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Developing manufacturing-relevant indicators for assessing circularity of a product’s life cycle in the long-run behavior

Yong Han Kima\*, Sidi Denga, Thomas Maania, Nehika Mathurb, Matthew J. Triebeb, John W. Sutherlanda

aEnvironmental and Ecological Engineering, Purdue University, West Lafayette, IN 47907, USA

bNational Institute of Standards and Technology, 100 Bureau Dr. Gaithersburg, MD 20899, USA

\* Corresponding author. Tel.: +1-765-496-9697; fax: +1-765-494-4482. *E-mail address: kim3822@purdue.edu*

Abstract

The manufacturing industry holds a significant position in the U.S. economy, simultaneously contributing to a substantial share of energy and material usage, as well as environmental impacts. Developing manufacturing-relevant indicators will help decision-makers understand the consequences of their decisions in terms of end-of-life (EoL) product management and promote the closing of loops within product life cycles. Nevertheless, indicators for assessing progress towards a circular economy for the manufacturing sector with respect to long-run behavior do not currently exist. To address this issue, this paper proposes two manufacturing-relevant indicators and their foundational methodology. These newly proposed indicators can capture the long-term behavior of a product's life cycle and evaluate the associated circularity from both product and materials perspectives. Each scenario is presented to illustrate how these indicators could characterize the degree of circularity and the associated impacts for a given life cycle flow.

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1. Introduction

The awareness of “sustainability” has gained substantial attention in recent years in various sectors as a response to the environmental challenges posed by the modern world. This attention has caused companies to realize the need for and to adopt circular economy practices [1,2]. To be more specific, as shown in Fig. 1., industries worldwide are recognizing the value of transitioning from linear models of production to closed-loop production, which can be more regenerative and resource-efficient [3]. As the global community places growing emphasis on environmental responsibility, companies find themselves not only accountable for their economic performance but also for their environmental footprint [4,5]. With the increasing environmental consciousness, companies are starting to recognize the necessity of embracing the concept of circularity. This is leading them to regard the measurement of their product life cycle's circularity as an essential step toward aligning with sustainability principles [6].

