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Evaluation of the Circularity of Recycled PLA Filaments for 3D Printers

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Featured Application: 3D printing.

Abstract: The circular economy model offers great opportunities to companies, as it not only allows them to capture additional value from their products and materials, but also reduce the fluctuations of price-related risks and material supply. These risks are present in all kind of businesses not based on the circular economy. The circular economy also enables economic growth without the need for more resources. This is because each unit has a higher value as a result of recycling and reuse of products and materials after use. Following this circular economics framework, the Polytechnic University of Madrid (Universidad Politécnica de Madrid, UPM) has adopted strategies aimed at improving the circularity of products. In particular, this article provides the result of obtaining recycled PLA filament from waste originating from university 3D FFF (fused filament fabrication) printers and waste generated by "Coronamakers" in the production of visors and parts for PPEs (Personal Protective Equipment) during the lockdown period of COVID-19 in Spain. This filament is used in the production of 3D printed parts that university students use in their classes, so the circular loop is closed. The obtained score of Material Circularity Indicator (MCI) of this material has been calculated, indicating its high level of circularity.

Keywords: 3D printing; circular economy; PLA filaments; recycling

1. Introduction

The set of metrics that establishes how effective a company is in making its way from "linear" to "circular" is still under development. The Circularity Indicators Project (CIP) [1] aims to develop indicators that will identify how well a product performs in the context of a circular economy. The methodology covers all the scene in the life cycle of the product such as material flows and a variety of complementary indicators (additional impacts and risks) that make it possible to estimate the degree of progress in this transition in terms of products and materials. The most significant indicator is called Material Circularity Indicator (MCI). This indicator measures how restorative and regenerative the material flows of a product or company are.

Decision-making models are used based on circular economy indicators and then can be suitable for other purposes such as internal reporting, procurement decisions and the evaluation/scoring of companies.

The CIP offers support to the designer decisions toward the circularity and helps them in the assessment for the implementation of a business model based on the circular economy.

The CIP is centered on quantifying material flow restoration and developing the MCI [2]. The MCI represents the degree of circularity of a product. The Circularity Indicators let us analyze to what extent the use of material in a product maximizes the restorative flow, as represented in the MCI.

The current model of linear economy generates high levels of waste and creates dependence between economic development and the entry of new virgin materials into the system. It is estimated that between 7000 and 10,000 million tons of waste are generated annually [3]. In a world of limited resources, this model cannot be sustained in the long run and there are already signs showing that it is reaching its limits.

Circular economy is based in the regeneration of the components and materials. It uses the waste as a participant in the manufacturing process so decreases the use of virgin materials. Circular economy distinguishes two different cycles: a biological cycle, which the waste returns to regenerate the natural systems, and a technical cycle, which the materials, parts and components are kept in flows that regenerate other products or systems increasing their time in the market as much as possible. In the technical cycle, materials and components can be repaired, reused, reconditioned, and finally recycled. Figure 1 represents the previous cycles in the diagram of circular economy systems. This picture is also known as "Ellen MacArthur butterfly diagram" and shows in green color the biological cycles and in blue color, the different technical flows.

