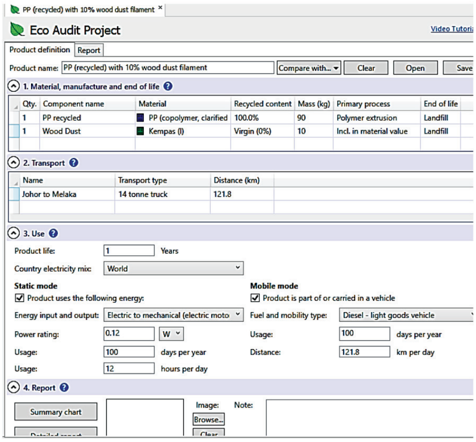
This study identifies Polypropylene (PP) polymer as traditional filament types to be compared with recycled PP material reinforced with natural fibre obtained from Kapur wood dust for use in the creation of composite FDM. For the purposes of this study's analysis, each material's inputted data had the same assumed value and statistics. The inputted figures are based on Malaysia's climate and circumstances. As references, Table 2 explains each data entry in Eco Audit Tool for Life Cycle Assessment (LCA) of PP polymer and Figure 4 shows the result from Eco Audit for PP virgin material in filament production.

The Use phase of the ECO auditing tool is separated into two operational modes: static and mobile. The static mode applies to (usually) immobile products that require energy to function. Examples include electrically powered items, such as electric kettles, refrigerators, and power tools. In the meantime, mobile mode relates to transportation systems, where mass has a significant impact on energy consumption. Utilizing the 'Energy input and output' drop-down menu, the product's energy efficiency is defined. This defines the product's energy conversion efficiency and the environmental impact of its energy source. The energy equivalence and CO_2 footprint values for electric products vary by country of use. The 'Power

Table 1: Methods for utilizing the ECO Audit instruments in the CES EduPack software

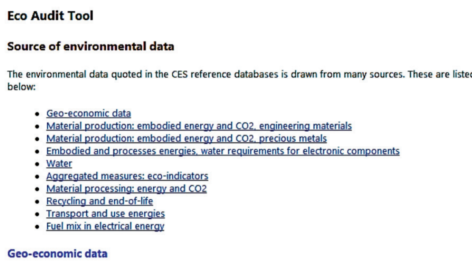
Steps	Software Interface	Explanation
1		Launch the software CES EduPack
2		Access the ECO Audit tools within the CES EduPack. These tools permit environmental impact assessments, including life cycle assessments.
3		Specify the stages of the product's life cycle, including extraction of the basic materials, manufacturing, use, and disposal.

4



Enter the necessary details for each life cycle stage. This comprises the material properties, inputs and outputs of the process, energy consumption, waste generation, and distance travelled. Use the materials and information available in the software database, or submit your own data.

5


Eco Audit Tool

Source of environmental data

The environmental data quoted in the CES reference databases is drawn from many sources. These are listec below:

- Geo-economic data
- Material production: embodied energy and CO2, engineering materials
- Material production: embodied energy and CO2, precious metals
- Embodied and processes energies, water requirements for electronic components
- Water
- Aggregated measures: eco-indicators
- Material processing: energy and CO2
- Recycling and end-of-life
- Transport and use energies
- Fuel mix in electrical energy

Geo-economic data

Run the calculation to determine the environmental effects related to each stage of the life cycle once all the necessary data has been entered. The LCA model and algorithm are included in the software to analyse the supplied data.

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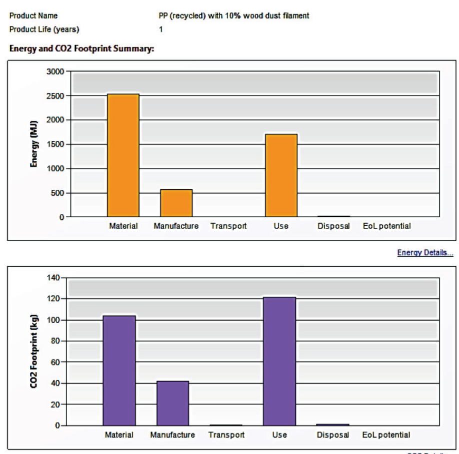

Phase	Energy (MJ)	Energy (%)	CO2 (kg)	CO2 (%)
Material	2.53e+03	52.4	104	38.5
Manufacture	562	11.6	42.1	15.7
Transport	10.4	0.2	0.735	0.3
Use	1.71e+03	35.3	121	45.0
Disposal	20	0.4	1.4	0.5
Total (for first life)	4.83e+03	100	269	100
End of life potential	0		0	

NOTE: Differences of less than 20% are not usually significant.
See notes on precision and data sources.
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The interpretation and reporting of data. Eco Audit Instruments CES EduPack provides LCA studies to comprehend the environmental impacts of a material or product.

