Product Circularity Assessment Methodology

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Abstract. In today's dynamic economic environment, industry is facing global challenges such as meeting the needs of a growing population, resource scarcity and landfill space shortage. These issues highlight the need for a dramatically more efficient use of natural resources to create social and economic value for society while respecting the carrying capacity limits of the planet. Additive manufacturing technologies provide opportunities to support sustainable manufacturing and the circular economy paradigm. These opportunities can be leveraged throughout the product lifecycle: energy and material consumption reduction in manufacturing, lower material use through maintenance, reuse, remanufacturing and recycling. Despite these benefits being more broadly recognised in recent years, industrial applications are still scarce. This work proposes a quantitative methodology to assess the circularities arising along the lifecycle of a product fabricated with additive manufacturing technologies, thereby supporting the shift to more circular industrial systems and sustainability.

Keywords: Circularity · Assessment methodology · Additive manufacturing

1 Introduction

1.1 Background

This research investigates the role of advanced manufacturing technologies in the digital revolution era which hold the promise of shaping the factories of the future [1]. The digital world is becoming an integral part of industrial systems and of our society, and is enabled by new technological developments such as Additive Manufacturing Technologies (AMT). ASTM international defines Additive Manufacturing (AM) as a fabrication process used to build physical objects, starting from 3D computer-aided design (CAD) file and by adding material layer upon layer until the final object is completely formed [2].

Advances in science and technology are increasing our ability to deal with new threats and challenges facing industry and society. New discoveries and technological inventions contribute to the evolution and betterment of our society, but also result in unintended impacts on natural resources' availability (consumption rate is currently faster than regeneration cycles) and the surrounding environment (pollution, waste and toxicity from industrial activities). Uncontrollable ecosystem changes, increasing consumerism and irresponsible use of virgin materials lead to natural resource depletion and to dangerous, irreversible environmental damages, affecting the economy and society at large. Therefore sustainability is an essential prerogative to ensure the stability of economic systems and natural ecosystems within which industries are operating.

Beside technology innovation, manufacturing companies need to compete in a responsible manner by addressing all three pillar of sustainability (economic, environmental and social) [3]. In recent years, financial and environmental crises have caught the attention of many world governments. Furthermore, acceleration in global growth and the gap between the world leading and developing countries creates an imbalanced environment for competition. In this context, traditional models for the economic development have proven to be unsustainable and the growth trend characterizing the last century is not feasible anymore. Over this period, the world population has increased by a factor of 4, the economic product by 40, and the use of fossil fuels by 16. On the one hand, this growth led to developed countries' rise in wealth and prosperity. But on the other hand, it has produced negative consequences on the environment, dangerous economic discrepancies between the richest and the poorest members of society, and an unfair access to resources by the wealthiest countries over the rest of the world.

Industry and society need to change the way it operates by undertaking intelligent and integrated actions to enable long-term development while respecting human values and natural resources. In other words, we need to ensure human continuity through responsible monitoring of our impact on the ecosystem and sustain economic growth. The circular economy paradigm has been emerging among other economic philosophies as it pursues the goals of economic, social and environmental sustainability [4].

1.2 Circular Systems and Circular Economy

Circular systems provide a value-creation mechanisms decoupled from resources depletion. This can be supported by the creation of a sustainable model able to better capture and maintain the value embedded in resources while avoiding economic loss and environmental impacts on the long term [5]. Flows are dynamic and move in a circular manner in a closed loop (same application) or open loop (for a different application) [5]-[6]. Thus, circular economy is "a continuous positive development cycle that preserves and enhances natural capital, optimises resource yields, and minimises system risks by managing finite stocks and renewable flows" [7].

Opportunities for circularities might occur at different phases of the product lifecycle. When occurring closer to the consumption point, fewer additional resources and actions are required for recovery and treatment activities to restore the product value.

Therefore, *reuse* is the most advantageous scenario as resources or products can be used again without the need for additional resources and circularity is maximized. *Recycling* aims to recover materials back into the system as crude feedstock and substitute virgin material inputs. This work accounts for material quality and properties as they change through recycling activities, and for the economic viability of recycling. On the one hand, the Substitution Ratio (SR) accounts for materials' qualitative deterioration due to the number of use and recycling cycles [8]. On the other hand, the Recyclability index (R) compares the economic value associated with a material in its recycled and virgin form which impacts the chances for recycling [9]. *Energy recovery* is generally characterized by a waste incineration process from which energy is generated and handed back to the system, lowering the need for energy provision. *Landfill* is the least sustainable scenario as resources leave the economic and industrial system, preventing the chance for further exploitation.