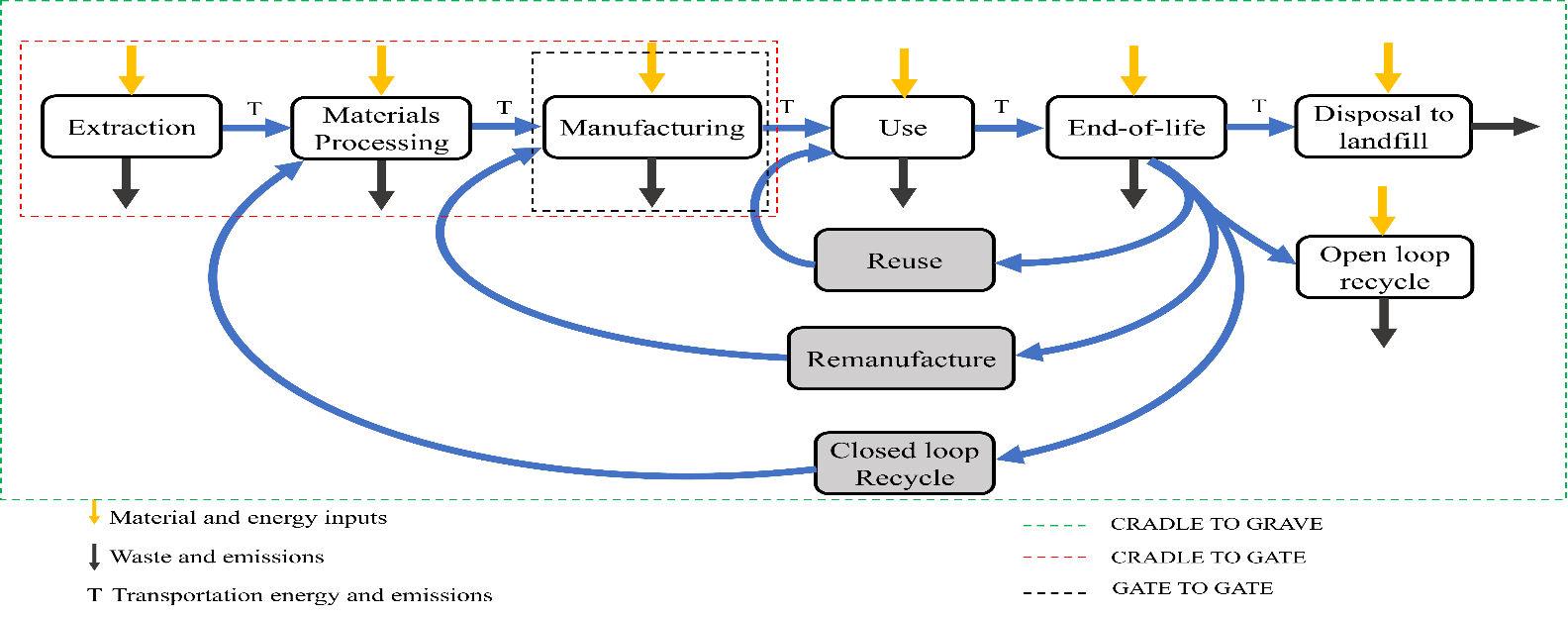


Fig. 1 linear and circular economy paths.

By creating indicators to measure the circularity of product life cycles tailored to their business context, companies can accurately assess the degree to which their products conform to circular principles. These indicators serve as valuable tools for self-assessment, enabling companies to identify strengths, weaknesses, and opportunities for improvement within their product life cycles [7]. Ultimately, the ability to quantify the circularity of products not only demonstrates a commitment to sustainable practices but also provides a competitive edge by resonating with environmentally conscious consumers and investors who increasingly prioritize businesses that align with their values [8].

The manufacturing industry plays a pivotal role in the U.S. economy. In the year 2021, the manufacturing industry contributed $2.3 trillion to the U.S. GDP, constituting 12% of the overall U.S. GDP [9]. Additionally, manufacturing industries have a direct influence on economic value, material consumption, and waste generation [10]. Since the manufacturing sector possesses a signification proportion of the U.S. economy, developing indicators customized to the manufacturing of products is essential for accurately assessing progress toward a circular economy. Manufacturing-relevant indicators provide insights into the circularity of products and materials, enabling decision-makers to identify areas for improvement, make informed choices about materials and processes, and quantify the sustainability impacts of circular strategies.

While circular economy principles have been widely acknowledged, the lack of standardized indicators for assessing circularity in the manufacturing sector in terms of long-run behavior presents a significant challenge. Although many studies acknowledge the importance of circular economy practices, they often fall short in assessing the related impacts of these practices over extended time horizons. Existing efforts on developing circularity indicators have undoubtedly made remarkable strides in assessing the circularity of product life cycles. However, a noticeable gap persists, wherein the majority of these circularity indicators primarily focus on immediate or short-term effects, failing to encapsulate the impact from long-run product life cycle behavior. Measuring the circularity of product life cycles in long-run behavior, would not only enable decision-makers to anticipate long-term environmental and economic outcomes of their decisions but also empower them to formulate robust business strategies that adhere to the principles of circularity. To bridge this gap, this paper explains the methodology to illustrate long-run aspects and develops two indicators (product and materials perspective) that can describe the level of circularity and its related long-

term effects pertaining to a specific life cycle. For situations where the indicators lead us to decisions that are not economically feasible or environmentally friendly, this paper proposes efforts that may offer guidance on decision-making strategy intervention.

The rest of the paper is formed as follows. First, in the literature review section, an overall summary of existing indicators is provided, and observed shortcomings of the current literature are discussed. Second, the development of circularity indicators section proposes two new indicators and provides a methodology to develop manufacturing-relevant indicators in the long term. Lastly, the discussion and conclusion section illustrate the efforts and main contribution of this paper with the potential future research direction.

