This is the accepted version of the following published article. Please cite as:
Hapuwatte, B. M., Seevers, K. D., & Jawahir, I. S. (2022). Metrics-based dynamic product sustainability performance evaluation for advancing the circular economy. Journal of Manufacturing Systems, 64, 275-287.
DOI: https://doi.org/10.1016/j.jmsy.2022.06.013

Metrics-based Dynamic Product Sustainability Performance Evaluation for Advancing the Circular Economy

Buddhika M. Hapuwatte [a,*], *K. Daniel Seevers* [a,b] *and I.S. Jawahir* [a]

[a] Institute for Sustainable Manufacturing (ISM), Department of Mechanical Engineering, University of Kentucky, Lexington, KY, USA.

[b] Lexmark International Incorporated, USA.

Abstract

Creating products that support the circular economy (CE) requires evaluating product sustainability performance (PSP) and planning the production process during the design stage. Evaluating PSP disregarding demand and production variations over the time a product is produced can lead to significant calculation errors, and therefore, misinformed design decisions. This has severe consequences in the CE-focused closed-loop productions. However, current literature on product sustainability and circularity evaluation methods is largely design-specific and explicitly or implicitly assumes a steady-state production. Thus, there exists a gap in the literature concerning PSP forecasting over multi-period productions with closed-loop flows. Therefore, this paper proposes a metrics-based framework that quantifies, simulates, and forecasts the PSP, considering the dynamic variations in demand forecast, closed-loop resource constraints, and end-of-use resource allocations. Accordingly, based on the literature on PSP evaluation as well as production planning, and input from industry experts, a new methodology was formulated to synthesize and develop this framework. A numerical application demonstrates that the PSP significantly varies with the demand curve profile (up to 25% change in certain metrics), even when the product design is constant. Most importantly, this paper introduces the concept of PSP as a “dynamic” measure over the temporal dimension, providing a framework to evaluate it comprehensively and with greater accuracy. Thereupon, this concept transforms how sustainability and circularity are viewed conventionally. When adopted, the concept will offer the designers greater insights that significantly improve the product design and planning process to advance the CE.

Keywords:

Product Design; Sustainable Manufacturing; Circular Economy; Closed-loop; Multi-period Production; Total Life Cycle;

1. Introduction

Sustainable manufacturing (SM) provides a foundational and comprehensive basis to implement the circular economy (CE). Understanding the product sustainability performance (PSP) in terms of economic, environmental, and social dimensions (i.e., the *triple bottom line* - TBL) is crucial during the product design stage. It allows corrective design choices to minimize negative sustainability consequences throughout a product's life, including improvements to end-of-use (EoU) recovery and integration with the CE. Thus, the product design stage requires accurate methods to evaluate PSP over the life cycle.

PSP evaluations typically assess TBL impacts focusing on the design attributes and neglecting the production-related variations that happen over time. This is evident by many measures of product sustainability and circularity being "design-specific." Since SM and CE promote closed-loop production that interlink the supply chain with *demand cycle*[1]—typically identified by the *market introduction*, *growth*, *maturity*, and *decline* phases—these time-dependent variations are further consequential to the PSP. The following example illustrates this.

Figure 1 visualizes the production forecast and the forward and return product-flows (depicted as batches to simplify) for a timeline spanning multiple production periods. The production forecast corresponds to the demand cycle. The delay in returns (due to the product's time in use) and the cumulative effect (due to progressively increasing number of production periods contributing EoU products) cause the amount of recovered EoU products to dynamically change over the production timeline. Therefore, the primary resources and processing needs for a product

[1] The term "product life cycle" is often used to refer to these market phases. However, to avoid confusion, the term "product life cycle" in this paper refers to the product's physical life stages of *pre-manufacturing*, *manufacturing*, *use*, and *post-use*, following the SM literature.

produced in a later period can considerably reduce compared to a product produced in an initial period (visualized by reducing solid yellow lines below the x-axis). Thus, depending on the processes and EoU activities utilized (e.g., reuse, remanufacture, recycle), the per product TBL impacts and the resulting PSP dynamically differ over time, even for the same product design.

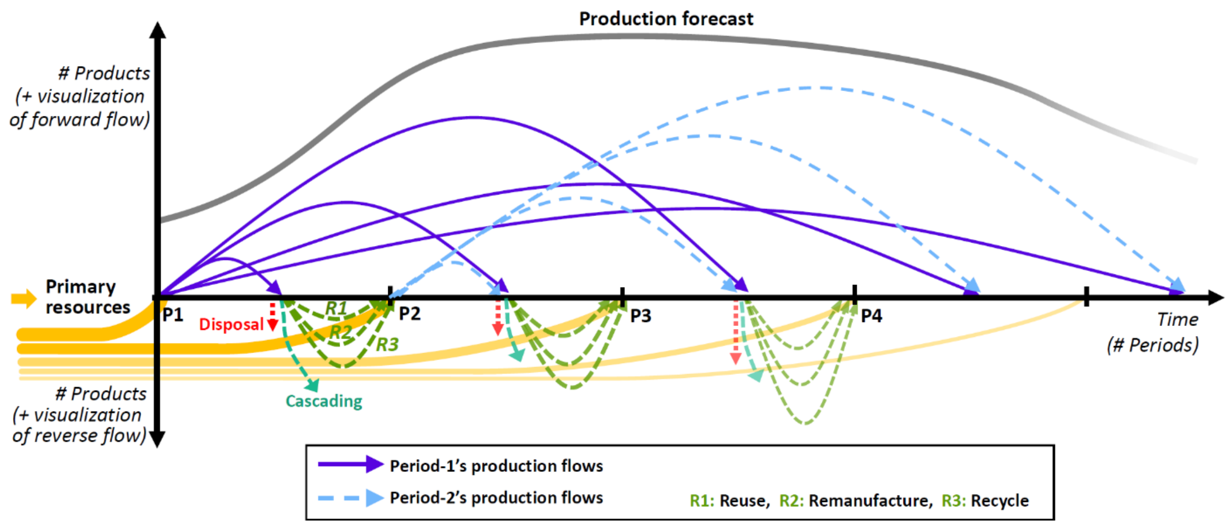


Fig. 1 Visualization of production forecast, and forward and closed-loop return flows along the production timeline

Current methods evaluate product sustainability and circularity assuming (either explicitly or implicitly) a "steady-state" in production. However, due to dynamic variations (identified in Figure 1) occurring over the demand cycle, such a steady-state production assumption can lead to a significantly inaccurate PSP assessment. Therefore, a PSP calculation that considers these "dynamic" production variations enables a more realistic evaluation. Moreover, the authors' direct interactions during project meetings with design experts from multiple industries (e.g., automotive, aerospace, and consumer electronics) also suggested that designs teams understand the need for dynamic evaluation. Nevertheless, there is a lack of design stage tools that account for the dynamic secondary resource availability and the resulting PSP implications.

Therefore, the novel evaluation framework presented in this paper quantifies and forecasts a product design's PSP through its closed-loop production timeline, considering the dynamic variations in demand, production, and EoU-appropriation (involving reuse, remanufacture, recycle, sell, and disposal streams). *Section 2* provides the theoretical background related to building this new framework. *Section 3* details the development of the proposed metrics-based framework, adapting to the design stage's limited data and resource availability. The PSP metrics were chosen from a recently established sustainable product design evaluation method [1]. However, the notion of *dynamic* PSP applies to any product sustainability evaluation method. Furthermore, while this paper focuses on the product level, the presented framework also applies to the module level in production-platforms where multiple product designs are produced using common modules. *Section 4* presents an example as a numerical application of the proposed framework. The different demand curves in the example demonstrate the potential for significant variations in PSP measures over time, even when the product design is kept constant. It highlights the importance of considering the *PSP as a dynamic measure in the temporal dimension*. Since the CE benefits are drawn from comprehensive sustainability evaluations, this shift in approach to evaluating product sustainability is fundamental to advancing the CE. The last section summarizes the significant contributions of this paper.

Table 1 List of frequently used abbreviations

Abbreviation	Description
6Rs	Reduce, Reuse, Recycle, Redesign, Recover, Remanufacture
B2B	business-to-business
CE	circular economy
CO2e	carbon dioxide equivalent
DC	demand curve
EoU	end-of-use
EPR	extended producer responsibility
GHG	greenhouse gas
LCA	life cycle analysis

LCC	life cycle costing
MCI	material circularity indicator
OEM	original equipment manufacturer
PCI	product circularity index
PSP	product sustainability performance
ProdSI	product sustainability index
SM	sustainable manufacturing
SS	steady state
TBL	triple bottom line

2. Background

2.1. Sustainable Manufacturing (SM) and Circular Economy (CE)

SM strives to reduce negative TBL impacts of manufacturing by minimizing waste, toxic emissions, and resource use; improving safety and product/process quality; and improving life cycle cost benefits [1]. Enabling SM requires effective planning during the product design stage [2]. Product sustainability and SM are essential to advancing the CE [3, 4]. Given the importance of accurate evaluation for proper life cycle planning [5], this paper focuses on measuring and forecasting PSP at the design stage.

The CE transforms the current “take-make-use-dispose” linear economy to a restorative and regenerative one [6]. Literature also discusses the direct relevance of the CE to the manufacturing sector [7, 8]. A recent comprehensive review by Kirchherr et al. [9] identifies over 100 different definitions for the CE. They synthesized an exhaustive definition for the CE, emphasizing the fundamental connection to sustainability [9]. Many other CE definitions lack a direct link to SM, where some fail to consider all three TBL dimensions [4, 9, 10]. However, in another extensive literature review comparing the SM and CE, Geissdoerfer et al. [4] establish many similarities between the two concepts and find the CE often considered a condition or a positive influence on sustainability.

Since SM entails complex and sometimes contradicting objectives due to its TBL focus, in some cases, a higher circularity-level does not necessarily equate to better sustainability [11, 12]. Moreover, the CE-related EoU activities (e.g., remanufacture and recycle) themselves have different TBL impacts depending on the exact processes/materials used. Thus, their *net* sustainability impact in each application must be carefully analyzed [13]. While some authors suggest separating environmental sustainability concerns from the circularity measures for clarity [14], products must be evaluated in terms of both sustainability and circularity [1, 10]. Accordingly, the following two sub-sections discuss the available product sustainability and circularity measures.