1.3 Additive Manufacturing and Sustainability

Current literature highlights the potential of AM to enhance efficiency and sustainability, basic principles of circular economy, and is estimated to reduce costs by 170–593 billion$ and CO_2 emissions by 130.5–525.5 Mt by 2025 [10]. Benefits include energy savings linked to dematerialization and simplified logistics, improvements in parts design intended for better performances in use, new recycling opportunities and landfill avoidance [11]. AM has the potential to reduce virgin materials mining and polluting auxiliary inputs in the production phase and subsequent activities [12]. Faludi et al. propose a LCA comparing the environmental sustainability of AM and CNC and found that Fused Deposition Modelling (FDM) is more sustainable than CNC [13]. While software and hardware cost are still high, reduction in tooling and lead time from design to production are making AM competitive and cost-effective [14]. Baumers et al. also performed a cost assessment of AM use and determined that, despite economies of scale still applying for AM, machine cost has the highest impact on the overall cost [15]. Further benefits might come for the product lifecycle stretching by means of reuse, repair and remanufacturing, together with new business model opportunities, shorten and high-value supply chains, lowering in production volumes and stocks due to customization [16]. Despite the chances for AM in terms of circular economy, further work is required to address this topic.

Apart from Ellen MacArthur Foundation's proposal of performance indicators specifically intended to capture the impact of the design phase on the ability to reduce waste and sustain circularity [7], it is mainly about adapting ecology and sustainable assessments together with cost-driven tools to circular economy purposes. Starting form a lifecycle perspective and resources flows analysis, the next sections are intended to propose a methodology to assess products' ability in triggering circularity.

2 CPA Methodology

This section describes the product circularity assessment (CPA) methodology, a quantitative tool intended to capture and quantify the amount of circular flows occurring along the product lifecycle. The expected outcome is the circularity product indicator (CPI), a percentage value intended to capture the product performances in terms of circularity.

2.1 CPA Methodology Principles

While the CPA methodology is not sector- or technology-specific, it is adaptable and flexible to a broad range of applications. It accounts for various types of circular flows based on four principles:

1. Use less. This principle consists in reducing the resource requirements for a given useful output (i.e. thermodynamic efficiency and eco-efficiency), enabling a reduction of mining activities and impacts deriving from treatments, consumption and disposal activities.
2. Absorb circularities. This principle relies on the use of non-virgin materials (recycling), reuse and energy recovery. It creates benefits in terms of circularity, as it reduces the need for virgin materials to be processed and energy to be provisioned.
3. Generate circularities. This principle refers to the opportunity generated from the product-system for material to be reused, recycled and for waste to undergo the energy recovery.
4. Use of renewable energy sources. This last principle is one of the circular economy pillars as renewable resources can be used at a sustainable rate, if exploitation does not exceed regeneration rate.

Circular flows cannot be categorized *a priori* as generated or absorbed, but depending on the resource flow history. Absorption of resource flows coming from within the product-system itself or from other systems is counted when defining the CPI. Circular flows generated by the product-system and re-entering the system as absorbed circularities are neglected, as to avoid to double counting. Finally, generated circularities destined to other systems are not accounted at this stage of development of the methodology.

2.2 CPA Steps

The proposed CPA methodology is designed in four steps:

CPA Step 1: Objectives and System Boundaries. The functional unit is the product or component considered for the assessment. Electricity, thermal energy, materials and other auxiliary resources (such as water, cooling fluids, chemical additives, consumables, etc.) embody the reference flows. The methodology follows a "cradle to cradle" approach and the boundaries of analysis account for inter-systemic exchanges, relying on an open-system frame.

CPA Step 2: Inventory Analysis. System mapping and data specification provide a detailed description of the product-system analysed, the related processes and the resource flows. Then, the inventory analysis is performed, with the intent to collect detailed information. Data gathered include power consumption [Wh] and resource quantities [kg].

