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Measuring and Enhancing Circularity of the Healthcare Sector: The Circularity Model of Products & Spare Parts

Soufiane El Bechari^{1,2}, Ghada Bouillass², Bernard Yannou², Michael Saidani^{2,3}, Alexandru Volanschi¹ and Robert Heidsieck¹

¹ GE Healthcare, 283 Rue de la Minière, 78530 Buc, France

² Université Paris Saclay, CentraleSupélec, Laboratoire Genie Industriel, Gif-sur-Yvette, France

³ Luxembourg Institute of Science and Technology, Environmental Research and Innovation Department, 5 Avenue des Hauts Fourneaux, L-4362 Esch-sur-Alzette, Luxembourg

{soufiane.el-bechari, ghada.bouillass, bernard.yannou,
michael.saidani}@centralesupelec.fr}
robert.heidsieck@gehealthcare.com
alexandru.volanschi@gehealthcare.com

Abstract. The medical sector is lagging behind in adopting circular economy practices due to its heavily regulated operating environment. A lack of a framework for measuring circularity performance of large-scale medical equipment is one of the main challenges. To address this, a Circularity Model of Products & Spare Parts (CMPP) was developed by integrating three main features: adapted to the healthcare sector, data-driven automated model, and decision-oriented. The CMPP provides a systematic way to measure and track circularity performance of healthcare industries. It can also be adapted to fit other industrial systems and sectors. The research offers valuable insights into the potential of digitalization and data-driven culture in fostering the transition from linear to circular models both from conceptual and operational perspectives.

Keywords: economy, medical equipment, circularity performance, digital cockpit, decision-making support.

1 Introduction

The global transition towards more sustainable production is fostered by the adoption of circular economy (CE), which is “an economic system that is based on business models which replace the ‘end-of-life’ concept with reducing, alternatively reusing, recycling and recovering materials in production/distribution and consumption processes, with the aim to accomplish sustainable development, which implies creating environmental quality, economic prosperity and social equity, to the benefit of current and future generations” [1].

The healthcare sector is a major contributor to the climate crisis, responsible for almost 5% of global carbon emissions [2]. It is thus fundamental to investigate the offered opportunities by CE models to enhance the environmental performance of the healthcare sector. In this regard, appropriate circularity indicators are needed to assess the effective implementation of CE practices and guide decisions. In this regard, substantial research studies have been focusing on CE indicators [3] [4] [5] [6]. The Material Circularity Indicator (MCI) and Product Circularity Indicator (PCI) are widely cited metrics [7][8], calculating circularity values based on linear flow index and utility factor [9].

In parallel of the pursuit of a circular economy, leveraging data is emerging as a crucial opportunity to better understand the circularity of products and systems. Recent research, often presented in review articles, highlights the profound impact that data can have on our understanding of circularity [10] [11] [12] [13]. These studies emphasize underscore the potential of data to serve as a cornerstone for advancing circular economy goals, ultimately contributing to a more sustainable and efficient use of resources. For instance, digital platforms are recognized as key enablers of circularity, mediating transactions that reduce resource inputs and waste outputs, potentially accelerating the circular economy across diverse value chain stages and industry sectors [14][15]. Furthermore, digital technologies, such as the internet of things and big data analytics, have attracted a great deal of attention from academics, industry professionals and policymakers, primarily because of their ability to accelerate progress towards the UN's sustainable development goals [16][17][18]. These examples illustrate the burgeoning interest in digital tools as powerful allies in the quest for a CE.

To the best of our knowledge, there is still a lack of comprehensive framework for measuring the circularity performance of large-scale medical equipment such as interventional guided systems, invasive cardiology,

magnetic resonance Imaging and mammography systems, while effectively handling the inherent data complexity associated with circularity assessments [19] [20]. Additionally, it is difficult to obtain and structure the data required in the context of CE, which can be resource-intensive for companies and a practical obstacle to measuring CE, particularly for the healthcare sector [10]. In this work, we fill this gap by formulating the Circularity Model for Products and Parts (CMPP) that measures the circularity performance of a product system. The CMPP tackles the above-mentioned challenges by encompassing three main features. First, it is a data-driven model based on a structured database of the product system under investigation. Second, it is automated to enable a systematic calculation of circularity indicators at both the products and parts levels. Finally, the CMPP is decision-oriented, which allows exploring new design and remanufacturing pathways to improve the circularity performance.