2.1.1. Product Sustainability Measures

Metrics-based quantification at the product design stage enables SM by allowing targeted improvements [15]. Prior literature identifies many methods and measures to evaluate sustainability [16, 17]. Life Cycle Assessment (LCA) [18] based methods and the National Institute of Standards and Technology (NIST) initiated work (including a repository of over 200 SM indicators [19]) are some of the prominent early product-level specific evaluations [1, 19].

Given the bias towards the environmental dimension in sustainability, it is vital to choose correct sustainability measures [20]. Although *social-LCA* [21, 22] and manufacturing process social impacts [23] literature offers some measures, the social dimension generally lacks comprehensive metrics [17, 24]. Additionally, fuzzy-logic-based [25] or optimization-based [26] approaches can be used to improve assessment and aggregate different TBL dimensions.

To overcome the drawbacks of many other methods, the *Product Sustainability Index* (ProdSI) [27] method incorporated over 90 metrics spanning all three TBL dimensions to provide a framework for comprehensively evaluating PSP. A recent work [1] further expanded ProdSI and adapted it to the design stage. *Section 3.2.1* discusses the use of this expanded method and its metrics within this paper's proposed framework.

2.1.2. Product Circularity Measures

Recent reviews [10, 28, 29] identify numerous metrics and indicators to assess circularity at the product level (i.e., nano-level of the CE [30]). Saidani et al. [30] highlight the crucial role of circularity measures for improved CE implementations. Given the wide range of CE definitions, different circularity measures focus on a variety of aspects. In general, many of these measures focus on material and resource recirculation and fail to fully assess all three sustainability dimensions [10, 31]. Similar to sustainability measures, many CE measures are also based on LCA-related methods [5, 7].

A review of three common product-level measures (including the *Material Circularity Indicator* (MCI)) found that although they provide a good overview of product circularity, these methods miss certain CE elements and lack guidance for product designers [30]. Bracquené et al. [32] introduced the *Product Circularity Indicator* (PCI), expanding on MCI and other previous circularity measures. PCI made critical improvements to add accounting for the tightness of cycles (reuse vs. recycling) and links with other product systems. *Section 3.2* of this paper discusses incorporating circularity metrics (including PCI) in the dynamic PSP measurement.

2.2. Planning Resource Reutilization at the Product Design Stage

Careful planning of EoU resource utilization is essential to advance the CE. Therefore, *Section 2.2* discusses background literature on elements that must be considered for sustainable and circular production.

2.2.1. The Necessity for Closed-loop Production

SM requires evaluating TBL impacts of all product life cycle stages to avoid burden shifting [33]. The CE identifies business opportunities in EoU resource recovery to overcome SM challenges [34]. Notably, efficient disassembly and recovery of EoU products are vital to enable TBL benefits and support adoption of the CE [35]. The recovered EoU resources can be utilized in value chains of both the same product (i.e., closed-loop flow) and other suitable applications beyond the original product (i.e., cascading or open-loop flow [6]) [36, 37]. However, the CE and SM both promote *tighter cycles* (i.e., closest restoration paths that require the minimum transformation of EoU resources) as the preferable option [6, 33]. Owing to increasing extended producer responsibility (EPR) regulations [38-40], manufacturers are further compelled to take back EoU products and be responsible for the *post-use* stage. Also, due to the unique knowledge and access to materials and design of the original product, there are merits to manufacturers themselves carrying out EoU activities such as remanufacture [34, 41]. Furthermore, previous studies establish closed-loop supply chains' ability to create economic, environmental, informational, and customer value [7, 42, 43]. Thus, closed-loops are crucial to implementing the CE and SM, and will be the primary focus of this paper.

2.2.2. End-of-Use (EoU) Activity Hierarchy and 6Rs

An EoU activity hierarchy is key to the CE as it can prioritize the more effective and sustainable *tighter cycles* [9]. A European Union directive [44] recommends the descending priority order of EoU options: *prevention*; *reuse*; *recycling*; *other recovery methods* (e.g., energy recovery [45]); and *disposal*. Likewise, the 6Rs concept (*reduce*, *reuse*, *recycle*, *redesign*, *recover*, and *remanufacture*) [7, 46] transforms the traditional 3Rs (*reduce*, *reuse*, and *recycle*) into a more comprehensive EoU activity framework. It further underscores the purposeful EoU activity planning at the product design stage to minimize TBL impacts [46]. Though there are recent discussions of additional "Rs" (up to 10Rs, such as *refuse*, *rethink*, *repair*, *refurbish*, and *repurpose*) in the literature [9], the 6Rs concept provides the necessary basis for the closed-loop system discussed in this work. Importantly, the 6Rs concept was also established as a technical element of advancing the CE [47]. *Section 3.1.1* discusses the application of 6Rs-based production planning.

2.2.3. Dynamic Production Considerations

The CE's increased push for prolonged and multiple circulations [48] makes evaluating TBL impacts due to EoU activities and the *primary* (i.e., virgin) vs. *secondary* (i.e., sourced from recovered resources) resource-flows essential. Therefore, planning a sustainable production requires keeping track of the resource's recirculation [29], availability [29], and quality [34].

There is a dynamic link between the product demand cycle and the return resource availability [49]. The mean product lifetime, technical innovation rate, and component failure rate are some of the primary influencing parameters. Thus, the EoU activity levels vary with the demand cycle, leading to dynamic TBL impacts over time. As the demand cycles become shorter [50], understanding the dynamic variation of PSP becomes paramount.

Multiple previous works [49, 51, 52] discussed the demand cycle's impact on remanufacturing potential, particularly concerning the economic dimension. Geyer et al. [51] presented analytical modeling for closed-loop production with remanufacturing and considered the limited durability and finite product cycling aspects. This work demonstrated the need for careful coordination of demand cycle, return rate, and component durability. Wang et al. [52] studied dynamic diffusion modeling to identify optimal economic benefits. However, research studying the demand cycle's interaction with other TBL dimensions or multi-EoU streams has been minimal. One such reported study presented the economic and environmental impact of remanufacturing [53]. Another study introduced the novel concept of the *sustainable half-life model*—which integrated the profit and loss curve with the demand cycle's half-life [54]. A recent study on modeling the demand cycle and EoU returns over a multi-period production timeline [55] set the necessary groundwork for modeling overall PSP. *Section 3* of this paper details modeling the TBL impacts of multiple EoU streams for a typical production.

2.2.4. The Necessity for Product Design Stage-focused Evaluation

Design stage decisions affect these dynamic production concerns, including through limiting/promoting of specific EoU activities. Design stage was also identified critical to remanufacturing for both improving the production planning as well as quality [56]. Thus, the PSP must be estimated and planned at the design stage. Early work on Life Cycle Costing (LCC) [57, 58] identified approaches to model and estimate life cycle metrics but was limited to the economic dimension. Developing manufacturing process information models to aid more sustainable decisions at the product design stage is another necessity [59]. Especially, the production planning level lacks TBL-focused decision support frameworks [20]. In addition, other publications discussed how production concerns (e.g., quantity and complexity) directly impact PSP [60] and the importance of multi-life cycle production planning for optimum product configuration design [55].

However, current sustainability and circularity measures (discussed in *Sections 2.1.1* and *2.1.2*) concentrate on the product design attributes rather than production. Even the comprehensive methods (e.g., ProdSI, MCI, or PCI), while providing valuable information in their own right, implicitly or explicitly assume a steady-state production.

Thus, in the current practice, the product design stage lacks comprehensive evaluation tools that consider the factors discussed in this section and forecast the PSP over closed-loop production. Therefore, *Section 3* details the development of a quantitative framework that transcends the available "retrospective" evaluations.

3. Proposed Methodology

Figure 2 provides an overview of the new two-step framework. *Sections 3.1* and *3.2* discuss Step 1 and Step 2, respectively. The framework utilizes the Monte Carlo method to simulate the

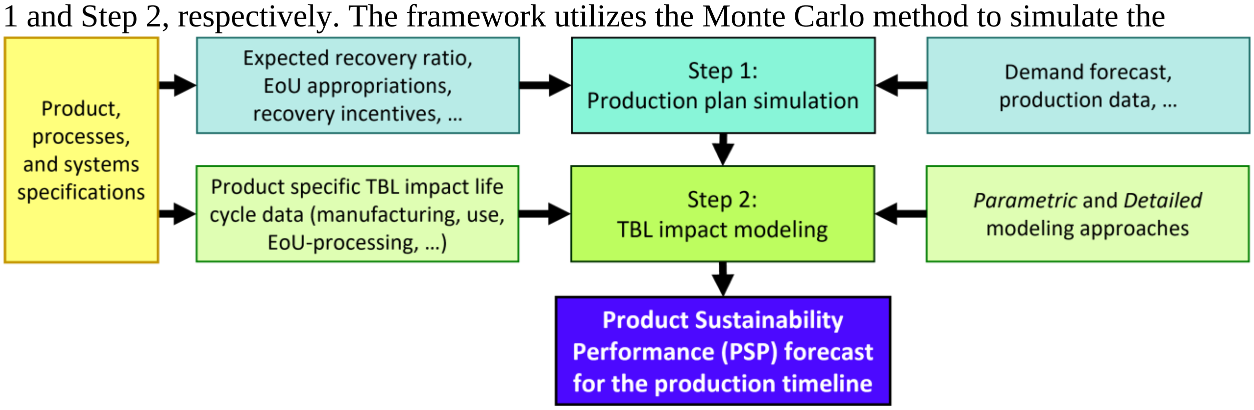


Fig. 2 An overview of the developed framework evaluating product sustainability performance over production timeline

stochastic primary input uncertainties in the production factors (periodic demand, product life span, and EoU recovery ratio) and calculates the TBL impact metrics. Finally, the metrics are aggregated over the production timeline to forecast the PSP.

3.1. Production Plan Simulation

3.1.1. Modeling Multi-Period Production

Demand forecast for each period of the production timeline is available at the design stage. It typically uses previous product generation data or market analysis and is calculated at the product level (i.e., as a number of products). Most products consist of multiple sub-assemblies or components. For brevity, the term “component” is used in this paper to designate the secondary level (i.e., component, part, or sub-assembly levels). The concepts presented for these two levels (i.e., product and component) can be easily extended to more complex multi-level designs.