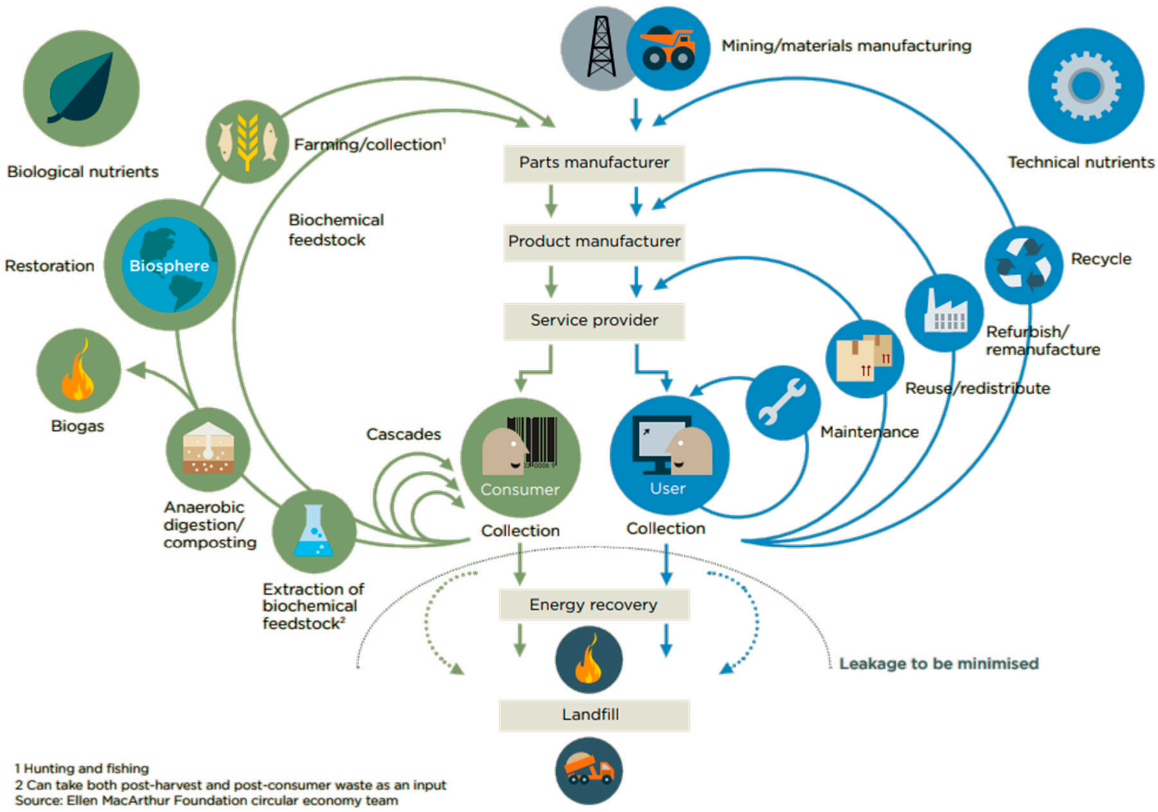


Figure 1. Cycles in Circular Economy. Source: Ellen MacArthur Foundation [4].

2. Scope and Objectives

This paper focuses on the product level. There are indicators to measure the circularity of departments, companies, or organizations but they are out of our scope.

Indicators help companies to classify and compare their products inside this new circular framework. In addition, it also becomes a criterion in the design processes. New products should become more and more circular (Figure 2). Finally, indicators help to position a band or a company inside the circular economy.

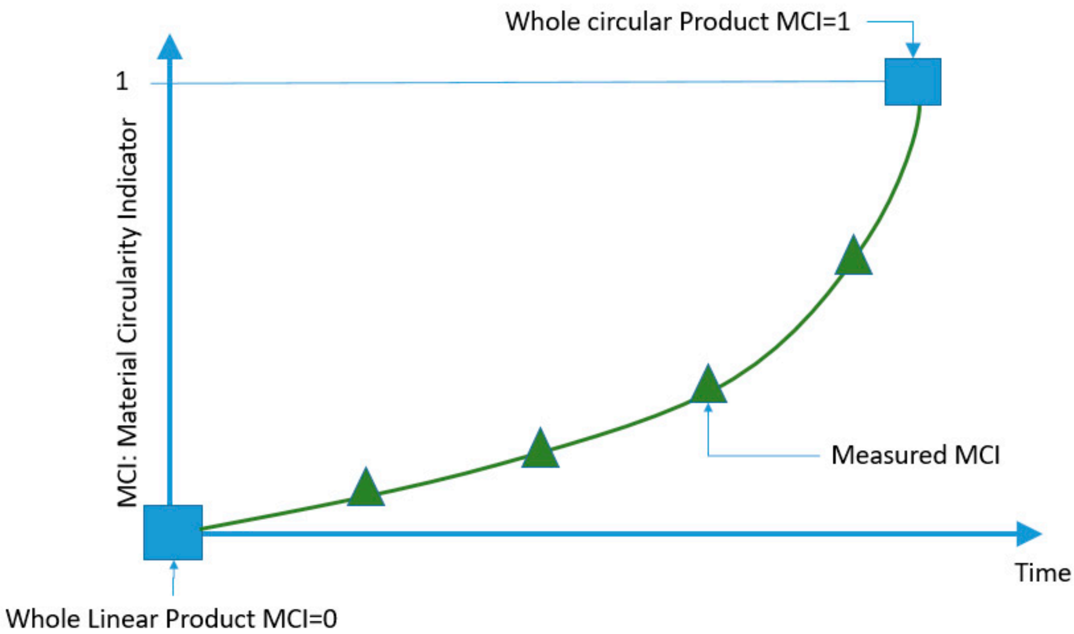


Figure 2. Transition towards Circularity.

The MCI focusing on restoring the material of the flows at the product and company level is based on the following six principles:

1. Biological materials should come from sustainable sources.
2. Use feedback from recycled or reused sources.
3. Keep the goods in use longer (reusing, redistributing, increasing durability).
4. Reuse recycled components or materials after use
5. Intensive use of the products (via service, sharing or performance models).
6. Biological materials should remain biologically accessible and uncontaminated.

With this scope, improving the MCI of a product or company does not necessarily mean improving the circularity of the whole company or system. However, an extended use of this methodology could be part of such improvement.

The highest value proceeds from reusing components that keep all the functions and performances and are more valuable than recycled materials. MCI includes a factor representing the efficiency of the recycling process, while reuse is assumed to be 100% efficient.

The debate is whether products are more circular if used for longer periods of time, even if they end up in landfill after use. The circular economy encompasses initiatives that can create a significant impact on material use, and case studies have shown that an increase in shelf life or greater intensity of use leads to substantial material savings (such as in reusable bottles). Longer lifetimes also allow for repair, reuse and/or resale (such as refillable products and second-hand stores) and are therefore correlated with the idea of increased circularity (Figure 2).