Table 2: Explanation of the LCA Eco Audit Instrument for PP filament Material

No.	Eco Audit Criteria	Explanations
1	Material, manufacture and end of life	Opting for Polypropylene Browse the material library's tree to find the following sequences: Polymers > Polymers > Thermoplastics > Polypropylene (PP). Input 100 amount as constant. Set virgin (0%) as the recycled content because the final phase of the material is landfill. The anticipated weight of the substance was 0.002 Ib. Molding of polymers is the primary process. Select a landfill for disposal.
2	Transportation	Using a 14-tonne truck, the distance between the manufacturing site (in Skudai, Johor) and the landfill (in Ayer Keroh, Melaka) in Malaysia is 121.8 kilometres.
3	Use	Material was believed to be available one year after the product's EOL. Asia-based power mix-producing nation. Material is in Static Mode, which prohibits frequent movement or transport. Energy input and output are configured as Electric to Mechanical (Electric Motor), with a power rating of 0.12 kW, 2 days per year, and 24 hours per day for standard extrusion.

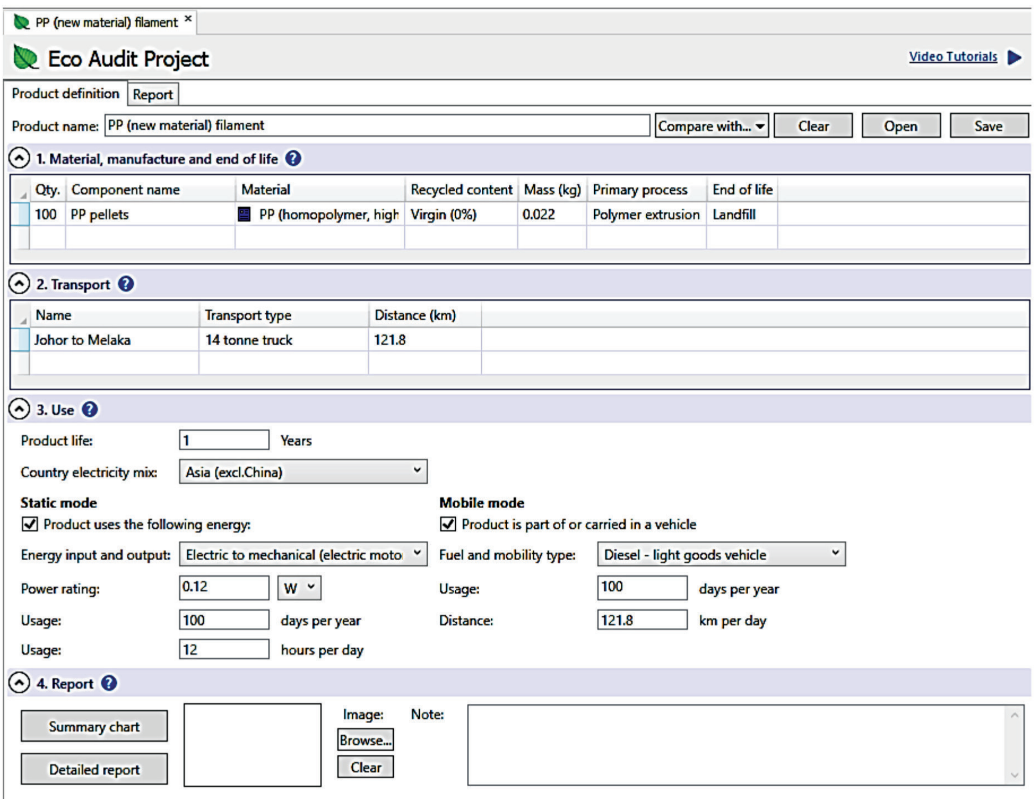

Figure 4: Eco Audit Tool for LCA of PP new material filament

rating' and 'Usage' entries specify the product's power rating and duty cycle. These metrics, in conjunction with the product's efficiency numbers, are used to calculate the static mode contribution, as shown in equations (1) and (2) below:

$$\text{Static use energy (J)} = \text{Power rating (W)} - \text{Duty cycle (s)}. \frac{Energy\ equivalence\ (source)}{Product\ efficiency} \quad (1)$$

$$\text{Static use } CO_2 \text{ (kg)} = \frac{Power\ rating(W).Duty\ cycle(s)}{1 \times 10^6} . \frac{CO_2\ footprint\ (source)}{Product\ efficiency} \quad (2)$$

where:

Duty cycle(s) = Product life (years). Days per year. (Hour per day. 36000)

Results and Discussion

It is the purpose of the eco audit tool to facilitate the capability of product designers to swiftly evaluate the impact that their product has on the environment and offer advice on how to reduce that impact. This is accomplished by concentrating on two environmental stressors that are already well-understood, namely energy consumption and CO_2 footprint, and determining which of the product's five major life stages (material, manufacture, transport, use, and end-of-life) is the most demanding in terms of both of these factors (see Figure 5) (Ashby *et al.*, 2009).

The utilised software (CES EduPack 2011, tool Eco Audit) performs by estimating the energy consumption and CO_2 emissions resulting from the selection of the material and its production, the mode of transportation and travel distance, as well as the energy consumption during the usage phase. This kind of product's energy consumption includes cooling. Figure 6 depicts the results of the eco audit or life cycle analysis. The results of the life cycle analysis will disclose which phase consumes the most energy or generates the most CO_2 emissions. The next stage is to distinguish the contributions of the phases of life, as the action that follows depends on which phase is dominant. If material production is required, selecting a material with minimal embodied energy is the best course of action. But if it is the use phase, selecting a material with a higher embodied energy that is less energy-intensive is the correct strategy.

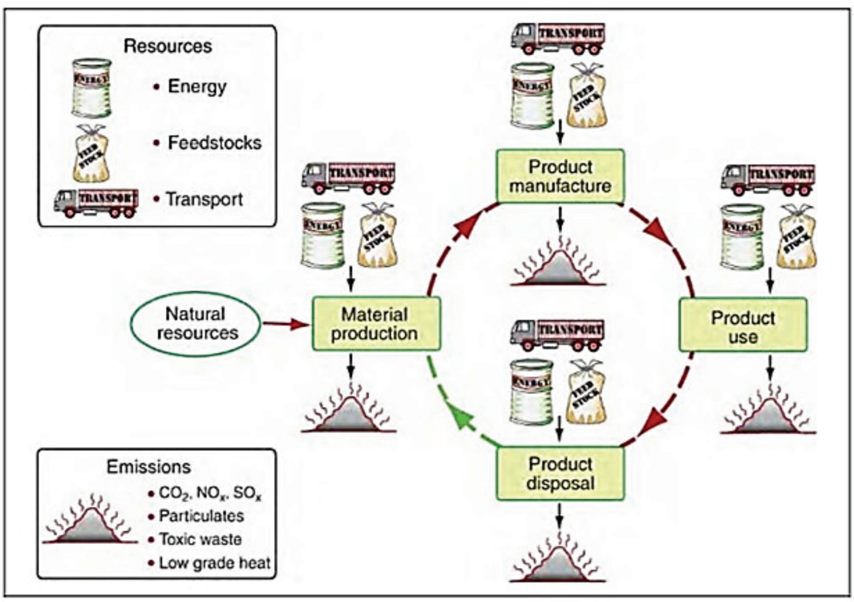

Figure 5: Overview of component lifecycle (Ashby *et al.*, 2009)