EoU returns happen at the product level and are then disassembled into components during recovery processing. Many products return due to failures of one or a few components, while numerous other components are still functional. Thus, for recovery and other EoU activities, the number of reusable/remanufacturable components must be calculated. In the proposed model, the “production-mix” is the total number of new (i.e., “newly manufactured”), reused, and remanufactured components produced in a specific period.

When the number of periods analyzed is N, number of unique components c in a single product is λ_c, and total number of components is C, the inputs to calculate production numbers are as follows:

Demand for product in period $i = D_i$ *for* $i = 1, 2, \ldots, N$

Demand for component *c* in period $i = D_i\lambda_c$ *for* $i = 1, 2, \ldots, N$ and $c = 1, 2, \ldots, C$

Fraction of products produced in period *ip*, which comes to EoU in period $i = \omega_{ip,i}$

Due to the nature of product failure, the variable $\omega_{ip,i}$ can be considered a normally-distributed parameter with an expected value of *E*—which reflects the product's expected life.

$$\text{Number of products coming to EoU in period } i\ (N_i^{EoU}) = \sum_{ip=1}^{i} D_i\omega_{ip} \quad (1)$$

$$\text{Number of recovered products in period } i\ (N_i^{recov}) = \sum_{ip=1}^{i} D_i\omega_{ip}R_i \quad (2)$$

R_i is the recovery ratio (the proportion of EoU products returned to OEM/EoU-agent for recovery, out of the total number of products that becomes EoU) for the period *i*. EoU products not returned to the manufacturer are considered "lost products."

$$\text{Number of "lost products" in period } i\ (N_i^{lost}) = \sum_{ip=1}^{i} D_i\omega_{ip}(1 - R_i) \quad (3)$$

Given that these production calculations are forecasts, there is inherent uncertainty in the input parameters. The Monte Carlo method stochastically simulates feasible ranges of values for the uncertain parameters. Previous studies have detailed the use of Monte Carlo simulation to quantify and address such uncertainties of production parameters in closed-loop supply chain applications [61, 62]. *Section 4.1* presents the stochastic modeling of periodic demand (D_i), product life span (*E*), and EoU recovery ratio (R_i), based on the Monte Carlo simulation.

The returned products of period *i* are disassembled and evaluated at the component level to identify the most appropriate EoU option based on the CE idea of "tighter circles" and are utilized in period ($i+1$). Components (or products) that can be used after cleaning or repackaging are commissioned for *reuse* in the same application (e.g., products returned to the manufacturer due to packaging damages). From the remainder, components that can be brought back to original specifications by some additional processing are commissioned to *remanufacture*. From the rest, components that can be recycled into raw material are designated to *recycle*. The remaining components with a residual value that can be utilized in other applications are then allocated for *sale* (which may include energy recovery). Since such "other applications" are varied and indefinite, the *sale* fraction's metric-level measurement's scope was limited to the disassembly processing. Any remaining components without recoverable value are finally allocated to *disposal*.

The fractional-allocation for each EoU option (i.e., EoU appropriation) at the component-level (illustrated in Figure 3) are defined as reuse ($\gamma_{c,i}^{reuse}$), remanufacture ($\gamma_{c,i}^{reman}$), recycle ($\gamma_{c,i}^{recyc}$), sale ($\gamma_{c,i}^{sale}$) and dispose ($\gamma_{c,i}^{dispo}$).

$$\text{Number of components allocated for } \textit{reuse}, \; N_{c,i}^{reuse} = \gamma_{c,i}^{reuse} \times N_{i-1}^{recov} \tag{4}$$

$$\text{Number of components allocated for } \textit{remanufacture}, \; N_{c,i}^{reman} = \gamma_{c,i}^{reman} \times N_{i-1}^{recov} \tag{5}$$

$$\text{Number of components allocated for } \textit{recycle}, \; N_{c,i}^{recyc} = \gamma_{c,i}^{recyc} \times N_{i-1}^{recov} \tag{6}$$

$$\text{Number of components allocated for } \textit{sale}, \; N_{c,i}^{sale} = \gamma_{c,i}^{sale} \times N_{i-1}^{recov} \tag{7}$$

$$\text{Number of components allocated for } \textit{disposal}, \; N_{c,i}^{dispo} = \left[1 - \left(\gamma_{c,i}^{reuse} + \gamma_{c,i}^{reman} + \gamma_{c,i}^{recyc} + \gamma_{c,i}^{sale}\right)\right] N_{i-1}^{recov} \tag{8}$$

$N_{c,i}^{new}$ is the number of component *c* that needs to be manufactured new for the period *i*. A production capacity maximum can constrain it ($N_{c,i}^{new\_max}$).

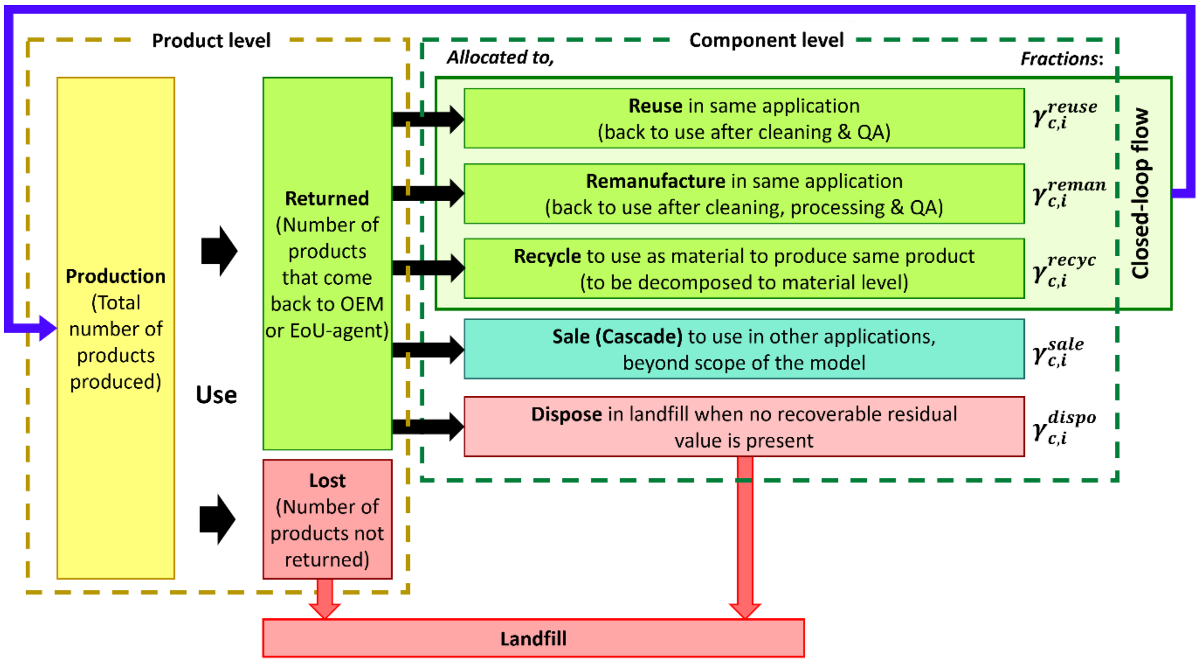


Fig. 3 Transition of products through life cycle stages and EoU-appropriation at component-level

The total number of components *c* produced and delivered to the market in period *i* ($N_{c,i}^{Prod}$) is:

$$N_{c,i}^{Prod} = N_{c,i}^{new} + N_{c,i}^{reuse} + N_{c,i}^{reman} \quad (9)$$

(at $i = 0$: $N_{c,0}^{reuse} = 0$ and $N_{c,0}^{reman} = 0$)

For each period *i* at the component level (component *c*), the production-mix ($N_{c,i}^{Prod}$) is calculated matching their demands ($D_i\lambda_c$) while constrained by the $N_{c,i}^{new\_max}$ and EoU allocation levels (as visualized in Figure 4).

Taking the EoU hierarchy [44] as the initial basis of calculation, first, any available reuse allocation ($N_{c,i}^{reuse}$) is used to fulfill demand of the period ($D_i\lambda_c$). If that does not suffice, remanufactured components ($N_{c,i}^{reman}$) are used to fulfill the demand. If both those allocations do not suffice, newly manufacturing is sought. If the demand for the product/component is lower than the reuse or remanufacture allocations, the excess is allocated for recycling (updating the

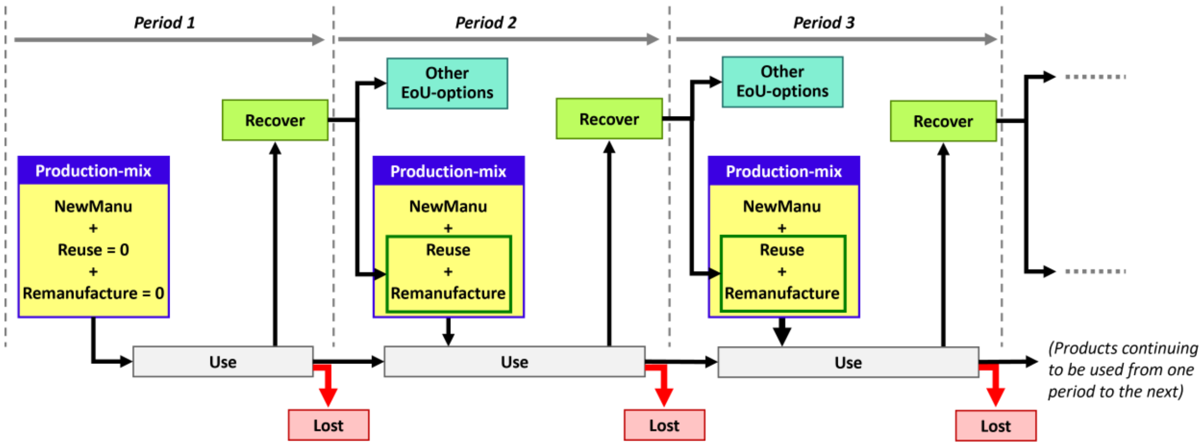


Fig. 4 Multi-period production-mix and EoU appropriation

total number of components recycled to $N_{c,i}^{recyc*}$). All recovered content of each period *i* is allocated to an EoU option in the next period (*i+1*).