2 Methodology

2.1 Research Methodology

In order to enable a systemic measurement of circularity performance over the lifecycle of a medical system. We first conduct a literature review to identify the existing circularity indicators that best fit the healthcare sector. Following this step, the Circularity Index (CI), developed by The European Coordination Committee of the Radiological, Electromedical and Healthcare IT Industry (COCIR), was selected. This index was deemed the best fit for this study as it was initially developed for imaging devices, and the product system under investigation here is a medical device/equipment.

However, the CI does not fully account for circularity loops such as the upgrade of medical systems, extension of the equipment lifecycle, and harvested parts used for maintenance services. Therefore, the possibility of reusing or recycling the packaging and extras waste generated in the front-end of the lifecycle, i.e., from suppliers to customers, is not considered which represent a significant portion of the waste generated.

To address these limitations, the CI is enhanced by extending its scope to the different lifecycle stages of the medical equipment and encompassing the different circularity loops that are missing from the CI. Furthermore, the present study not only enhances the CI, but also, seeks to develop a digital tool to facilitate the measurement of circularity within a medical equipment manufacturer. Hence, a parameterized model is proposed : the Circularity Model for Products and Parts (CMPP). Such model allows for the simulation of several scenarios to see the impacts on the circularity performance results, enabling better decision-making. Moreover, the proposed model is designed using object-oriented programming to facilitate data structuring and enable automated circularity measurement for a large portfolio of products. The CMPP relies on a series of different steps that future studies can adopt and are detailed in the following sub-section 2.2.

2.2 Circularity Model for Products and Parts (CMPP)

This section describes the newly designed Circularity Model for Products and Parts (CMPP), enabling the measurement of circularity index and the exploration of circularity improvement pathways through scenarios' simulation. The CMPP methodology comprises six main steps, (1) scope definition, (2) lifecycle modeling, (3) indicators selection, (4) model development, (5) data collection and structuring, (6) model implementation and validation. An iterative approach is adopted as illustrated in Figure 1, which allows the practitioners to adjust each step when required. The following subsections describe step-by-step the methodology that can be adopted for other product systems and parts with a similar objective. In the present study, the CMPP model is further experimented on imaging medical equipment.

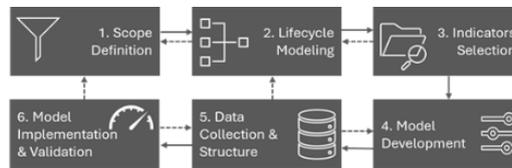


Fig. 1. The main steps of the research methodology adopted in this study

Scope definition

The scope definition allows to depict the system under study to enable the definition of appropriate circularity indicators and their effective implementation within the model deployment. This encompasses two key aspects:

- **System's definition:** the system to be examined is defined by including its functional unit, which serves as a foundation for circularity measurement, its lifetime, and its main characteristics.
- **System boundaries:** the system's perimeter is defined by including all the lifecycle stages on which the circularity measurement is performed. This involves all the stages of the product's life cycle – from

suppliers of materials and production to use and eventual disposal or reusing/recycling – that are relevant to the study.

Lifecycle modeling

In this second phase, the aim is to gain insight into the operations, services and activities related to the system under study. These activities include maintenance services, systems upgrade and refurbish, together with systems' harvesting, which consists of retrieving systems from the market to extract reusable parts. The analysis comprises an in-depth exploration of material and spare parts flows, based on the defined system boundaries (see step 1). Additionally, this step includes the identification of potential circular loops, encompassing reuse, remanufacturing, refurbishing and recycling. As a result, relevant flows and activities are characterized through a material flow diagram as illustrated in Fig. 2. Key influencing parameters are also identified to enable their integration within the CMPP through a set of controllable variables.