In the development of MCI, the proportion of the product that is restored through component reuse and recycling (principles 2 and 3) and comes from recyclable and reusable sources is described as the restorative part, while the linear part of the flow refers to the proportion coming from virgin raw materials and ending up in landfill (or energy recovery).

Principles 4 and 5 are treated as improvements in utility, an additional component in the calculation of MCI that depends on the linear part of the flow. The addition of biological materials to this methodology has required the introduction of principles 1 and 6. The first principle aims to ensure that the extraction of renewable materials from biological sources does not exceed the replenishment capacity of those materials by those sources. It also attempts to go further and regenerate natural systems. The sixth principle seeks to ensure that at the end of the life of biological materials, the nutrients they contain are returned usefully to the natural environment in a way that does not compromise the future ability of that source to create new materials.

The MCI indicates how much of the materials that make up a product are circular, but it does not consider what materials they are or provide information on other impacts. Therefore, this methodology recommends using the MCI together with a group of complementary indicators. These indicators have been developed at the product level.

MCI has the following differences and similarities with Life Cycle Assessment (LCA) methodologies. MCI is related of the use of materials throughout use. MCI aims to reuse or recycle materials or components so that we can increase the durability and the intensity use of the product. In the side, LCA is focused on the environmental impacts throughout the product life cycle for different scenarios. MCI uses similar input data than LCA and probably in a short future MCI would be included as a parameter on an LCA.

3. Development of the Methodology

This methodology serves to calculate the MCI of products and companies with technical and/or biological materials. The original 2015 version that only considered technical materials was published by the Ellen MacArthur Foundation and Granta Design after a two-year project. This project was co-financed by the European Commission and supported by around thirty organizations, including investors, regulators, consultancies, and universities. At that time, the circular strategies and associated business benefits of technical cycles were better understood than those of biological alternatives. A group of pilot companies participated in the development of this version to test the methodology using real data. The iterative testing process was carried out over five phases and included both classroom and virtual workshops.

In 2019 the methodology was updated by ANSYS Granta [5,6] using data from several leaders in circular economy from the Ellen MacArthur foundation's CE100 network, who are leading the transition to circular economy. The new version includes analysis of biological materials and energy recovery. This significant advance allows the inclusion and proper evaluation of all types of materials. Grants Design has developed a commercial data base tool that helps to measure circularity.

4. Product Level Methodology

The MCI takes a value between 0 and 1, with the highest values indicating high circularity. Going into more detail, the following entries are used to calculate the MCI:

- The inputs to the production process—how much comes from virgin materials and how much from recycled materials and reused components?
- Utility during the use phase—how long and how intensive is the product used compared to the average in your industry? This considers the increased durability of the goods and the business models of repair, maintenance, and shared consumption.
- Destination after use—how much material ends up in landfill (or is destined for energy recovery), how much is collected for recycling and which components are collected for reuse?
- Recycling efficiency—how efficient are the recycling processes used to produce recycled material inputs and the processes to recycle material after product use?

The MCI is built with a combination of three product characteristics: the mass V of virgin material used in its manufacture, the mass W of its unrecoverable waste, and the utility factor X that reflects the intensity and duration of its use. Any good manufactured using only virgin raw materials and ending up in landfill at the end of its life is considered completely "linear" (MCI = 0). On the other hand, anything that does not contain virgin raw materials and is completely collected for recycling or reuse of components and where the recycling efficiency is 100%, can be considered completely "circular" (MCI = 1). In practice, products will be between these two extremes and the MCI assigns a value to their circularity between 0 and 1. Figure 3 summarizes the material flows associated with technical materials.