In remanufacturing, the term "core" designates a key component (e.g., an engine cylinder block, a toner cartridge casing) that is typically repurposed when other components are replaced or repaired. In complex multi-level products, each sub-assembly can contain a "core." When calculating the number of new components to be manufactured in each period, the number of cores ($N_{c_{core},i}$) and other components retained for remanufacturing ($N_{c,i}^{reman\_retain}$) are factored in. The retain ratio (λ_c^{retain}) indicates the percentage of a specific component type *c* retained. For cores, the λ_c^{retain} is 100%. Thus, the total number of new components necessary to produce from the component *c* in period *i* is:

$$N_{c,i}^{new} = D_i\lambda_c - (N_{c,i}^{reuse} + N_{c,i}^{reman\_retain}), \quad (10)$$

$$\text{where } N_{c,i}^{reman\_retain} = \lambda_c^{retain} N_{c_{core},i}.$$

3.1.2. Material Requirement Calculations

Material mass requirement calculation for a "new" component considers the material efficiency in component production (φ^{new}). It compensates for the material scrappage during processing. If the material *m*'s final mass in component *c* is $m_{c,m}$, the total material *m* necessary to produce a "new" component *c* is $M_{c,m}^{new} = m_{c,m}/\varphi^{new}$.

For remanufactured components, the material requirement factor ($\mu_{c,m}^{reman}$) is the average fractional material amount necessary to remanufacture a component back to its specification. Thus, for a remanufactured component *c*, the additional material *m* needed is $M_{c,m}^{reman} = \frac{m_{c,m}}{\varphi^{new}}\mu_{c,m}^{reman}$. This assumes remanufacture processing has a similar material efficiency to "new" component processing.

The total raw material *m* mass required ($M_{m,i}^{req}$) for producing the total number of new and remanufactured components in period *i* (assuming reused components do not require additional raw material) is,

$$M_{m,i}^{req} = \sum_c M_{c,m}^{new} N_{c,i}^{new} + \sum_c M_{c,m}^{reman} N_{c,i}^{reman}. \quad (11)$$

Using the recycling efficiency of material *m* (φ_m^{recyc}), the total material mass available from recycling in each period (RM_m^{avail}) can be estimated by:

$$RM_{m,i}^{avail} = \sum_c m_{c,m}\varphi_m^{recyc} N_{c,i}^{recyc*} \quad (12)$$

For period *i*, the actual material *m* mass recycled ($RM_{m,i}^{actual}$), total material *m* virgin mass required ($VM_{m,i}$) and excess material *m* mass allocated as *sale* in other applications ($RM_{m,i}^{sale}$) are calculated by comparing the material *m* requirement ($M_{m,i}^{req}$) and available recycled material *m* ($RM_{m,i}^{avail}$) masses.

If $RM_{m,i}^{avail} > M_{m,i}^{req}$, then (13)

$$RM_{m,i}^{actual} = M_{m,i}^{req}, \quad RM_{m,i}^{sale} = RM_{m,i}^{avail} - M_{m,i}^{req} \text{ and } \quad VM_{m,i} = 0.$$

Otherwise, $RM_{m,i}^{actual} = RM_{m,i}^{avail}$, $VM_{m,i} = M_{m,i}^{req} - RM_{m,i}^{avail}$ and $RM_{m,i}^{sale} = 0$

3.2. Product Sustainability Performance (PSP) Evaluation

The scope of this work spans evaluating TBL impacts in all life cycle stages: *pre-manufacturing* (material extraction and energy generation); *manufacturing* (processing and sales); *use* (product's functional and maintenance); and *post-use* (returns, recovery-processing, and disposal). It also includes the *transportation* between and within those stages.

3.2.1. Product Sustainability Performance Metrics Considered

Quantifying PSP is a challenging task. It is particularly true in the design stage—a stage markedly constrained by resources, time, and data. A recent PSP evaluation method [1] developed specifically for the design stage was selected for the proposed analysis. The tables below list several sustainability metrics and metric-clusters used for analyzing the economic (Table 2), environmental (Table 3), and social (Table 4) impacts. Uniquely, this method also explicitly quantifies the TBL impacts on three broad stakeholder groups (manufacturer, customer, society-at-large), allowing a more comprehensive evaluation going beyond the typical manufacturer-focused methods. The metric-clusters here are arranged to provide a more distinct perspective for each stakeholder. In addition, listing both *costs* and *revenues* allows a greater understanding of each stakeholder's economic impact.

The new framework was developed to be generic and look at high-level impacts to assess a PSP, especially considering the production and EoU-appropriation. Many LCA-based methods evaluate endpoint impact categories. Due to the design stage's constraints, midpoint impact categories and readily quantifiable metrics were found to be more apt. Furthermore, the metrics were selected to reflect this paper's focus on studying the production variations' impacts on PSP. The elemental metrics here provide a proof-of-concept for the framework. It is expandable to incorporate the complete set of metrics and clusters discussed in [1], especially when relevant modeling data and resources are available.

The social dimension, as identified in *Section 2.1.1*, is typically more challenging to quantify. Table 4 lists some of the metrics and metric sub-clusters available to evaluate social dimension. Prior studies [22, 63, 64] have detailed the methodologies and calculation of these metrics.

Table 2 Economic impact evaluation metric sub-clusters and specific metrics (Adapted from [1])

Affected/ Benefitted Primary Stakeholder Category	***Life Cycle Stage***	***Metric Sub-clusters***	***Specific Metric Examples***
Cluster: "Manufacturer" stakeholder category Gross Profit ($) = R_Manu - C_Manu			
i. Cost for "Manufacturer" stakeholder category (C_Manu)			
Manufacturer	M	Capital cost	Cost acquiring technology, employee training
	PM, M, PU	Material cost	Virgin material acquisition cost, material recycling cost
	M	Processing cost	Energy cost, labor cost
	PU	Product recovery cost	Buyback cost (portion), sorting cost
	PU	EoU activities cost (reuse, remanufacture, etc.)	Processing cost related to each EoU activity
	PM, M, PU	Waste disposal cost	Landfill cost, labor cost
	PM, M, PU	Transportation cost	Material transportation cost, EoU transportation cost

ii. Revenue for "Manufacturer" stakeholder category (R_Manu)			
Manufacturer	M	Product sales revenue	Revenue from new, reuse, and remanufactured product sales
	PU	Recovered components/assembly sales revenue	Revenue from component or assembly sales
	PU	Excess recycled material sales revenue	
Cluster: "Customer" stakeholder category Gross Profit ($) = R_Cust - C_Cust			
i. Cost for "Customer" stakeholder category (C_Cust)			
Customer	U	Product purchase cost	Purchase cost of new, reused, or remanufactured products, tax
	U	Product operational cost	Consumables' cost, operator labor cost
ii. Revenue for "Customer" stakeholder category (R_Cust)			
Customer	U	Product operational revenue	
	PU	Product disposal value	Product buyback value, product resell value
Cluster: "Society-at-large" stakeholder category Gross Profit ($) = R_Soc - C_Soc			
i. Cost for "Society-at-large" stakeholder category (C_Soc)			
Society-at-l.	PU	Landfill costs	
	PU	Recovery incentives	Buyback cost (portion)
ii. Revenue for "Society-at-large" stakeholder category (R_Soc)			
Society-at-l.	PM, M, U, PU	Labor compensation	Labor compensation in manufacturing processes
	PM, M, U, PU	Tax revenue	Sales tax, carbon/energy tax

Note: PM = Pre-Manufacturing; M = Manufacturing; U = Use; PU = Post-Use;

Table 3 Environmental impact evaluation metric sub-clusters and specific metrics (Adapted from [1])

Affected/ Benefitted Primary Stakeholder Category	***Life Cycle Stage***	***Metric Sub-clusters***	***Specific Metric Examples***
Cluster: Primary material consumption *(by material's mass or a 'weighted' sum based on scarcity, value, etc.)*			
Society-at-l., Manufacturer	M, PU	Primary material mass in products	Primary material mass in new, reused, and remanufactured products
	M, PU	Material mass discarded as waste	Scrapped/consumable material mass in new, reused, and remanufactured products
Cluster: Greenhouse gas emission (GHG) *(GWP in Carbon Dioxide Equivalent (CO_2e))*			
Society-at-l.	PM	GHG emission due to material production	
	M	GHG emission due to manufacturing processes	
	U	GHG emission due to product usage	
	PU	GHG emission due to EoU activities	
	PM, M, U, PU	GHG emission in transportation activities	

	PU	(-) GHG emission reduction due to recovery	
Cluster: Energy consumption *(Btu, kWh, etc.)*			
(expandable similar to Cluster on GHG)			
Cluster: Water/Other resource consumption			
(expandable similar to Cluster on GHG)			
Cluster: Waste emissions			
(expandable similar to Cluster on GHG)			

Note: PM = Pre-Manufacturing; M = Manufacturing; U = Use; PU = Post-Use;

Table 4 Social impact evaluation metric sub-clusters and specific metrics (Adapted from [1])

Affected/ Benefitted Primary Stakeholder Category	***Life Cycle Stage***	***Metric Sub-clusters***	***Specific Metric Examples***
Cluster: Product quality and durability score *(product specific metrics)*			
Customer	U	Expected product lifespan (design dependent)	
	U	Product repairability score (design dependent)	
Cluster: Safety and health impact score			
Society-at-l.	M	Safety incidents in production	Injury rate of processes
	PM, M, U, PU	Hazardous material exposure risk rating	Human toxicity potential of activities
Cluster: Regulatory and broader impacts score			
Society-at-l.	M	Direct employment opportunities created	Number of employees in manufacturing/operation
	PM, M, U, PU	Product regulatory compliance rating	
Cluster: Circularity compliance score			
Society-at-l.	PM, M, PU	Product Circularity Indicator (PCI)	
	PU	Cascaded value to other CE loops	Value of material cascaded to other applications
	M	Product design’s fit to larger CE system	Percentage of standard components in the product

Note: PM = Pre-Manufacturing; M = Manufacturing; U = Use; PU = Post-Use;

3.2.2. Modeling Simplification Using Basic Measurement Categories

Due to this framework’s intended utility as a designer (and manufacturer) decision support tool, the data collection and analysis process require simplification. For that, a combination of *parametric* and *detailed* modeling methods [57, 58] was chosen. The following five "basic measurement categories" were used to simplify the modeling of sustainability metrics. The categories were selected based on whether the product design can (directly or indirectly) influence the type of measure considered in each category.

i. Material-use based measurements:

This category of TBL metrics is estimated based on the correlations between primary material masses used and metric-of-interest (e.g., cost of material, GHG emission in raw material extraction). The primary (virgin) materials calculations are based on the $VM_{m,i}$. The TBL impacts due to closed-loop recycled (i.e., secondary) material are computed in the processing-time-based category evaluating EoU-activities.