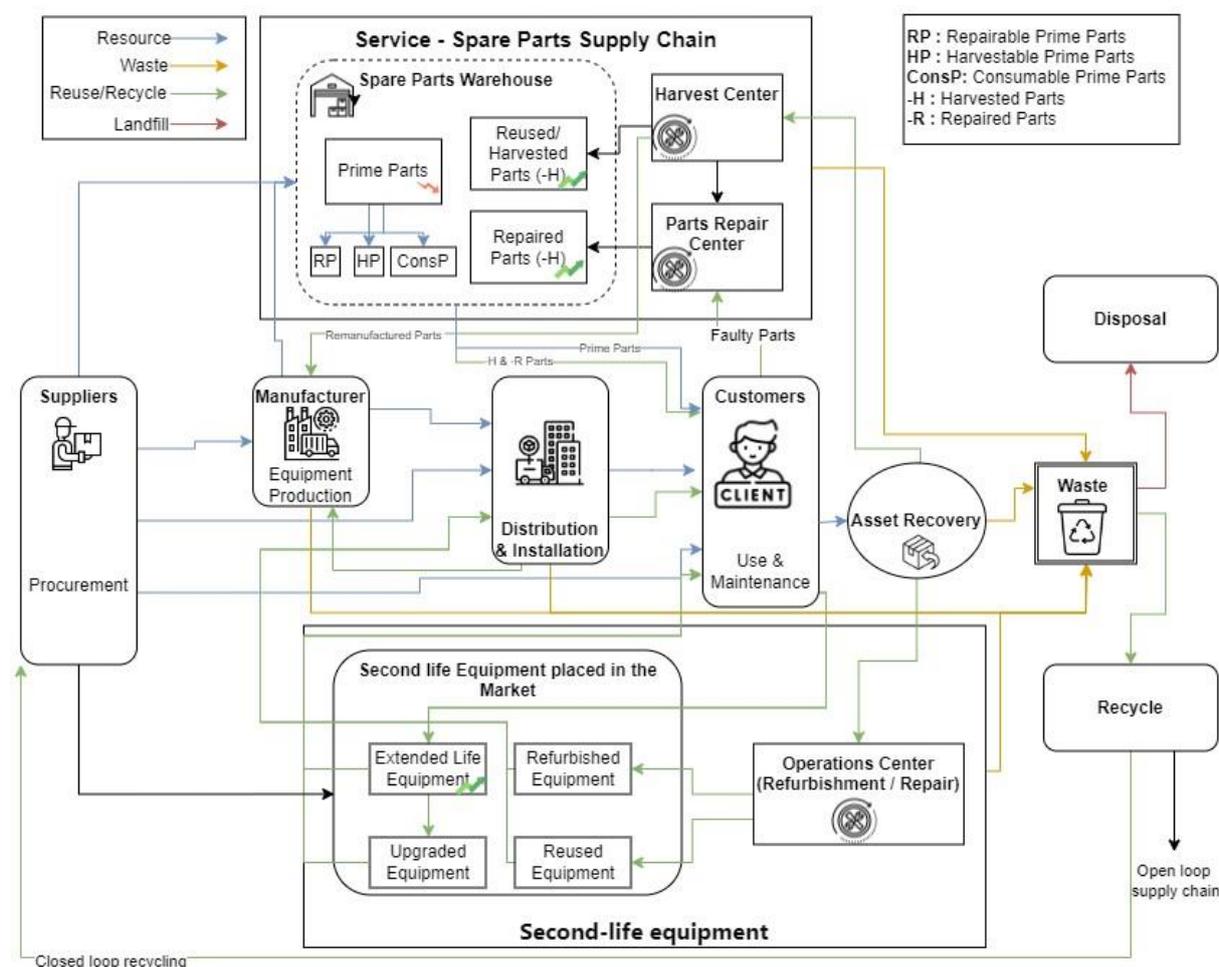


Fig. 2. The Material flow diagram: resources flows (blue), reuse, remanufacture and recycle flows (green), and landfill flows (red).

Fig. 2 presents the material flow diagram developed in this work for medical equipment by emphasizing all the lifecycle steps and the circularity loops that need to be covered within the CMPP model for a comprehensive measurement of medical equipment's circularity performance. It covers flows from various suppliers providing components/parts, which are then transformed into final products, distributed, and installed at customer sites. The diagram also illustrates the supply chain of spare parts servicing the fleet of equipments existing at customer sites and different second-life equipment in the market, each with a distinct impact on circularity. Considering the existence of different types of spare parts (prime parts, repaired parts, harvested parts) and equipment (upgraded, refurbished, reused, with extended life benefits), each type will have a different impact on circularity. Waste management throughout the entire process plays a crucial role in recycling and disposing of waste material,

significantly impacting the circularity of products and parts throughout their lifecycle. All these elements are included in the developed model to serve as an operational tool for monitoring progress at different levels of detail, covering flows, loops, and product/spare parts hierarchy throughout the entire lifecycle.