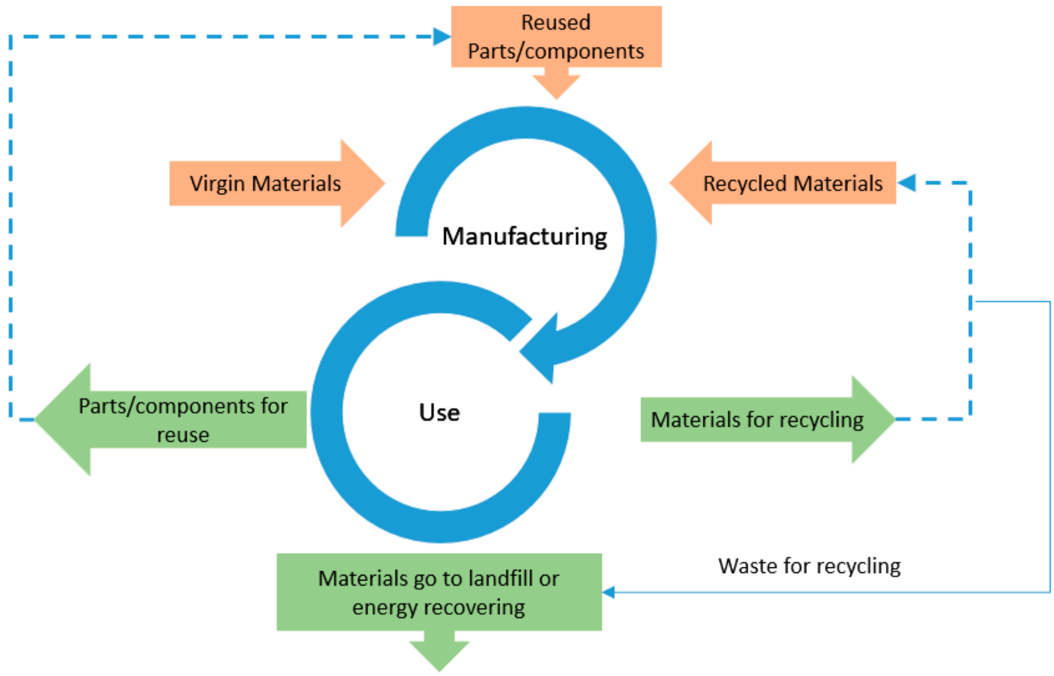


Figure 3. Material flows of technical materials Circularity Indicators Methodology.

The dashed lines in the Figure 3 indicate that this methodology does not necessarily require a closed loop. This means that, for example, the recycled raw material does not have to come from the same product but can be found on the open market. The methodology is therefore based on the mass flow of the system, i.e., the calculations do not vary depending on whether it is an open or closed loop.

It should also be noted that the material flows in the Figure 4 are directly associated with those materials that end up being part of the final product. There will be additional material flows such as waste streams that take place during the manufacturing process.

In most cases, it is expected that the MCI will be calculated using detailed component and material information. However, to explain the mathematical formulas used in a simpler way, the derivation of the MCI formula will first be explained using a view of the product without differentiating its different materials and components. Later, the explanation will be adapted by incorporating the consideration of the different components and materials in a more comprehensive view.

A study has been carried out as an example of the MCI methodology. For this, the MCI of an ETSII-related product has been measured. It is about the parts printed with 3D printers inside the project named 'CircularizatE' of the ETSII College. These parts are going to be manufactured in common 3D FFF printers with filaments of 1.75 mm of diameter made of a mixture of virgin PLA (Polylactic acid, a thermoplastic) and recycled PLA. The afore process is depicted in Figure 4.

For this, the ETSII College has bought three machines: a shredder, a dryer, and an extruder with a puller. These machines are used in this project to generate sustainable PLA (a mix between virgin and recycled) filaments that can be used in 3D printers and therefore close the loop for the PLA plastic. Our lab works as a sink of PLA coming from of some companies and Coronamakers. Coromakers is an informal association of makers that produced parts for sanitary uses (PPE, masks, visors, ventilators components, etc.) through 3D printing with PLA during the COVID-19 crisis. Coromakers let us have enough PLA waste to start our investigation. All PLA waste are classified by color (Figure 5a). After the PLA waste are shredded to get small granules (Figure 5b) and dried for three hours to eliminate moisture (Figure 5c).

Finally, the extruder warms and melts the granules and push them through a calibrated dye head so we can obtain a filament of 1.75 mm diameter. The puller helps us to coil the filament in the spools (Figure 5d). The filament is distributed in the spools of the virgin PLA filaments (Figure 6).