Equation (14) expresses a general form for the material-use based impact measure of metric *x* (XM_i) in period *i*, where it is a function of $VM_{m,i}$. Equation (15) suggests a simplified equation, which calculates XM_i using the rate of metric *x* impact per unit mass of material *m* ($Xu_m^{mat-use}$) and the mass of virgin material *m* consumed ($VM_{m,i}$). The rest of this paper uses simplified equations to represent the calculations. These expressions require adaptation depending on the application, and available data, measurements, or modeled variables-metric correlations.

$$XM_i = \sum_m f(VM_{m,i}) \quad (14)$$

$$XM_i = \sum_m Xu_m^{mat-use} VM_{m,i} \quad (15)$$

For instance, when calculating costs, the cost of material m_1 for period *i* ($CM_{m1,i}$) is calculated using the unit material m_1 cost ($Cu_{m1}^{mat-use}$) and total virgin material m_1 ($VM_{m1,i}$) required.

ii. Process-time based measurements:

This category is estimated by correlating the different manufacturing and EoU activity processing times (e.g., cost of processing, GHG emission during processing).

The processing-time based impact measure of metric *x* ($XP_i^{act\_type}$) in period *i* is calculated at the production-type level (i.e., new manufacture, reuse, remanufacture, recycle, sale, and disposal). It uses the number of components processed in each activity type ($N_{c,i}^{act\_type}$), average processing-time of process *p* for component *c* ($t_{c,p}^{act\_type}$), and the rate of metric *x* impact per unit processing-time (Xu_p^{proc-t}):

$$XP_i^{act-type} = \sum_p \sum_c N_{c,i}^{act\_type} Xu_p^{proc-t} t_{c,p}^{act\_type} \quad (16)$$

iii. Product usage-based measurements:

This category estimates TBL impacts during the "use" stage. It considers metrics that can be modeled based on product usage (e.g., average number of hours of usage per period, number of use cycles per period). All relevant metrics are evaluated at the product level (e.g., usage cost, GHG emission in use of the product).

For a specific period *n*, the number of products in the *use* stage (N_n^{use}) is:

$$N_n^{use} = \sum_{i=1}^{n} Prod_i - \sum_{i=1}^{n} EoL_i \quad (17)$$

An average usage factor (t_{use}) is defined based on the number of hours (or another applicable unit of measurement tracking usage) a single product is expected to be used during a period. The usage-based impact measure of metric *x* (XU_i) is calculated using the metric *x* impact rate per unit time of usage, per product (Xu_u^{usage}):

$$XU_i \; = \; N_n^{use} t_{use} Xu^{usage} \tag{18}$$

For products with multiple types of uses or multiple distinctive usage patterns, the parameters Xu_u^{usage} and t_{use} represent multi-value arrays.

iv. Number of products based measurements:

TBL impacts model for this category is based on the number of products (or components) produced. Calculations differentiate between the production types (i.e., new-manufactured, reused, and remanufactured) in each period i ($Prod_i^{type}$). Example metrics for this category include manufacturer's sales revenue, customers' purchase cost, revenue from the sale of components for other applications.

The production-number based impact measure of metric *x* (XN_i) is expressed using the metric *x* impact rate per unit product ($Xu_{type}^{prod.num}$):

$$XN_i \; = \; \sum_m Prod_i^{type} \, Xu_{type}^{prod.num} \tag{19}$$

Transportation can also be simplified to measure using this category when every individual product follows a similar path.

The EoU products unreturned to the manufacturer (i.e., lost products) are often discarded improperly, ending up in landfills. For each metric, the burden of a single "lost product" is assumed to be the same as the burden of discarding a single product in a landfill (or the most common EoU-option taken, as appropriate for the application). This simplification assumption enables TBL-impacts estimation for the disposal aspect of "lost products" using the "number of products" category.

v. Fixed overheads and other measurements:

TBL impacts that are not variable (i.e., fixed) with other design and production parameters or not applicable in the last four categories are quantified under this category (e.g., fixed overhead cost (including capital costs) of operation, overhead GHG emissions).

When comparing product design alternatives, if a specific fixed aspect is common across all alternatives, the evaluation can be simplified by disregarding those (e.g., multiple product designs produced at the same facilities with the same fixed overhead metrics).

3.3. Aggregation of Metric-level Calculations

The estimated metrics (and sub-clusters) are then aggregated at the "Cluster" levels. This aggregation is done for the entire production timeline (i.e., all periods studied) based on the products and components quantities calculated in *Section 3.1*. If multiple basic measurement categories are available for a metric, they are combined. For example, the total GHG emissions cluster combines GHG emissions based on material production, manufacturing processes, and product usage.

The *economic* dimension aggregation is straightforward as all metrics are typically calculated in a single unit ($). In the *environmental* dimension, each cluster is calculated in a specific unit. However, in the *social* dimension, the metrics within a cluster may not be directly compatible. Thus, a "score" is calculated here, through aggregating the metrics sub-clusters as suggested previously [27], by normalizing each metric using a benchmark.

For the *economic* dimension, the "Gross Profit" cluster is defined for each stakeholder category (by taking the difference between cost and revenue). Understandably, an accurate gross profit value is incalculable without all applicable costs and revenue metrics. The cost and revenue clusters are also individually significant when comparing different product design alternatives. Additionally, all economic values are taken at the *present value* using an appropriate discount rate to compensate for the economic value created over several periods.

Furthermore, the values estimated for each stakeholder category depict values for the entire category of stakeholders (as further detailed in [1]) rather than for the individuals within that category.

Once all PSP metrics are calculated for the entire production, per product metrics can be calculated by dividing the values by respective production numbers (except for the “scores” which are independent of production numbers).

4. Results and Discussion

This section illustrates the application of the proposed methodology to a consumer electronics product with an established closed-loop flow. For this simplified example, the life cycle and production data provided in the *Supplementary Document* was used as inputs. Since the specific data are proprietary to the manufacturer, and the intention here is to examine the proposed model’s concept (rather than making specific assertions on the TBL impacts of given activities), these input values were based on typical data available in relevant literature [65, 66] and reasonable approximations made consulting an industry expert. Moreover, to keep the comparisons fair, all cases use the same input life cycle data set.

4.1. Case Study Setup

MATLAB (version R2020a) computing environment was used to code and simulate the models. At the product design stage, only *imperfect information* is available (say, from the marketing department of the manufacturer, based on historical data and market models) regarding the future states of demand and other production parameters. After consulting the typical information available to the designer/manufacturer and its margin of error, the input values for the *periodic demand*, *product life*, and *recovery ratio* were identified needing to be approximated by normal distributions. Table 5 lists the system parameters, including the descriptive statistics of the respective normal distributions. These parameters were also approximated by consulting the typical historical and market data available.

Table 5. Parameters relating to the analyzed product system

Parameter name	Value	
Price of a new product	$ 55	
Price of a rebuilt product	$ 45	
Product demand	*	CV = 0.1
Product life (i.e., average use time, in # periods)	$\mu = 6$	$\sigma = 1.5$
Recovery ratio (R_1)	$\mu = 0.4$	CV = 0.1
EoU appropriations for returned products:		
Reuse fraction	5%	
Remanufacture fraction	80%	
Recycle fraction	10%	
Sale fraction (cascade)	5%	
Disposal fraction	0%	

NOTE: A "rebuilt product" is a product with a reused or remanufactured component. In this manufacturer-involved recovery, rebuilt products are brought back to the original specification, and are functionally comparable to brand-new products.

**Figure 5 presents periodic demand mean values. μ = mean, σ = standard deviation, CV = Coefficient of Variation (CV = σ/μ).*

Figure 5 visually depicts the iterative process of forecasting the PSP. To account for the above-mentioned uncertainty, the Monte Carlo method-based production plan simulation tests for 10,000 random instances. This stochastic simulation is done by sampling from the variable input distributions of product demand, product life, and recovery ratio parameters. This process loops till the total number of periods examined (*T*) are simulated and then aggregated. The metric results (discussed in *Section 4.2.2*) were also found to follow normal distributions. Tables 6 and 8 summarize results by listing the expected (i.e., mean) values. Given the stochastic nature of the results, *Section 4.2.2* statistically analyzes the results to confirm they are in fact significant.

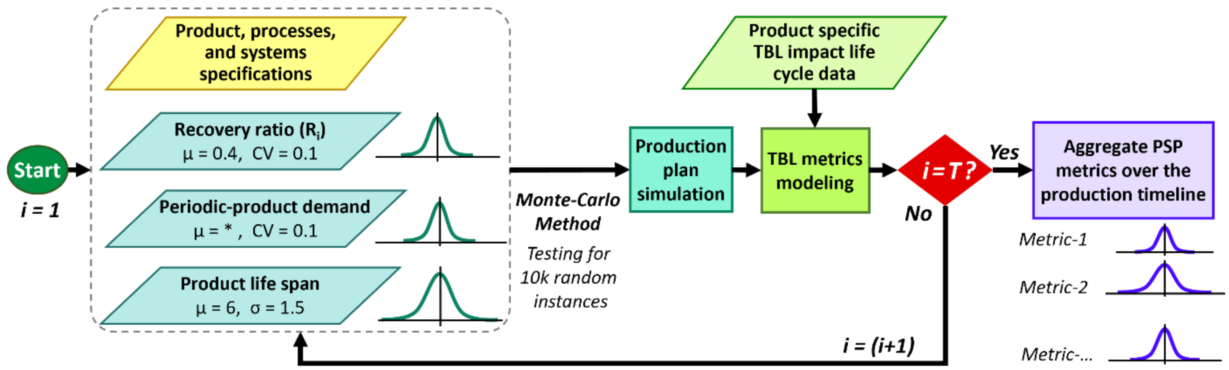


Fig. 5 Visual representation of the steps used in forecasting the PSP over the production timeline in four cases below

4.2. Comparison Between the Demand Curves (DCs)

The purpose of this section is to establish if the forecasted variation of PSP metrics due to demand/production changes over time are substantial enough to significantly affect the PSP of overall production, even after accounting for the uncertainty in data available at the design stage. Therefore, it compares the PSP metrics for three distinct demand curve (DC) profiles (*D1-D3*) and a hypothetical steady-state instance (*SS*)—that mimics the conventional sustainability evaluations.