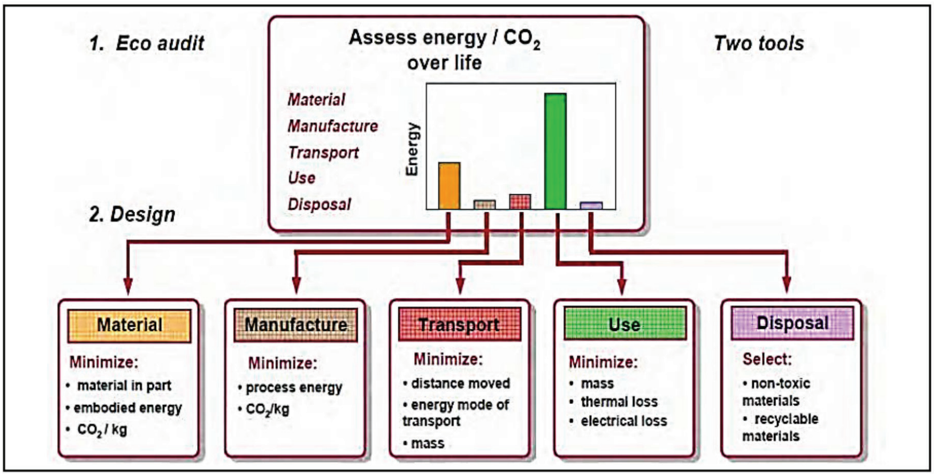

Figure 6: Eco Audit and Eco Design (Ashby *et al.*, 2009)

In this case study, we discussed the utilisation of three different filament types, with data on their life cycles, energy costs and CO_2 production, as shown in Table 3. According to the summary chart provided by the tool (Figure 7), it is clear that the reference PP filament (new material) requires a significantly higher amount of energy to produce during the material and manufacturing phases than the novel composite filament does. This is due to the fact that the amount of energy needed for recycling being far lower than the amount

Table 3: Comparison of energy consumption (MJ) and CO2 generated (kg) by filaments

Energy consumption (MJ) for filaments						
	Material	**Manufacture**	**Transport**	**Use**	**Disposal**	**End of Life Potential**
PP (new material) filament	164	13.6	0.228	39	0.44	0
PP (recycled) with 10% wood dust filament	52.4	12.2	0.228	39	0.44	0
PP (recycled) with 30% wood dust filament	45.8	9.53	0.228	39	0.44	0
CO_2 generated (kg) by filaments						
	Material	**Manufacture**	**Transport**	**Use**	**Disposal**	**End of Life Potential**
PP (new material) filament	4.36	1.02	0.0162	2.76	0.0308	0
PP (recycled) with 10% wood dust filament	1.53	0.919	0.0162	2.76	0.0308	0
PP (recycled) with 30% wood dust filament	1.62	0.714	0.0162	2.76	0.0308	0

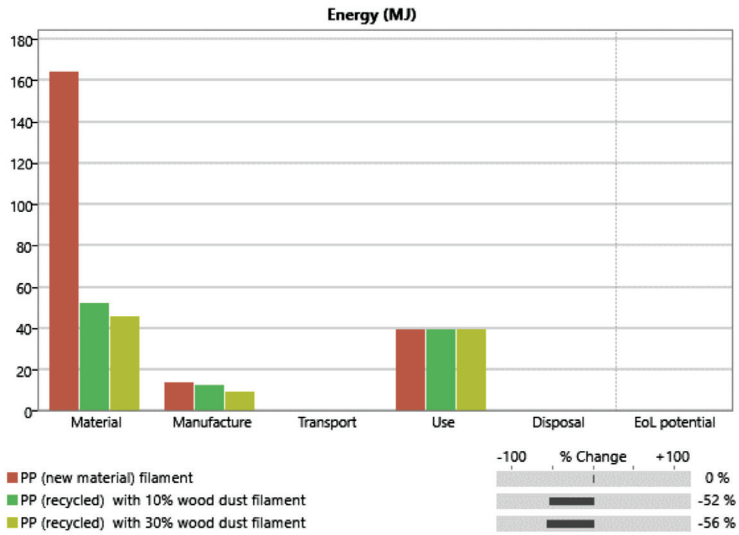

Figure 7: The summary chart of the comparative energy analysis

needed for primary production. The overall difference in energy use is represented by the percentile change that is depicted in grey on the lower portion of the photo. Additionally, a decrease in the amount of energy required can be seen when there is an increase in the amount of wood dust utilised as a reinforcement element in the composite filament.

Figure 8, a chart produced by the tool, demonstrates that the CO_2 Footprint of the reference PP filament is greater than that of the new composite filament over both the materials and manufacture life phases. This is due, once more, to the additional requirements placed on the production of the new PP materials. The overall difference in CO_2 Footprint between the products is represented by the percentile change that is depicted in grey in the lower portion of the image.