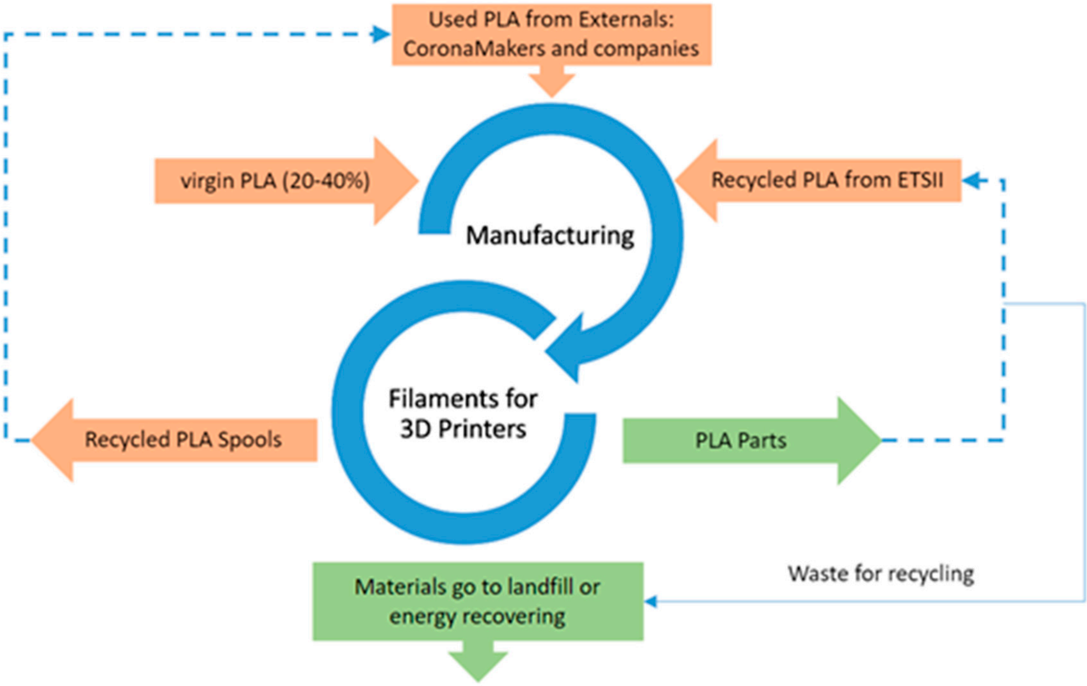
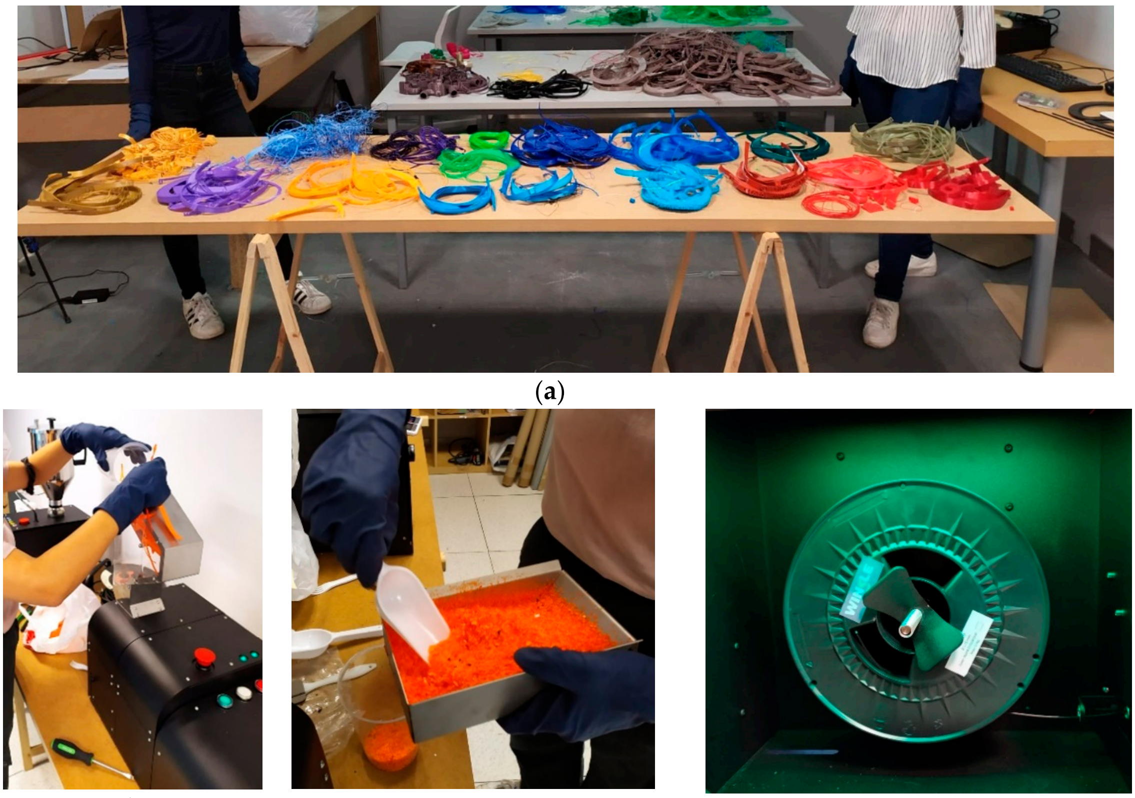


Figure 4. Materials flow for recycled filaments for 3D printers.



(**a**)

(**b**) (**c**) (**d**)

Figure 5. Manufacturing process of recycled PLA. (**a**) Color Classification; (**b**) Shredding; (**c**) Dried granulates; (**d**) Coiling the extruded filament.

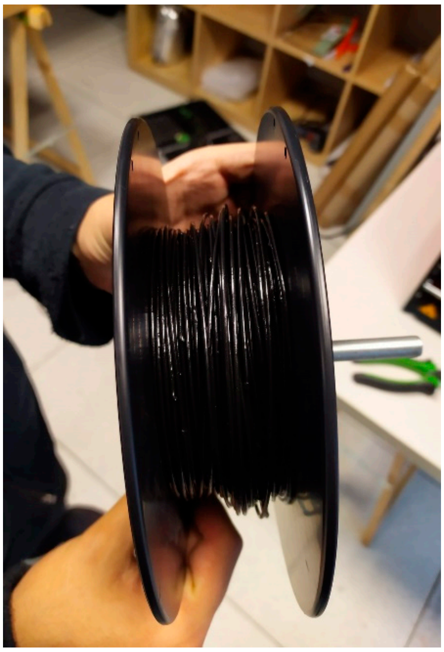


Figure 6. Recycled PLA Filament.