1. Literature review

Numerous circularity indicators have emerged from efforts to quantify circularity. In the domain of circularity assessment, the conceptual framework has often been divided into and mostly focused on three distinct levels of analysis: micro, meso, and macro [11–13]. This categorization involves evaluating circularity at the micro level, which encompasses products, consumers, and companies; the meso level, which considers eco-industrial parks and industrial symbiosis; and finally, the macro level, which extends the assessment to city, region, nation, and even beyond [14,15].

Various studies probe each level of circularity assessment to develop indicators and provide a deeper understanding of that level’s practical implications. At the micro level, the analysis of product life cycle circularity primarily focuses on particular products or processes of limited scope [16–18]. For example, the Material Circularity Index (MCI) quantifies the extent to which the material flows of a product contribute to its restoration. The MCI indicator enables the participating company to thoroughly assess products, aiming to precisely quantify the circularity of material flows related to specific items [19]. The Reuse Potential Indicator (RPI) delineates the extent to which a material resembles a resource, encompassing the diverse range of material qualities [20]. The Circular economy Performance Indicator (CPI) is used to assess the potential for circularity in industrial products throughout the stages of (re-)design, development, or benchmarking [21].

Moving on to the meso level, the focus shifts towards larger systems such as eco-industrial parks and industrial symbiosis. In this domain, researchers have explored the synergies that can be fostered between industries to promote resource sharing, waste reduction, and energy efficiency [22–25]. An eco-efficiency indicator was proposed as a comprehensive measure for concurrently assessing the economic and environmental effectiveness of industrial symbiosis (IS) networks [26]. The methodology of substance flow analysis (SFA) was integrated with the resource productivity (RP) indicator to assess how IS systems contribute to the advancement of the circular economy concept [27]. An IS indicator was introduced to identify changes in symbiosis over time, offering a dynamic viewpoint of eco-industrial parks [28].

Expanding the scope to the macro level, researchers have extended their assessments to broader entities, encompassing cities, regions, and nations. These studies provide a holistic view of circularity's impact on larger scales of urban planning, regional development, and national policies [29–31]. A macro-level monitoring framework for circular economy was developed to create indicators that assess the extent of material input and output streams [32]. A detailed Material Flow Analysis (MFA) of the Swiss waste management system is proposed, including comprehensive subsystem MFAs that focus on the fractions of municipal solid waste that are recycled [33]. A socio-metabolic approach was employed to evaluate the circularity of material flows on a global scale [34]. The paper traced all material flows within societies, both worldwide and in the European Union, from their initial extraction to their ultimate disposal.

Nonetheless, these indicators, while informative, often lack the necessary granularity to capture specific sector’s nuances. Consequently, decision-makers are often left without appropriate tools to evaluate the circularity potential of their specific products’ life cycles. As noted by Pollard et al. [35], the lack of sector-specific indicators might hamper the ability to comprehensively measure circular economy progress and guide decision-makers effectively. The Material Circularity Indicator (MCI) was revised by Rocchi et al. [36] to make it suitable for application in biological cycles. The "modified MCI" that they proposed could evaluate the level of circularity within rearing systems and enable the comparison of various types of breeding species. A framework for monitoring the circular economy was proposed in Droege et al. [37], highlighting the need for sector-specific indicators to assess progress in circularity.

One prevailing deficiency in the current literature with regard to circularity indicators is the limited consideration of long-term behavior. Circular economy initiatives aim to achieve sustainability not only in the immediate operational context but also in the broader scope to provide informed decision-making and long-term strategic planning. However, a substantial proportion of existing research tends to emphasize short-term outcomes, without adequately addressing how these measures will translate into sustained circularity benefits over a long period of time. Neglecting the long-term implications can result in misleading conclusions, since apparent circularity gains in the manufacturing phase may not yield the expected outcomes when the extended time horizon is considered. Addressing this issue is crucial to ensure that circular economy initiatives are thoroughly evaluated for their effectiveness in achieving long-term circularity goals.

Therefore, the following section provides two simplified indicators and a fundamental methodology that can measure the circularity of the product life cycle in the long-run behavior. The suggested indicators were able to describe the level of circularity and resulting effects for a specific phase within a life cycle.