Multiple elements significantly contribute to the circularity of products and parts throughout the lifecycle. Notably, these include various categories of second-life equipment available in the market, diverse types of spare parts utilized in maintenance services, and the recovery and reuse of extras and packaging at different stages of the product lifecycle. Key parameters associated with these elements, such as recovery rate, reuse rate, waste collection rate, closed-loop recyclability rate, closed-loop recycling efficiency rate, open-loop recyclability rate, open-loop recycling efficiency rate, and recycled content rate, play pivotal roles in shaping the overall circularity profile of the system. Therefore, these parameters are further used within the development of the CMPP to calculate the circularity performance both at the equipment level, i.e., global circularity performance, and parts level.

Indicators selection

A set of potential circularity indicators are identified is this according to step (1) and (2) followed by the selection of one or more suitable indicators to be incorporated into the CMPP. The selection step is conducted according to the product system under investigation, here a medical equipment. The "COCIR index" is therefore identified as the best fit for the purpose of the study as it was initially developed for imaging devices [21]. The European Coordination Committee of the Radiological, Electromedical and Healthcare IT Industry (COCIR) introduced a Circularity Index (CI) [21] measuring circularity as mass of recycled materials, parts reused in manufacturing of new equipment, refurbished equipment, and reused parts in repair and maintenance divided by the mass of new products and parts placed on the market.

$$C.I. = \frac{RM+PM+RE+RP}{POM} \quad (1)$$

Where:

RM: Mass of recycle materials

PM: Mass of parts re-used in manufacturing of new equipment

RE: Mass of refurbished equipment

RP: Mass of reused parts in repair and maintenance

POM: Mass of new products and parts placed in the market

However, such index does not fully account for circularity loops such as the upgrade of medical systems, extension of the equipment lifecycle, and harvested parts used for maintenance services. Hence, it neglects the possibility of reusing or recycling the packaging and extras waste generated in the front-end of the lifecycle, i.e., from suppliers to customers. Moreover, the COCIR index is annually calculated, with a scale ranging from 0 for a perfect linear economy to 1 for a perfect circular economy. The results can therefore fail short to provide valuable insights for decision making as the lifetime of the equipment is not considered. Therefore, step (4) proposes a set of adjustments, based on the COCIR index to enable a more comprehensive model for circularity measurement.

Model development

The aim of this step is to adapt and expand the COCIR CI to include the elements that are currently not accounted for. This involves integrating packaging, open-loop recycling and upstream chain considerations, which are essential to the analysis in order to cover the entire lifecycle of medical equipment and increase the results representativeness. Based on the COCIR index, other key features are added enabling the design of the Circularity Model of Products & Spare Parts (CMPP). In fact, the proposed CMPP accounts for second-life equipment, spare parts, and asset recovery steps. Moreover, it is more granular than the original COCIR model, it can calculate at different levels (systems, spare parts) and can be adapted to specific manufacturer's activities. Finally, the CMPP is a parametrized model that allows to simulate different scenarios and see the impact on the circularity outcomes based on a set of key input parameters.

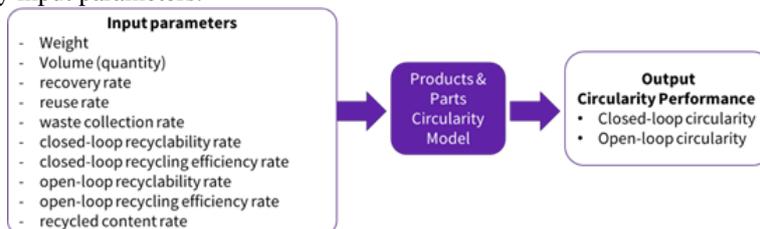


Fig. 3. The CMPP Model key inputs and outputs

Fig. 3 depicts the model's inputs and outputs, while the accompanying formulas below offer a detailed insight into the underlying mathematical operations governing its functionality.