5. Input Data

This methodology is designed to be used in conjunction with data representative of the products of what happens in the market. The model input data should be based on the knowledge of the good being analyzed. Where the information is not known, generic industry data or the most accurate approximations should be used.

While this methodology can be used in predicting alternative scenarios by guiding the design and setting circularity objectives, the design data are not used to calculate the MCI of an actual product. For example, a product may be 100% recyclable or 100% reusable, but the actual recycling or reuse rates should be used in the calculations. Similarly, in the case of a product that is designed for a longer life than it actually experiences, the actual lifetime is considered in the calculations and not the lifetime for which it was designed.

6. Life Time

Industries are expected to have information about the lifespan L and the functional units U that their products provide. U symbolizes the number of functional units achieved on average during product use, and U_{av} is the number of functional units achieved on average in the industry. They can get this information from the quality tests they perform and from the data provided by customers (such as return and repair rates). The average lifetime in the industry L_{av} is more complicated to establish, although estimates can be made by knowing the penetration and size (in relation to annual sales) of the market. The utility X has two components: one to represent the length of the product usage phase (L) and one for the intensity of use (U). These two components combine to find the utility X:

$$X = \frac{L}{L_{av}} * \frac{U}{U_{av}}$$

If L/L_{av} cannot be estimated, then $L/L_{av} = 1$ will be considered giving the functional units more influence on the utility X. Similarly, if U/U_{av} could not be estimated, it would be taken as $U/U_{av} = 1$, giving more importance to L/L_{av} in the calculation of utility X, in general only L/L_{av} or U/U_{av} will be used, not both.

One way to increase the MCI of a product is through shared use, as this increases its usefulness. To calculate the number of functional units U of a shared good, we will use the average of functional units per client U_r and the total number H of different people using the product, according to $U = H{\cdot}U_r$.

In the case of consumables, these usually have different lifetimes than the products to which they are related. This is the example of printer cartridges (consumables) and the printers (products). Therefore, it is advisable to calculate an MCI for the consumable and another for the product.

7. Impact on Profitability

As mentioned above, a circular economy has significant benefits related to business profitability (resource savings, lower costs, higher revenues due to new markets and opportunities). The profitability of a circular initiative depends on several factors and, in general, there will not be a simple correlation between the MCI obtained and the profitability of the product.

The Ellen MacArthur Foundation, in its MCI methodology, suggests four strategies for earning higher incomes. The first consists of resale and extension of the period of use. The foundation believes that this is the strategy that can have the greatest impact on profitability due the complexity and integrity of the product is preserved. This strategy manages to increase income and reduce costs by accessing new markets, carrying out maintenance and repair operations, and offering more expensive but higher-yielding alternatives.

Reconditioning [7] is the second strategy. This consists of repairing or replacing the parts of a product that have stopped working or for which updates are available. Products can be sold as new after this process. Great savings and revenue are generated with this strategy since it manages to preserve most of the product's integrity. The design stage is critical to this strategy.

When reuse or repair is not possible, go for recycling (third strategy). This is not as profitable as the previous strategies since neither complexity nor integrity is preserved, but it generates great savings and new income (depending on whether the recycled material is used in the same system or sold to third parties). Product design should be done in such a way that its components and materials can be easily separated.

Finally, the adaptation of service and performance models is also suggested as a strategy to increase profitability. These include rentals, leasing, pay-per-use models (such as self-service laundries) and services including maintenance, repairs, and future upgrades. Through these actions, a higher market value is captured.

8. MCI Calculation

The objective of this study is to find the approximate MCI of a 3D printed part for educational use (parts to explain mechanical assemblies to students) with this mixture of virgin PLA and recycled PLA, using approximate data required for its calculation, already explained in the methodology at the product level of the MCI. It is not intended to produce a report like that which would be obtained through the MCI process via the Ellen MacArthur Foundation. This study only aims to calculate the MCI of the product, without considering complementary indicators or analysis of components and materials.

The following considerations have been made:

- The average mass of the part is 73 g, then M = 73 g.
- A part is only made of PLA plastic, 70% of which is recycled and 30% is virgin material ([8,9] recommend using 20–40% virgin PLA so as not to alter the quality of the pieces obtained). Therefore, the fraction of the $\mathrm{F_r}$ feedstock that comes from recycled material is $F_r = 0.7$. This makes $V = M{\cdot}(1 - F_r) = 21.9$ g.
- It is considered that the fraction of the product that can be recycled C_r is 99% (1% is removed because of defects due to blows and similar actions that can make a piece detach part of material). Therefore, the amount of unrecoverable waste from a piece is $W_o = M{\cdot}(1 - C_r) = 0.73$ g.