4.2.1. Demand Curves Considered

DCs are typically product-category and market-specific. However, by introducing minor product updates, the designer can influence the DC shape. Figure 6 visualizes periodic product demands of *D1-D3* and *SS*, plotted for a 24-period production timeline. For each DC, the total product demand over all periods (each period equals one month) adds up to 240,000 units. While demand only spans 24-periods, the analysis in the simulation extends to capture sustainability impacts due to entire production (*T*), including the EoU products returning after 24-periods.

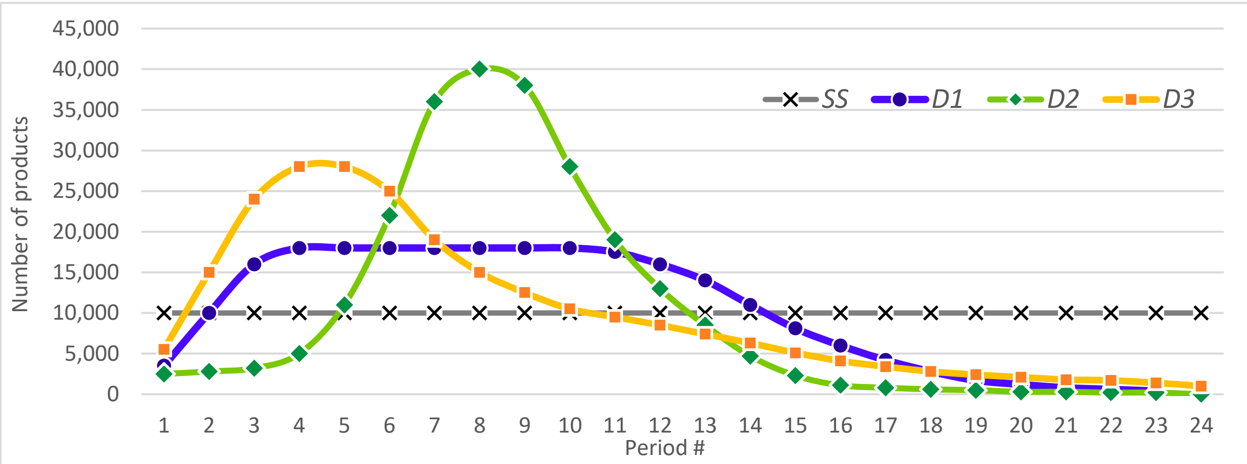


Fig. 6 Demand curve profiles of the three dynamic cases (D1-D3) and SS

Though not stated explicitly, due to their steady-state assumption, conventional sustainability evaluations use averaged production parameters for the entire timeline. The *SS* case simulates this. Since the total production is 240,000 units in 24-periods, in *SS*, the periodic production sets to 10,000 units for all periods. Also in *SS*, the recovery and its EoU activity allocation are set to their initial values listed in Table 5 for all periods (rather than deriving from *Section 3.1's* methods). Since the number of total products going into the "use" stage equals the total number of products leaving it as EoU in *SS*, the EoU rate equals the production rate.

Table 6 lists the aggregate demand and production values estimated by the production-mix calculations (from *Section 3.1.1*) for each case.

Table 6. Average aggregated demand, production, and lost product numbers through all production periods for each case

	D1	***D2***	***D3***	***SS***
Demand	239,918	240,326	239,869	239,918
Production total	239,918	240,326	239,869	239,918
Brand new products	181,609	209,551	168,047	158,300
Rebuilt products	58,309	30,775	71,822	81,618
Lost products	143,895	144,051	143,965	143,898

4.2.2. Metric Cluster Results

Due to the repetitiveness and limited space, a select set of metric clusters was chosen from Tables 2, 3, and 4 to evaluate the PSP of studied cases. The clusters (listed in Table 7) were chosen to represent all TBL dimensions, primary stakeholder categories, and the entire product life cycle. For the social dimension, individual metrics specific to each cluster were identified as proxy measures. It simplifies calculations and enables direct comparison between different cases considering relative variations (as given in Table 8 and Figure 8).

Table 7. Metric clusters used for product sustainability evaluation

#	**Sustainability Dimension**	**Primary Stakeholder Category Impacted**	**Metric Cluster (Specific Metric)**
1.	Economic	Manufacturer	Gross profit
2.			Cost
3.			Revenue
4.	Economic	Customer	Gross profit
5.			Cost
6.			Revenue
7.	Economic	Society-at-large	Gross profit
8.			Cost
9.			Revenue
10.	Environmental	Society-at-large	Primary material consumption
11.	Environmental	Society-at-large	GHG emissions
12.	Social	Society-at-large	Safety and health impact score (Human toxicity potential)
13.	Social	Society-at-large	Regulatory and broader impacts score (Direct employment opportunities)
14.	Social	Society-at-large	Circularity compliance (Cascaded material mass)
15.	Social	Society-at-large	Circularity compliance (Product Circularity Index - PCI)

Individual metrics and metric clusters in Table 7 were modeled using the approach presented in *Section 3.2.2*. Individual metric value results are not presented here due to limited space. Figure 7 illustrates a breakdown of the manufacturer's costs in each period of *D1*, representing many similar calculations done.

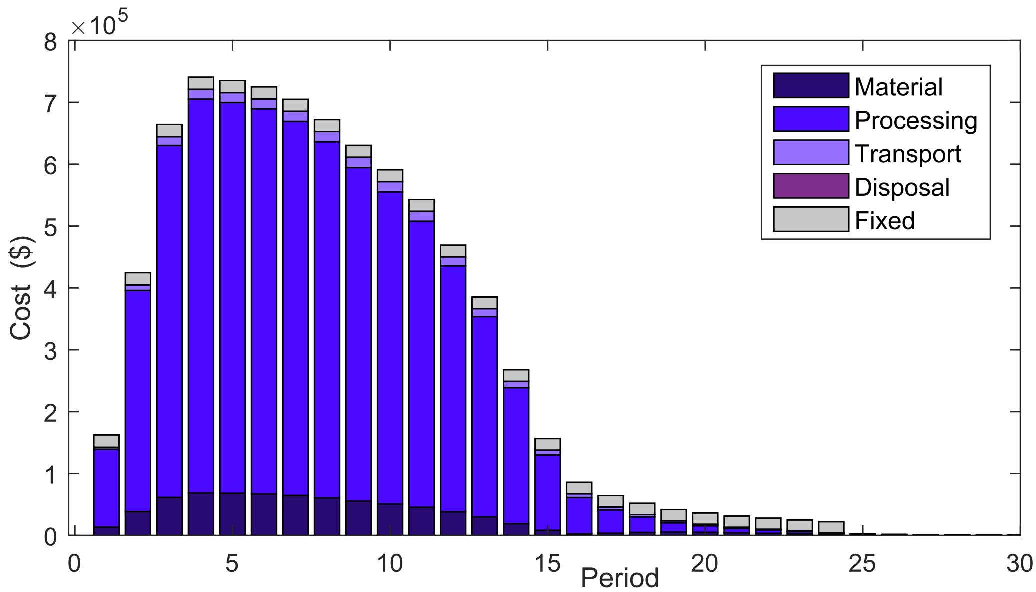


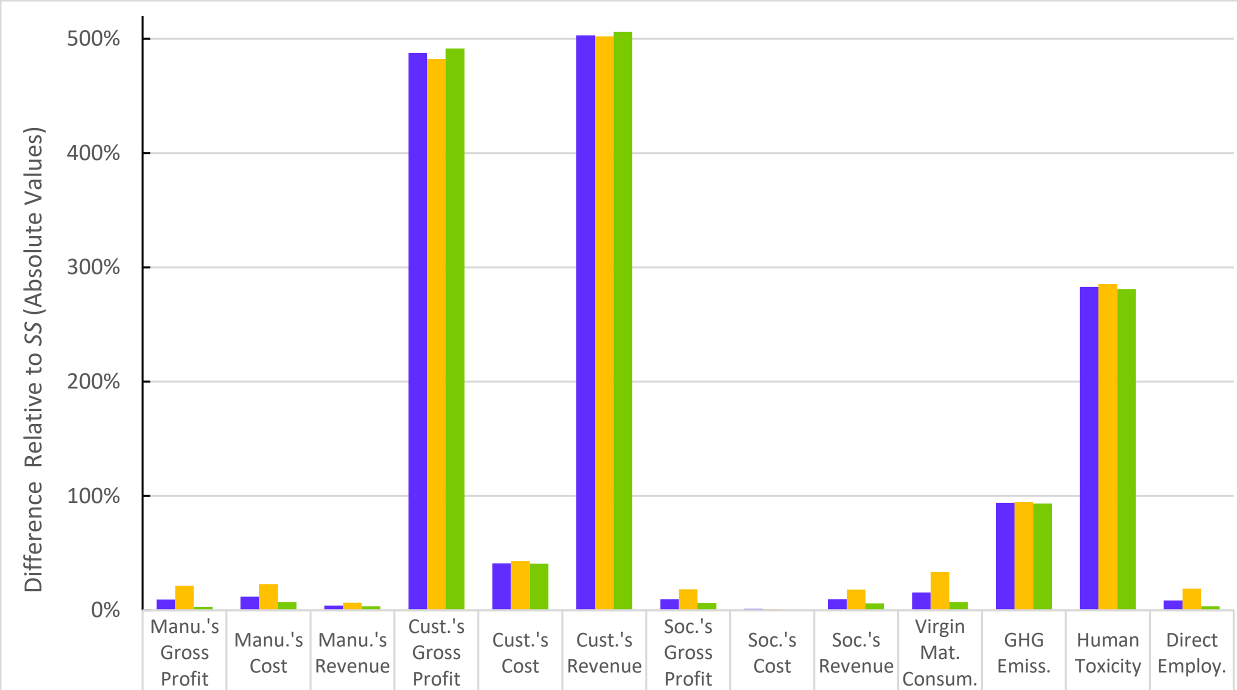
Fig. 7 Manufacturer's cost breakdown for D1 (in present value)

Table 8 summarizes per product average results of metric clusters for each case. The clusters are first aggregated for the entire production timeline (of 24 periods in this example) and then divided by the number of products produced (the "PCI" [32] is an exception as it is an index score). Table 8 lists the expected values of the resulting (normal) distributions after the calculation described in *Section 4.1.1*. The results illustrate that the changing DCs affect different sustainability clusters to different extents.