# Nomenclature

Mass of new products that are manufactured by virgin material.

Fraction of the end-of-life products that are successfully remanufactured.

M0 Amount (mass of) material needed for a virgin product.

Fraction of end-of-life material that can be recovered, used for recycling, and enter the next life cycle and stay in the material loop.

Product Multiplier

Expected Number of Additional Material Life Cycles

1. Development of Circularity Indicators
   1. Indicator 1: The Product Multiplier ()

Our first indicator is inspired by the concept of “money multiplier” in economics. An initial deposit of one dollar into the banking system can potentially lead to an expansion of the money supply by more than one dollar as the deposited money circulates within the economy and undergoes multiple rounds of re-deposits [38,39]. In a similar vein, the initial remanufacturing of one additional product may result in more than one remanufactured product.

Let us assume that the mass of new products manufactured by virgin material is (kg). These products are used, reach end-of-life, and are returned. All the virgin material “sees” one cycle of use. Let denote the fraction of the end-of-life products that are successfully remanufactured. The mass of products seeing an additional use cycle is ; these products ultimately reach their end-of-life. The mass of products moving on to yet another use cycle is then . Out of the initial mass of products, , which we produced using virgin material, the product mass seeing an nth use cycle is , where . After n use cycles, the total mass of products remanufactured (or “descended”) from the initial of virgin material (kg) is:

|  |  |
| --- | --- |
|  | (1) |

After an extensive number of life cycles, the mass of remanufactured products that “descend” from the initial converges to:

|  |  |
| --- | --- |
|  | (2) |

The above limit essentially quantifies the mass of products that can be remanufactured from the initial mass of products () that were manufactured from virgin materials. Dividing this limit by produces the first indicator:

|  |  |
| --- | --- |
|  | (3) |

where represents the total number of remanufactured products that can be created from each product manufactured from virgin material. We term as the “product multiplier,” as it is analogous to the concept of “money multiplier” in economics. Fig. 2. shows the Sankey diagram for the first indicator where the red arrow represents the fraction of the end-of-life products that are not successfully remanufactured and get disposed of.

A diagram of a magnet

Description automatically generated

Fig. 2. Sankey diagram for first indicator.

* 1. Demonstrating

According to Caterpillar’s Sustainability Report [40], Caterpillar collects and remanufactures 88% of their products at end-of-life; this corresponds to 127 million pounds. It is assumed that all collected products are eligible for remanufacturing. For this specific case, FR = 0.88. First, based on the method above, the product multiplier can be calculated as:

|  |  |
| --- | --- |
|  | (4) |

This indicates that for each unit of product to be remanufactured, in the long term, 7.33 units of “new” product can be created.

For this case, 127 million pounds ( 57,606,231kg) of products are remanufactured, i.e., million lbs. Therefore million lbs, which will result in a mass of million pounds ( 479,900,727kg) of remanufactured products. Suppose compared to virgin production, remanufacturing can save $900,000 for each million pounds of production. Then the anticipated amount of production cost that can be saved in the long run would be $900,000\*1058, which is approximately $1B.

* 1. Indicator 2: Expected Number of Additional Material Life Cycles ()

The second indicator aims to quantify the additional life cycles associated with materials resulting from recycling. Let us assume that the mass of material needed for producing a virgin product is M0. Let denote the fraction of end-of-life material that can be recovered, used for recycling, enter the next life cycle, and thus stay in the material loop. This implies that the mass of the initial virgin material that is carried to the nth additional life cycle is . In other words, FC can be viewed as the probability of a small piece of the material being recycled and starting a new life cycle. Consequently, the probability of a small piece of virgin material seeing n additional life cycles (but being lost in the next life cycle) is . Given this, the number of additional life cycles that a randomly selected small piece of virgin material will see, N, is essentially a geometric random variable. The expected value of N is:

|  |  |
| --- | --- |
|  | (5) |

The expected number of additional life cycles, E[N], will be termed . Fig. 3. represents the Sankey diagram for the second indicator where the red arrow represents the fraction of end-of-life material that cannot enter the next life cycle and therefore could not stay in the material loop and get disposed of.