- The efficiency of the E_c recycling process has been estimated at 95%. Thus, the waste from the recycling process is $W_r = M \cdot C_r \cdot (1 - E_c) = 3.61$ g.
- A 2% loss has been assumed in the process of creating the filaments formed by recycled PLA and virgin PLA. This is an estimated value, due that some PLA waste is burnt and some granulates are drop off. That is, the efficiency of the process of creating recycled raw material E_f is 98%. Therefore, $W_f = M \cdot F_r \cdot (1 - E_f)/E_f = 3.61$ g.
- As for the utility X, due to the difficulty of measuring the utility (lifetime or functional units) of the 3D parts with respect to others of equal measures, it has been chosen to consider the utility $X = 1$. That is, the lifetime of the part and its functional units are the same as those of parts of the same dimensions manufactured with other printers and similar materials. If the printer's MCI were to be measured, the number of parts printed per year could be used as the functional unit. We assume that we can print 4000 units/year. Therefore, we get $U = U_{av} = 4000$. Therefore, $X = U/U_{av} = 1$.

Both the efficiencies and the percentage of recycled material (R_c) are very high because it is a highly recyclable material (PLA). Almost 100% of the final product is used that is observed in an experimental way. Since the final product is made only of PLA, it can be converted back into PLA filaments for new parts. Even shavings and chips can be converted to PLA filaments. However, considering efficiencies of 100% and material losses of 0% seems utopian and ideal. Therefore, these small losses have been considered in the recycling process. This means that the actual result of the MCI will surely be better than the one obtained in this first study carried out in a conservative way.

With W_o, W_c, and W_f, you get W (the waste mass of the system), used together with W_c, W_f, V and M to calculate the LFI (Linear Flow Index). With the utility X (assumed to be equal to the unit) and the LFI, MCI* is calculated. As the LFI can be negative, the MCI will be the maximum between 0 and MCI*.

As shown in Table 1, using the formulas explained in the methodology at the product level of MCI, the score obtained was an MCI of 0.84 (out of 1).

Table 1. Study of the circularity of a 3D part made with recycled PLA based on the EMF MCI method.

<table>
<tr><th colspan="2">Entry Values</th><th colspan="8">Calculated Variables</th></tr>
<tr><td>M</td><td>73</td><td>M</td><td>73</td><td rowspan="5">LFI
$\frac{V+M}{2M+\frac{W_f-W_c}{2}}$</td><td rowspan="5">0.17</td><td rowspan="7">MCI*
$1 - LFI * \left(\frac{0.9}{X}\right)$</td><td rowspan="7">0.84</td><td rowspan="7">MCI
Max(0; MCI*)</td><td rowspan="7">0.84</td></tr>
<tr><td>V</td><td>21.9</td><td>V</td><td>21.9</td></tr>
<tr><td>W_0</td><td>0.73</td><td rowspan="3">W
$W_o + \frac{(W_f+W_c)}{2}$</td><td rowspan="3">3.06</td></tr>
<tr><td>W_c</td><td>3.61</td></tr>
<tr><td>W_f</td><td>1.04</td></tr>
<tr><td>U</td><td>4000</td><td rowspan="2">X
(U/Uav)</td><td rowspan="2">1</td><td rowspan="2">X</td><td rowspan="2">1</td></tr>
<tr><td>U_{av}</td><td>4000</td></tr>
<tr><td>E_c</td><td colspan="4">Efficiency of the recycling process</td><td>95%</td><td rowspan="5" colspan="4">M: Mass of product
V: Virgin Mass
W_o: Amount of unrecoverable waste
W_c: Waste of recycling process
W_f: Waste of creating recycled materials</td></tr>
<tr><td>E_f</td><td colspan="4">Efficiency of the process of creating recycled raw material</td><td>98%</td></tr>
<tr><td>C_r</td><td colspan="4">Fraction of product that can be recycled</td><td>99%</td></tr>
<tr><td>F_r</td><td colspan="4">Recycled Feedstock</td><td>70%</td></tr>
<tr><td>V</td><td colspan="4">Fraction of virgin material</td><td>30%</td></tr>
</table>

On the other hand, as the production of parts using these filaments is not yet in operation, 70% has been taken as the percentage of PLA recycled in the filaments. In order not to affect the quality of the pieces, it is recommended to use a F_r between 60% and 80% [9]. Therefore, the following graph (Figure 7) has been made to compare the MCI obtained according to the Fr used, including cases that are outside this range, such as the case in which the F_r is 100%. It should be remembered that by varying the F_r, one also varies V (since $V = 1 - F_r$) and, therefore, the LFI (thus varying the MCI).

As shown in the graph above, there is a linear relationship between F_r and MCI. As is logical, the higher the F_r, the higher the MCI, since virgin raw materials V decrease, making the product more circular and sustainable. It can be seen that the MCI for F_r = 100% is not the unit, but 0.98. This is since in the study carried out neither efficiencies nor R_c are 100%, considering minimal material losses due to shocks or similar actions.