Table 8. Variation of product sustainability metric-cluster values for each case, averaged per product

#	Metric Cluster	Unit	*D1*	*D2*	*D3*	*SS*
1.	Manufacturer - Gross Profit	*$*	16.15	14.02	17.32	17.85
2.	Manufacturer - Cost	*$*	34.47	37.86	33.02	30.79
3.	Manufacturer - Revenue	*$*	50.63	51.88	50.34	48.64
4.	Customer - Gross Profit	*$*	106.09	104.66	107.19	-27.37
5.	Customer - Cost	*$*	82.77	83.99	82.66	58.70
6.	Customer - Revenue	*$*	188.86	188.64	189.85	31.33
7.	Society-at-large - Gross Profit	*$*	12.13	13.09	11.75	11.05
8.	Society-at-large - Cost	*$*	0.21	0.21	0.21	0.21
9.	Society-at-large - Revenue	*$*	12.34	13.30	11.96	11.27
10.	Primary Material Consumption	*kg*	1.08	1.24	1.00	0.93
11.	GHG emissions	*kg CO2eq*	36.07	36.24	35.95	18.60
12.	Human Toxicity Potential	*DALY*	4.90E-06	4.93E-06	4.87E-06	1.28E-06
13.	Direct Employment Opport.	*#work-hrs*	1.89E-01	2.07E-01	1.80E-01	1.74E-01
14.	Cascaded Material Mass	*kg*	6.37E-02	1.36E-01	3.22E-02	0.00E+00
15.	Product Circularity Index (PCI)	*(score)*	0.23	0.15	0.26	0.29

Figure 8 illustrates the percentage (absolute) change in PSP measures for each case, taking *SS* as the reference. A few cluster results (e.g., customer's gross profit, customer's revenue, and human toxicity) of *D1-D3* cases show a substantial discrepancy (up to 5 times) from the steady-state results. It is also important to note the considerable differences (up to 25%) within some clusters (e.g., manufacturer gross profit, virgin material consumption, and direct employment opportunities), which depend on the DC.



	Manu.'s Gross Profit	Manu.'s Cost	Manu.'s Revenue	Cust.'s Gross Profit	Cust.'s Cost	Cust.'s Revenue	Soc.'s Gross Profit	Soc.'s Cost	Soc.'s Revenue	Virgin Mat. Consum.	GHG Emiss.	Human Toxicity	Direct Employ.
D1 vs SS	9.5%	12.0%	4.1%	487.6%	41.0%	502.8%	9.8%	1.2%	9.6%	15.5%	94.0%	282.9%	8.5%
D2 vs SS	21.4%	22.9%	6.7%	482.4%	43.1%	502.1%	18.4%	1.2%	18.1%	33.5%	94.9%	285.5%	19.0%
D3 vs SS	2.9%	7.2%	3.5%	491.6%	40.8%	506.0%	6.3%	0.5%	6.2%	7.1%	93.4%	281.1%	3.6%

Fig. 8 Percentage difference of cluster results for each demand profile (D1-D3) relative to the steady-state (SS) case. (In absolute values)

Since the cluster results (Table 8) involve distributions, the statistical significance for mean differences of cases *D1-D3* and *SS* was tested. Welch's analysis of variance method was utilized due to the heterogenous case variances. At the 99% confidence level, all metric clusters show significant mean differences. The effect size was also calculated to characterize the magnitude of these differences. At the 99% confidence interval, most of the metric clusters exhibit a large effect size. Exceptions were clusters# 1, 2, 7, 9, and 13 with medium effect size, and clusters# 3 and 8 with a small effect size [67]. Therefore, the PSP variabilities due to demand and production variations are significant, even after accounting for the data uncertainty. It confirms that disregarding demand cycle and production factors from PSP evaluation (as done traditionally) leads to inaccurate assessment. Accordingly, product sustainability must be considered as a time-varying (i.e., *dynamic*) *measure*, influenced by factors beyond the product design attributes.

The results agree with a previous publication [68], which presented the importance of assessing sustainability performance after determining a design's production plan. Additionally, the results confirm that previously established sustainability and circularity metrics (e.g., PCI [32]) must also consider this "dynamic" nature, especially when evaluating closed-loop flows.

Compared to many previous methods identified in *Section 2.2.3*, this framework comprises a broader list of EoU streams, including reuse, remanufacturing, recycling, and cascade options. That along with the considerations for all TBL dimensions and primary stakeholder categories, the proposed framework allows for a more comprehensive assessment of PSP.

4.3. Limitations and Future Expansions

In this work, the data limitations restricted the number of chosen sustainability metrics. Like any modeling effort, the accuracy of input data (life cycle and production) and simplification assumptions (especially in detailed and parametric modeling) confine the accuracy of results. However, by applying the Monte Carlo method to simulate distributions of plausible input data for production parameters, an aspect of the data uncertainty was accounted.

Limitations also result due to the simplified assumptions made. The revenue and cost to society-at-large were simplified by assuming all tax revenue and landfill costs aggregate into a single entity (in reality, multiple entities such as city, state, and federal levels bear these). The lost products leaking out of the closed-loop were assumed to be sent directly to the landfill. The recovered products of one period were assumed to be used in the next period without inventory carry-over. The assumption of direct sales from manufacturer to customer also needs expansion to be applicable in other settings. In non-B2B applications, calculating the customer's revenue or economic value from a product can become rather complex.

By analyzing the variation of PSP with different DC shapes (such as *D1*-*D3* in Table 8), designers can reverse-model the DC that allows the best PSP for a product. Then, by introducing (minor) updates to retain customer interest in the product, the DC can be influenced to bring closer to the identified *best* shape. Additionally, this discussion on product sustainability and demand cycle can be extended to study product marketing planning to maximize PSP over time.

The decision to introduce major design updates (i.e., a new generation) must also consider the overall sustainability implications. A new generation can advance the production and product's usage efficiency (thus, improve sustainability performance). However, it can also increase the unusable secondary resources from the previous generation (late returns), negatively affecting the overall PSP. Therefore, designers planning the generation (*G+1)* at time t_0 (in Figure 9) must take design decisions considering the production factors and their PSP implications for the entire production timeline of generation (*G+1*). That requires the proposed framework to be extended to multi-generational systems. It will also substantially add to the preliminary work [69] on sustainable value creation for the CE through multi-generational product design.

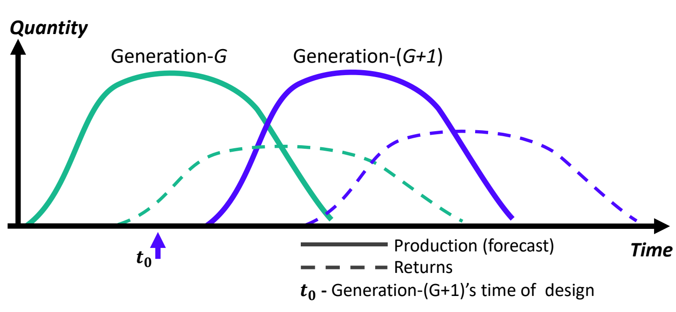


Fig. 9 Multi generation production and closed-loop planning

5. Conclusions

Conventional PSP evaluation methods overlook the time-dependent variations by assuming a steady-state production. This paper presents a novel and improved framework to comprehensively evaluate the PSP in a closed-loop production by incorporating the demand cycle and production variation using a simulation-based approach. Therefore, the proposed framework can be used in the product design stage to forecast the variation of PSP over the production timeline. Notably, the following major conclusions can be drawn from the present work:

- The new methodology incorporates production factors (demand cycle, supply constraints of closed-loop production, and EoU allocations) often disregarded in PSP and provides a more comprehensive assessment
- The results confirm that disregarding these factors leads to significant inaccuracies in PSP assessment
- The concept presented here quantifying the *PSP as a dynamic measure on the temporal dimension* (rather than a design attributes-specific static value) is a paradigm shift that applies to any measure of product sustainability and circularity

This framework was developed in cooperation with a consumer electronics company that is focused on designing a robust product line recognizing the reality of the dynamic effects of the demand cycle. The company also takes advantage of a closed-loop product eco-system that benefits the customers and the shareholders in the CE. By implementing the proposed dynamic PSP evaluation at the design stage to assess potential design alternatives, such companies can better predict the most suitable product design options considering the market and production factors. Therefore, any manufacturer who pursues incorporating sustainability value proposition in their business strategy should carefully consider the concept of dynamic product sustainability.

Future research into dynamic PSP evaluation must expand it to other production flow types, including cascading flows. Further domain-specific work must also be done to refine and correlate the shape and characteristics of demand curve profile, expected product life, and EoU-appropriation levels to the PSP. Additionally, fundamental work is being done to extend this method to design and plan multi-generational products and optimize PSP for the CE.