CPA Step 3: Resource Circularity Indicators. Following the circularity principles abovementioned and the opportunities for circularity at different stages of the product life cycle, energy, materials and other resources circularities are assessed for each process step:

$$\boldsymbol{ECI_p} = W^E{}_p * \left(EEC_p + TEC_p\right) * 100.$$

$$\boldsymbol{MCI_{m,p}} = \frac{(MFC\_in^{short}{}_{m,p} + MFC\_in^{long}{}_{m,p} + MFC\_in^{eol}{}_{m,p} + MFC\_in^{OS}{}_{m,p})}{MF\_in_{m,p}}$$

$$\boldsymbol{RCI_{r,p}} = \frac{\left(RFC_{in}{}^{short}{}_{r,p} + RFC_{in}{}^{long}{}_{r,p} + RFC_{in}{}^{eol}{}_{r,p} + RFC_{in}{}^{OS}{}_{r,p}\right)}{RF_{in_{r,p}}}$$

Electrical energy and thermal energy circularity (EEC_p and TEC_p) within process *p* is weighted for the occurrence of the flow of energy consumed within *p* in respect to the system energy balance ($W^E{}_p$). Material *m* flow circularity can be from reuse or recycle within *p* or from downstream processes, from the EoL of the product or generated from other systems. Each material *m* flows are assessed individually for each process *p*. Auxiliary resources are treated similarly.

Then, circularity indicators for energy (*ECI*), materials (*e*) and other resources (*RCI*) calculated for individual processes are aggregated to obtain overall product-system level indicators for each material *m*.

$$\boldsymbol{ECI} = \sum_{p=1}^{P} (ECI_p)$$

$$\boldsymbol{MCI_m} = \sum_{p=1}^{P} [MCI_{m,p} * \frac{MF\_in_{m,p}}{MF\_in_m}] \rightarrow \boldsymbol{MCI} = \sum_{m=1}^{M} [(MCI_m * W^M{}_m * IRC_m) * 100]$$

$$\boldsymbol{RCI_m} = \sum_{p=1}^{P} [RCI_{r,p} * \frac{RF\_in_{r,p}}{RF\_in_r}] \rightarrow \boldsymbol{RCI} = \sum_{r=1}^{R} [(RCI_r * w^R{}_r) * 100]$$

ECI is defined from simple aggregation of ECI_p. Material *m* circularity indicators MCI_m are defined and weighted for the share of material *m* consumed in *p* in respect to system consumption of *m*. IRC_m combines IR_m and R_m which account for the material physical properties when recycled and recycling convenience. Auxiliary resources circularity indicators RCI_m are treated similarly, apart from neglecting recycling opportunities.

CPA Step 4: Product Circularity Indicator. The last step consists of the CPI calculation as geometrical combination of ECI, MCI and RCI:

$CPI = \frac{K}{\sqrt{3}} = \frac{\sqrt{ECI^2+MCI^2+RCI^2}}{\sqrt{3}} * 100,\ 0 \leq CPI \leq 1,$ where $K^2 = ECI^2 + MCI^2 + RCI^2$.

In this research, all three variables are considered to have an equal impact on efficiency and sustainability, thus no hierarchy or weighted scale are adopted when combining them. The CPI is expected to range from zero to 1. If ECI, MCI and RCI are all equal to zero, then the CPI will have a null value, meaning that the product-system is purely linear with no resource recovery and no renewable sources. On the contrary, a CPI value equal to 1 is the ideal scenario where all resources involved in the product-system originate from and generate circular flows.

3 Short Application and Results

The CPA methodology is applied to a simplified case study of a mono-material biomedical product fabricated by Direct Metal Laser Sintering (DLMS) technology

(EOSINT M270 machine). The data available on material and energy are used to quantify the CPI of a metal (CoCr) dental crown which is the functional unit of analysis. The product-system is characterized by four processes as follow: (i) atomization, (ii) production, (iii) sandblasting, (iv) heat treatment. For this simplified life cycle assessment, material processing (metals mining and forming) is neglected, together with the creation of ingots used in atomization. It is assumed that the product cannot be recycled, i.e. it will be landfilled at its end-of-life. Due to some gaps in the data available and to ensure completeness of the application, data from literature and estimations along with experimental data supplied by the company were used for this analysis. The values for the volume and mass of dental crowns are shown in table 1.

Table 1. Material volume and mass of a dental crown.