Table 1. CMPP model formulas

Description	Formula
Closed – loop circularity	$\frac{\sum_i (\text{Reused Mass}_i + \text{Closed Loop Recycling Mass}_i + \text{Recycled Content Mass}_i)}{\sum_i \text{Total Mass}_i}$
Reused Mass _i	$\text{quantity}_i \times \text{weight}_i \times \text{recovery_rate}_i \times \text{reuse_rate}_i$
Collected Waste Mass _i	$(\text{quantity}_i \times \text{weight}_i \times \text{recovery_rate}_i - \text{quantity}_i \times \text{weight}_i \times \text{recovery_rate}_i \times \text{reuse_rate}_i) \times \text{waste_collection_rate}_i$
Closed Loop Recycling Mass _i	$(\text{Collected Waste Mass}_i \times \text{closed_loop_recyclability_rate}_i) \times \text{closed_loop_recycling_efficiency_rate}_i$
Materials Input Mass _i	$\text{Total Mass}_i - \text{Reused Mass}_i - \text{Closed Loop Recycling Mass}_i$
Recycled Content Mass _i	$\text{Materials Input Mass}_i \times \text{recycled_content_rate}_i$
Total Mass _i	$\text{quantity}_i \times \text{weight}_i$
Open Loop Circularity	$\frac{\sum_i \text{Open Loop Recycling Mass}}{\sum_i \text{Total Mass}_i}$
Open Loop Recycling Mass _i	$\text{Collected Waste Mass}_i \times \text{open_loop_recyclability_rate}_i \times \text{open_loop_recycling_efficiency_rate}_i$

i: represent various types of spare parts and product categories. Specifically, it signifies Prime parts, Repaired parts, and Reused parts, along with different product categories like Extended Life (operating for more than 10 years), Upgrade Products, Refurbished Products, and Reused Products and the diverse loops/flows elements associated with extras and packaging generated throughout the lifecycle of products.

The model developed here aims to encompass all elements depicted in the flow diagram (Fig. 2), providing an operational tool for monitoring progress across various levels of detail. It encompasses flows, loops, and the hierarchical structure of products/spare parts throughout the entire lifecycle. By employing this model, diverse scenarios can be simulated to assess their impact on outcomes, facilitating informed decision-making that bolsters circularity. A notable scenario involves increasing the utilization of repaired/reused spare parts in repair/maintenance services rather than prime parts, positively impacting circularity by reducing resource consumption. This effect is particularly significant given the availability of reused/repaired parts in the market, obviating the necessity for new procurements and thereby enhancing circularity performance (see use case section). However, it is essential to recognize that not all parts are designed for repair and reuse, and such constraints must be considered.

Data collection and structuring

During this stage, primary data is collected from multiple databases existing at GE Healthcare to feed the CMPP. Data to be collected include the medical equipment product lifecycle information (material flow, loops), the system bill of materials, the product group levels, and the number of spare parts consumed in the maintenance service to repair systems installed on the market. Moreover, other information on harvested systems, products considered to be in second life (e.g., upgraded systems, refurbished systems, reused systems, systems operating for more than 10 years) is also required to compute the circularity performance through the CMPP. A class diagram is developed to illustrate the interrelationships among these data components, facilitating structural and hierarchical organization.

To enable a parametrized CMPP, a code is developed to prepare the data and an object-oriented programming in Python is adopted to facilitate the implementation of the CMPP. Such data-driven approach adopted in this study enable flexibility in the data manipulation process and in calculating circularity.

Model implementation and validation

Based on the outcomes of the precedent steps, the CMPP is ran to test its functionality. A Python module is developed in this work to perform an automated circularity measurement for the equipment and generate the summary results in a html page format and an excel file that contains the details of the results.

To ensure the accuracy and reliability of the CMPP, we propose to validate the functioning of the model in an industrial use case. This provides baseline results for the circularity of the system. And finally, a set of future scenarios is proposed and explored by varying the key input parameters such as reuse rate, open-loop recycling rate, and closed-loop recycling rate to measure circularity outcomes.

3 Case study

The CMPP developed in this study is an enhanced version of the COCIR model [10], adapted to GE Healthcare's specific operational environment and can be applied to several products such as Interventional Guided Systems, Invasive Cardiology, Magnetic Resonance Imaging, Mammography, and Radiography (X-Ray). To ensure an enhanced coverage of all processes, flows, and scenarios within our business, several enhancements and modifications were made, as elaborated in section 2. To validate both the methodology and the model developed in this work, a use case is conducted on medical equipment, specifically the Interventional Image Guided System (IGS) family product produced by GE HealthCare, to evaluate its circularity performance. This selection was made due to the complex lifecycle of these products, characterized by multiple flows and loops, making it a representative case for other complex product scenarios.

- **System Characteristics:** The Interventional Image Guided System (IGS) is used for diagnosing and treating vascular tree problems.
- **Functional Unit Considered:** A 10-year usage.
- **Perimeter System:** Evaluation across the entire life cycle.

Using the developed methodology, the baseline circularity performance is calculated for the IGS System. Due to confidentiality concerns, only summarized results based on hypothesis data to show the potential of the CMPP tool to improve the circularity outcome (see Fig 4).