A diagram of a manucurizing process

Description automatically generated with medium confidence

Fig. 3. Sankey diagram for second indicator.

* 1. Demonstrating

Previous studies [41,42] mentioned that the maximum recycling rate of aluminum is anticipated to be about 90%. Let us assume that a company that sells aluminum products is able to recover and recycle 90% of its EoL products. Based on the definition discussed earlier, is assumed to be 0.90. Based on this information above, the expected number of life cycles for each unit mass of virgin aluminum can be calculated as:

|  |  |
| --- | --- |
|  | (6) |

Intuitively, this implies that with a recycling rate of 90%, the initial aluminum input in virgin production will on average stay in the material loop for approximately 9 additional life cycles. In summary, the indicator µN is able to translate the material recycling rate into the number of new life cycles that an initial small amount of raw material will experience.

* 1. Energy Threshold in Remanufacturing

One important aspect to consider is the threshold at which remanufacturing becomes an energy-efficient alternative to traditional manufacturing from virgin materials. We can frame this discussion using a generalized formula that relates energy savings to the product multiplier () and the ratio of energy required for remanufacturing to that required for manufacturing virgin product (). Let represent the energy required for manufacturing one unit of a product using virgin materials (e.g., in megajoules or megawatt-hours), and represent the energy required for the remanufacturing of one unit of the same product. Additionally, let denote the cumulative energy savings achieved through remanufacturing over multiple product life cycles.

Then can be expressed as a function of the product multiplier () and the ratio of energy required for remanufacturing to that required for manufacturing virgin product () as follows:

|  |  |
| --- | --- |
|  | (7) |

As shown in equation (7), energy savings () are directly proportional to both and . As increases, signifying a higher number of remanufactured products from each virgin product, and as increases, indicating more energy-efficient remanufacturing processes and energy savings become more substantial.

There exists a critical threshold for at which remanufacturing becomes an energy-efficient strategy. In a simplified scenario, when is less than 1, remanufacturing is not energy-efficient, as it consumes more energy than virgin production. Conversely, when is greater than 1, energy savings are achieved through remanufacturing, and it becomes an energy-sustainable option. It underscores the importance of not only increasing but also improving the to cross the energy threshold. This threshold can be similarly applied to our second indicator, .

In practice, achieving value greater than 1 may require optimizing remanufacturing processes, improving energy efficiency, and considering factors like transportation and material handling. To increase , companies should focus on increasing the fraction of end-of-life products that are successfully remanufactured (). This can be achieved by enhancing remanufacturing procedures, improving product designs to facilitate remanufacturing, and raising consumer awareness and engagement in the return of products for remanufacturing. As a result, this highlights the importance of increasing both and to cross the energy-saving threshold and promote sustainability.

1. Conclusion

This paper addressed the crucial need for indicators to evaluate progress towards a circular economy for a manufactured product over the long-term. The manufacturing industry's significant role in the U.S. economy, coupled with its environmental impact and resource consumption, emphasizes the importance and necessity of assessing circularity not only for a product life cycle but across several life cycles. This paper introduced two manufacturing-relevant indicators that provide insights into the circularity of product and material life cycles in the long-term. The first indicator, the Product Multiplier (), quantifies the expected additional cycles of remanufactured products from each unit of product manufactured from virgin material. The second indicator, the Expected Number of Additional Material Life Cycles (), gauges the expected number of new cycles that a unit mass of virgin material can undergo due to recycling. Through practical scenarios and calculations, this paper illustrated the application of these indicators, showing their relevance and effectiveness in evaluating circular economy practices. The main contribution of this paper is that it provides the fundamental methodology to develop these indicators.

The presented indicators and the methodology will offer valuable insights to evaluate long-term sustainability of manufacturing practices, contribute to more informed decision-making, and drive the adoption of circular economy principles in the manufacturing sector, ultimately promoting resource efficiency and environmental conservation. The two suggested indicators can be extended to a wider range of scenarios or more complicated product life cycle situations.

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