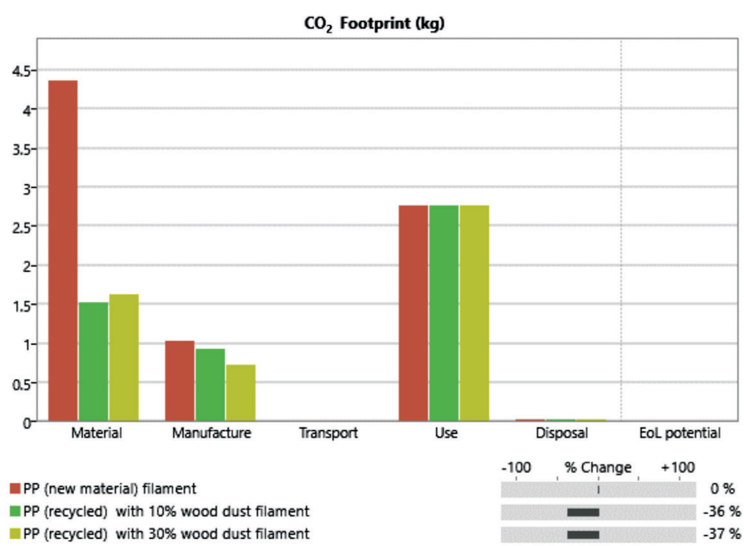

Figure 7: The summary chart of the comparative energy analysis

Figure 8: The summary chart of the comparative CO_2 footprint analysis

Furthermore, when compared to the new polypropylene material used to make filament, this study found a 56% and 37% reduction in energy usage and CO_2 emissions, respectively, demonstrating a significant improvement in terms of environmental impact. The use of recycled Polypropylene material combined with recycled wood dust from industrial waste may provide a new alternative choice for environmentally safe filament materials for future FDM technologies.

Compared to conventional raw materials, distributed recycling uses less energy, according to other LCA studies on recycled 3D printing filaments. It is expected that the recycling rate will rise from its current level as awareness of the economic benefits of manufacturing 3D filament from recycled materials spreads. For instance, according to Kreiger *et al*. (2014), LCA research revealed that recycling post-consumer HDPE for 3D printing filament uses less embodied energy than the best-case scenario for a city with a high population density utilizing fresh virgin material. More than 100 billion mega joules (MJ) might be saved annually in the United States if the entire HDPE supply was recycled utilizing the recycling technique, offsetting all virgin HDPE (Kreiger *et al*. 2014). Ulkir (2023) also noted that the recycling stage in LCA had the greatest environmental impact for all types of materials (ABS, PLS, PETG, and UV resin). They demonstrated lower material and energy usage, particularly when compared to earlier manufacturing devices. Due to the commercial PP filament utilized for the comparison, this study presents a traditional estimation of the benefits of the recycling process. In this study, natural fiber was used, which is a typical technique to improve the mechanical qualities of the printed product. Along with better structural integrity and longevity, 3D printed objects manufactured from this composite type of filament are suited for applications that call for higher performance (Deb and Jafferson 2021).

Granta Design's CES EduPack is predominantly utilized in engineering and design education for materials selection and eco-design. Although CES Edupack includes a simplified LCA module, it is important to note that it may not offer the same level of comprehensive analysis and functionality as other LCA software tools. Dedicated LCA software applications typically provide a more exhaustive database that includes material properties, process data, and environmental impact factors. These tools provide a wider array of impact assessment methods, enabling users to evaluate a variety of environmental categories, such as climate change, resource depletion, and toxicity, among others. Additionally, specialized LCA software typically provides greater modelling latitude and customization options for complex systems. They allow the user to define system boundaries, designate inputs and outputs, and model multiple life cycle stages in great detail. CES EduPack's LCA module may be more focused on providing simplified assessments and may have customization restrictions.

Conclusion

Life cycle assessment (LCA) is an efficient method to determine how a composite material affects the environment over its whole life. Because of this, it is important to the composites industry, especially for FDM (fused deposition modelling) filament manufacturers as a tool for choosing materials when figuring out if recycled materials can be used in the design phase of a component. This article looks at the LCA framework for using wood dust as a reinforcement material and recycled polypropylene to make composite filament for the FDM sector. Using recycled polypropylene with a higher percentage of wood dust to make new types of composite filament materials reduces the amount of energy used (MJ) and the amount of carbon dioxide released into the atmosphere (CO_2) (kg). This is because the amount of energy needed to recycle is much less than the amount needed to make something from scratch. Compared to the new polypropylene material that is used to make filament, this study shows that energy use and CO_2 emissions are both 56% and 37% lower. From an environmental point of view, this is a big step forward in FDM filament making.

Acknowledgements

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