Fig. 4. Closed-loop circularity results.

The summarized results reveal a closed-loop circularity of 0.62, indicating the need for intensified efforts to increase circularity. In response, the following study focuses on evaluating the impact of the opportunities of having more systems in extended life in the market and the usage of more repaired and harvested parts in the maintenance service on circularity performance.

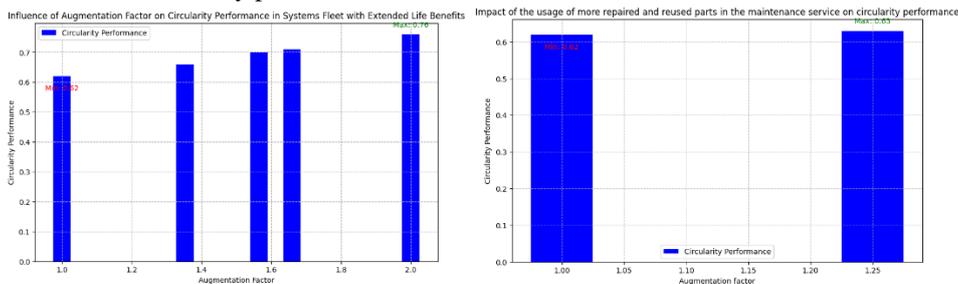


Fig. 5. (a) Influence of Augmentation Factor on Circularity Performance in Systems Fleet with Extended Life Benefits (b) Impact of the usage of more repaired and reused parts in the maintenance service on circularity performance.

Figure 5 illustrates the significance of extending product life cycles and the utilization of reused and repaired spare parts. A higher augmentation factor for these elements contributes to an enhanced closed-loop circularity performance. By analyzing these outputs and running different scenarios, the engineering teams can pinpoint design areas that require improvement to enhance circularity. Furthermore, this parameterized model enables us to adjust various variables to assess their influence on circularity outcomes. This aids in identifying critical factors that affect circularity performance and areas in need of optimization. Additionally, the model supports informed project investment decisions through scenario comparisons. However, such decisions should consider other factors like environmental performance (e.g., carbon footprint) and economic performance (e.g., costs), which will be essential considerations for future model extensions. It is important to note that the COCIR model used as a basis for the developed CMPP tool, considers equally reuse and recycling. However, it is preferable in terms of circularity to adopt more reuse loops rather than recycling. Therefore, it is recommended

in the future to investigate how can weighting factors be integrated to account for the type of circularity loops in the CMPP model.

4 Conclusion

The model developed in this study offers several advantages over the state-of-the-art. It allows for quantifiable circularity results at various levels (products and spare parts) and facilitates simulation of diverse scenarios to assess their impact on outcomes, thereby facilitating informed decision-making that bolsters circularity. The investigation shows the pivotal role of simultaneously promoting life extension programs such as upgrades and refurbished systems; optimizing usage of reuse (harvested) and refurbished spare parts; and finally enhancing the efficiency of the circularity closed loop. Addressing these multiple dimensions is imperative for achieving enhancement in circularity performance. The model developed in this work lays the foundation for various avenues of future works. Several key areas for future research can be identified.

A crucial aspect of advancing the CMPP is the exploration of additional scenarios that may affect materials, spare parts and product circularity. By doing so, researchers can identify and quantify and rank the influencing factors that play a role in enhancing or impeding circularity. While the CMPP primarily focuses on circularity performance, future work should expand the model to encompass economic and environmental performances.

It is essential however to acknowledge that some elements crucial for circularity, such as the relative impact of reuse vs recycle, downcycling are equally considered in the current model and future work needs to investigate how can weighting factors be integrated to account for the type of circularity loop. Additionally, the renewable/regenerative content is not accounted for in the circular inflow of the model [21]. Future research can focus on integrating the CMPP with other indicators or models specifically designed to capture these unaddressed aspects. Furthermore, data acquisition is not fully automated, and future efforts should prioritize the establishment of robust data acquisition processes to enhance the model. These integrations will lead to a more comprehensive assessment of circularity in products, spare parts, and materials.

Finally, the CMPP model developed in this study serves as an operational tool for monitoring progress at different levels of detail, covering flows, loops, and product/spare parts hierarchy throughout the entire lifecycle. It paves the way for future studies to fill the circularity measurement gaps in the healthcare sector, and therefore, contributes to achieving more circular and sustainable healthcare business models.

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