Dental crown	Sacrificial structures	Total
50.889 mm3	28.373 mm3	79.262 mm3
0.443 g (54%)	0.247 g (46%)	0.69 g (100%)

(i) Atomization. Powder formation is one key factor for resource consumption as it affects both the potential for dematerialization and the reduction of energy usage within the production phase.
(ii) Production. DMLS technique relies on a powder bed fusion process. Such metal AM processes often require post-processing for supports removal and surface finishing, depending on powder grains size. The energy consumption of these processes is usually high.
(iii) Sandblasting. The dental crowns are mechanically treated by corundum (aluminium oxide) to clean the metal surface from leftovers and corrosive deposits. This process requires a platform where a batch of dental crowns are laid.
(iv) Heat Treatment. Once blasted, the platform enters the furnace for the thermal treatment to release internal stresses. This is an energy intensive process which significantly impacts the overall efficiency and circularity of the product-system.

Fig. 1. Product-system characterization and resource flow mapping where P the nominal power and T the processing time for each process.

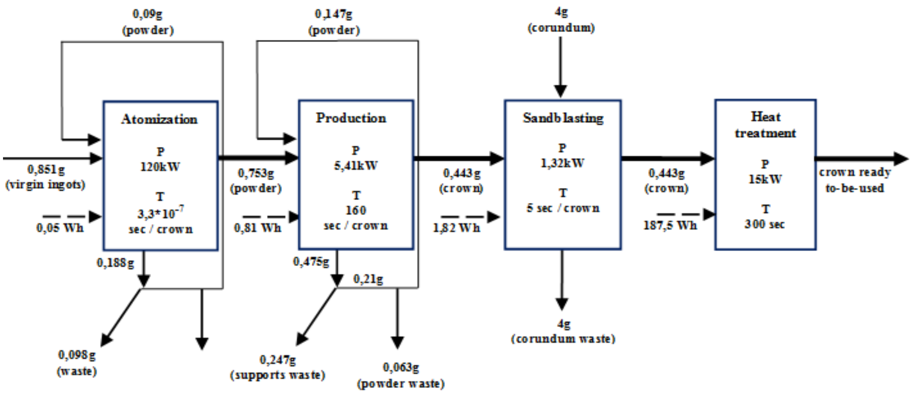

Figure 1 schematizes the flows within product-system pinpointing the opportunities for circular flows to occur. Thus, circularities are quantified to determine the ECI and MCI at system level. From the available data it comes to ECI=33,20% and MCI=20,10%. Thus, CPI=22,41%.

Energy has high impact on products' circularity (non-renewable energy sources). This case study excludes the ingots formation which is an energy intensive activity, and the thermal power as it does not significantly to influence the system's energy consumption. The material waste cannot undergo energy recovery and generate a positive impact on energy circularity. Materials' circularity is mainly linked to the possibility for atomization and production phase to recover powders from downstream and replace virgin feedstock. It is estimated that ingots fabrication could enhance material circularity as it is an efficient process. Due to the product's characteristics, it is not possible to account for a different EoL scenario from landfill. Finally, CoCr is produced from non-renewable resources and is currently not recycled. In order to create opportunities for non-virgin inputs of material, recycling of the supports and EoL products, further development of recycling technologies is required.

4 Conclusions

Technological and societal advancements have triggered innovations and development while causing undesirable consequences such as natural resources depletion, waste generation and damages to the natural ecosystem. It is clear that we need a more sustainable economic and industrial model. The circular economy paradigm respond to these needs with the aim to maximize economic, environmental and social value created from industrial activities. Among other advanced technologies, AM holds the potential to trigger circularity through dematerialization, product and process redesign, reduced energy consumption, elimination of tooling and auxiliary activities and resources, extended product lifecycle which generate economic and environmental benefits.

This paper proposes an assessment methodology to quantify the circularity of a product by a simplified lifecycle perspective and accounting for inter-systemic exchanges of resources. The methodology outcome is the circularity product indicator (CPI) which represents the percentage value of circular flows along the product lifecycle.

This paper presents an application example of the methodology using a simple mono-material biomedical product to assess the potentials of circularities created through the use of AM. The results show that the use of renewable energy sources together with the characteristics of the production process positively affect the ECI value. As expected, powder recovery and reuse without further treatment or resources addition can improve the MCI.

Future work will include assessment of repair and remanufacturing activities for product lifecycle extension and increased circularity. Moreover, CPA improvements should count for the generation of circular flows absorbed outside the system boundaries (i.e. open-loop recycling of the waste and by-product of the product system considered). A more advanced application should be conducted to show the wider impact of product circularity performance on sustainable manufacturing more broadly.

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