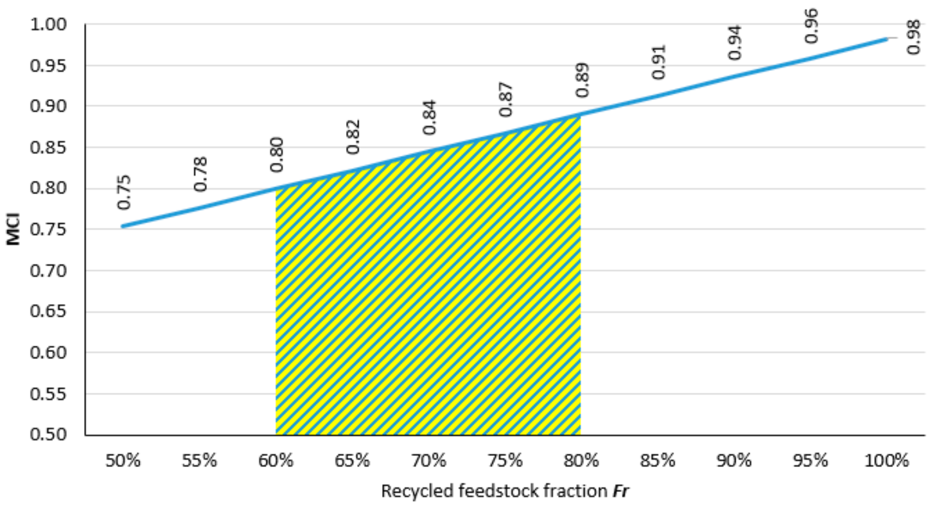


Figure 7. Relationship between the recycled feedstock fraction F_r and the MCI in the studied 3D part. The recommended area for a piece of sufficient quality has been shaded.

In calculating the MCI in this case study, it has become clear that these calculations do not consider the amounts of other resources used such as energy (in this case) or materials that facilitate manufacture (such as lubricants). This could be a line of improvement for future versions of the MCI tool.

9. Discussion

This methodology makes several assumptions:

- The MCI does not explicitly favor closed loops. This means that, for example, the recycled material of a good does not have to be returned to the original manufacturer of the good. However, it is true that closed loops have a higher MCI because they have higher efficiencies in the recycling processes and because they enable the reuse of components.
- It is assumed that the material recovered after the life of the product can be used with the same quality as virgin raw materials (no under-recycling).
- It is considered that there is no loss of material in the collection of components for reuse.
- Material losses during the use phase are neglected. This means that the mass is not considered to change from manufacture to the end of life.
- Material losses in the supply chain are neglected because they are difficult to establish.

If the current amount of recycled raw materials is unknown, the regional average values or, in their absence, the global ones should be used. This data can be obtained from various sources such as: the Inventory of Carbon & Energy (ICE) published by the University of Bath [10], the Life Cycle Data Network (LCDN) [11] or the U.S. Life Cycle Inventory (LCI) Database published by the National Renewable Energy Laboratory (NREL) [12].

When collection data for recycling is unknown, known data from the same industry sector will be used. Some goods are subject to legal restrictions regarding the collection of materials and components for recycling. This will facilitate access to this information. It should be noted that collection rates for recycling may be influenced by the prices of virgin raw materials.

The efficiency of a given recycling process for a particular material will depend on the type of material (metals, for example, are easier to recycle), the amount of material processed (the more material, the easier it is to recycle) and the presence of contaminants (they make recycling difficult). It is also convenient to separate the product into all its different materials and components before recycling. Each material and component will be destined to different recycling processes with different efficiencies. When the efficiency rate of a recycling process is unknown, a generic value will be used. Efficiency rates vary constantly with time and demand. However, these values can be obtained from sources such as the European Integrated Pollution Prevention and Control Bureau (EIPPCB) Best Available Techniques Documents [13] or the Waste and Resources Action Program (WRAP) [14].

This methodology does not consider downcycling [15], which refers to a recycling process that reduces the quality and economic value of the material/product, or upcycling, which does the opposite. There are, however, requirements to be met by recyclable materials. In order to consider a material as recyclable, it must be able to be previously separated into the different materials that make it up, unless the unseparated mixture is input to a manufacturing process, in which case this mixture is also considered recyclable. If this is the case, then the mixture will be considered recycled raw material.

This methodology is designed to be used in conjunction with data representative of the products of what happens in the market. The model input data should be based on the knowledge of the good being analyzed. Where the information is not known, generic industry data or the most accurate approximations should be used.

While this methodology can be used in predicting alternative scenarios by guiding the design and setting circularity objectives, the design data are not used to calculate the MCI of an actual product. For example, a product may be 100% recyclable or 100% reusable, but the actual recycling or reuse rates should be used in the calculations. Similarly, in the case of a product that is designed for a longer life than it experiences, the actual lifetime is considered in the calculations and not the lifetime for which it was designed.

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