References

[1] Hapuwatte BM, Jawahir IS. *Closed-loop Sustainable Product Design for Circular Economy*. Journal of Industrial Ecology, 2021. **25**(6): p. 1430-1446. https://doi.org/10.1111/jiec.13154

[2] Hapuwatte BM, Badurdeen F, Jawahir IS. *Metrics-based Integrated Predictive Performance Models for Optimized Sustainable Product Design*. in *Sustainable Design and Manufacturing 2017: Selected papers on Sustainable Design and Manufacturing*. 2017. Bologna, Italy: Springer International Publishing. p. 25-34. https://doi.org/10.1007/978-3-319-57078-5_3

[3] Bradley R, Jawahir IS, Badurdeen F, Rouch K. *A total life cycle cost model (TLCCM) for the circular economy and its application to post-recovery resource allocation.* Resources, Conservation and Recycling, 2018. **135**: p. 141-149. https://doi.org/10.1016/j.resconrec.2018.01.017

[4] Geissdoerfer M, Savaget P, Bocken NMP, Hultink EJ. *The Circular Economy – A new sustainability paradigm?* Journal of Cleaner Production, 2017. **143**: p. 757-768. https://doi.org/10.1016/j.jclepro.2016.12.048

[5] Ramani K, Ramanujan D, Bernstein WZ, Zhao F, Sutherland J, Handwerker C, et al. *Integrated Sustainable Life Cycle Design: A Review*. Journal of Mechanical Design, 2010. **132**(9): p. 091004-091004. https://doi.org/10.1115/1.4002308

[6] Ellen MacArthur Foundation. *Towards the Circular Economy: An economic and business rationale for an accelerated transition*. 2013, Ellen MacArthur Foundation: Isle of Wight, United Kingdom. p. 98. https://www.ellenmacarthurfoundation.org/assets/downloads/publications/Ellen-MacArthur-Foundation-Towards-the-Circular-Economy-vol.1.pdf

[7] Hapuwatte BM. *Redesigning Products to Optimize Sustainable Performance in Multi-generational Closed-Loop Production for Advancing the Circular Economy*, in

Mechanical Engineering. 2021, University of Kentucky. https://doi.org/10.13023/etd.2021.347
[8] Lieder M, Rashid A. *Towards circular economy implementation: a comprehensive review in context of manufacturing industry.* Journal of Cleaner Production, 2016. **115**: p. 36-51. http://www.sciencedirect.com/science/article/pii/S0959652615018661
[9] Kirchherr J, Reike D, Hekkert M. *Conceptualizing the circular economy: An analysis of 114 definitions.* Resources, Conservation and Recycling, 2017. **127**: p. 221-232. https://doi.org/10.1016/j.resconrec.2017.09.005
[10] de Oliveira CT, Dantas TET, Soares SR. *Nano and micro level circular economy indicators: Assisting decision-makers in circularity assessments.* Sustainable Production and Consumption, 2021. **26**: p. 455-468. https://doi.org/10.1016/j.spc.2020.11.024
[11] Linder M, Boyer RHW, Dahllöf L, Vanacore E, Hunka A. *Product-level inherent circularity and its relationship to environmental impact.* Journal of Cleaner Production, 2020. **260**: p. 121096. https://doi.org/10.1016/j.jclepro.2020.121096
[12] Lonca G, Muggéo R, Imbeault-Tétreault H, Bernard S, Margni M. *Does material circularity rhyme with environmental efficiency? Case studies on used tires.* Journal of Cleaner Production, 2018. **183**: p. 424-435. https://doi.org/10.1016/j.jclepro.2018.02.108
[13] Korhonen J, Honkasalo A, Seppälä J. *Circular Economy: The Concept and its Limitations.* Ecological Economics, 2018. **143**: p. 37-46. https://doi.org/10.1016/j.ecolecon.2017.06.041
[14] Linder M, Sarasini S, van Loon P. *A Metric for Quantifying Product-Level Circularity.* Journal of Industrial Ecology, 2017. **21**(3): p. 545-558. https://doi.org/10.1111/jiec.12552
[15] Reich-Weiser C, Vijayaraghavan A, Dornfeld DA. *Metrics for sustainable manufacturing*. in *Proceedings of the ASME 2008 International Manufacturing Science and Engineering Conference*. 2008. Evanston, Illinois, USA: ASME. p. 327-335. https://doi.org/10.1115/MSEC_ICMP2008-72223
[16] Feng SC, Joung C-B, Li G. *Development overview of sustainable manufacturing metrics*. in *Proceedings of the 17th CIRP International Conference on Life Cycle Engineering*. 2010. Hefei, PRC. p. I2. https://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.625.1538&rep=rep1&type=pdf
[17] Ahmad S, Wong KY, Rajoo S. *Sustainability indicators for manufacturing sectors: A literature survey and maturity analysis from the triple-bottom line perspective.* Journal of Manufacturing Technology Management, 2019. **30**(2): p. 312-334. https://doi.org/10.1108/JMTM-03-2018-0091
[18] ISO. *ISO 14040:2006 Environmental management–life cycle assessment–principles and framework: International Organization for Standardization*. 2006. https://www.iso.org/standard/37456.html
[19] Joung CB, Carrell J, Sarkar P, Feng SC. *Categorization of indicators for sustainable manufacturing.* Ecological Indicators, 2013. **24**: p. 148-157. https://doi.org/10.1016/j.ecolind.2012.05.030
[20] Zarte M, Pechmann A, Nunes IL. *Decision support systems for sustainable manufacturing surrounding the product and production life cycle – A literature review.* Journal of Cleaner Production, 2019. **219**: p. 336-349. https://doi.org/10.1016/j.jclepro.2019.02.092
[21] United Nations Environment Programme. *Guidelines for social life cycle assessment of products*. 2009, United Nations Environment Programme,: Belgium.

https://www.lifecycleinitiative.org/wp-content/uploads/2012/12/2009%20-%20Guidelines%20for%20sLCA%20-%20EN.pdf
[22] Sutherland JW, Richter JS, Hutchins MJ, Dornfeld D, Dzombak R, Mangold J, et al. *The role of manufacturing in affecting the social dimension of sustainability.* CIRP Annals, 2016. **65**(2): p. 689-712. https://doi.org/10.1016/j.cirp.2016.05.003
[23] Hutchins MJ, Robinson SL, Dornfeld D. *Understanding life cycle social impacts in manufacturing: A processed-based approach.* Journal of Manufacturing Systems, 2013. **32**(4): p. 536-542. https://doi.org/10.1016/j.jmsy.2013.05.008
[24] Kloepffer W. *Life cycle sustainability assessment of products.* The International Journal of Life Cycle Assessment, 2008. **13**(2): p. 89. https://doi.org/10.1065/lca2008.02.376
[25] Ghadimi P, Azadnia AH, Mohd Yusof N, Mat Saman MZ. *A weighted fuzzy approach for product sustainability assessment: a case study in automotive industry.* Journal of Cleaner Production, 2012. **33**: p. 10-21. https://doi.org/10.1016/j.jclepro.2012.05.010
[26] Hapuwatte BM, Badurdeen F, Bagh A, Jawahir IS. *Optimizing sustainability performance through component commonality for multi-generational products.* Resources, Conservation and Recycling, 2022. **180**: p. 105999. https://doi.org/10.1016/j.resconrec.2021.105999
[27] Shuaib M, Seevers D, Zhang X, Badurdeen F, Rouch KE, Jawahir IS. *Product Sustainability Index (ProdSI): A metrics-based framework to evaluate the total life cycle sustainability of manufactured products.* Journal of Industrial Ecology, 2014. **18**(4): p. 491-507. https://doi.org/10.1111/jiec.12179
[28] Saidani M, Yannou B, Leroy Y, Cluzel F, Kendall A. *A taxonomy of circular economy indicators.* Journal of Cleaner Production, 2019. **207**: p. 542-559. https://doi.org/10.1016/j.jclepro.2018.10.014
[29] Harris S, Martin M, Diener D. *Circularity for circularity's sake? Scoping review of assessment methods for environmental performance in the circular economy.* Sustainable Production and Consumption, 2021. **26**: p. 172-186. https://doi.org/10.1016/j.spc.2020.09.018
[30] Saidani M, Yannou B, Leroy Y, Cluzel F. *How to Assess Product Performance in the Circular Economy? Proposed Requirements for the Design of a Circularity Measurement Framework.* Recycling, 2017. **2**(1): p. 6. https://doi.org/10.3390/recycling2010006
[31] Corona B, Shen L, Reike D, Rosales Carreón J, Worrell E. *Towards sustainable development through the circular economy—A review and critical assessment on current circularity metrics.* Resources, Conservation and Recycling, 2019. **151**: p. 104498. https://doi.org/10.1016/j.resconrec.2019.104498
[32] Bracquené E, Dewulf W, Duflou JR. *Measuring the performance of more circular complex product supply chains.* Resources, Conservation and Recycling, 2020. **154**: p. 104608. https://doi.org/10.1016/j.resconrec.2019.104608
[33] Jawahir IS, Dillon OW, Rouch KE, Joshi KJ, Venkatachalam A, Jaafar IH. *Total life-cycle considerations in product design for sustainability: A framework for comprehensive evaluation*. 2006. Barcelona, Spain. p. 1-10. https://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.402.3563&rep=rep1&type=pdf
[34] Tolio T, Bernard A, Colledani M, Kara S, Seliger G, Duflou J, et al. *Design, management and control of demanufacturing and remanufacturing systems.* CIRP Annals, 2017. **66**(2): p. 585-609. https://doi.org/10.1016/j.cirp.2017.05.001

[35] Igarashi K, Yamada T, Gupta SM, Inoue M, Itsubo N. *Disassembly system modeling and design with parts selection for cost, recycling and CO2 saving rates using multi criteria optimization.* Journal of Manufacturing Systems, 2016. **38**: p. 151-164. https://doi.org/10.1016/j.jmsy.2015.11.002
[36] Özceylan E. *Simultaneous optimization of closed- and open-loop supply chain networks with common components.* Journal of Manufacturing Systems, 2016. **41**: p. 143-156. https://doi.org/10.1016/j.jmsy.2016.08.008
[37] Batista L, Bourlakis M, Smart P, Maull R. *In search of a circular supply chain archetype – a content-analysis-based literature review.* Production Planning & Control, 2018. **29**(6): p. 438-451. https://doi.org/10.1080/09537287.2017.1343502
[38] European Parliament. *Directive 2012/19/EU of the European Parliament and of the Council of 4 July 2012 on waste electrical and electronic equipment, WEEE.* Official Journal of the European Union, 2012. **197**: p. 38-71. https://eur-lex.europa.eu/eli/dir/2012/19/oj
[39] Kaffine D, O'Reilly P. *What have we learned about extended producer responsibility in the past decade? A survey of the recent EPR economic literature.* Organisation for Economic Co-operation and Development (OECD), 2013.
[40] EPR Canada. *Extended Producer Responsibility: Summary Report*. 2017. http://www.eprcanada.ca/reports/2016/EPR-Report-Card-2016.pdf
[41] Ellen MacArthur Foundation. *Towards a circular economy: Business rationale for an accelerated transition*. 2015, Ellen MacArthur Foundation: Isle of Wight, United Kingdom. https://www.ellenmacarthurfoundation.org/assets/downloads/TCE_Ellen-MacArthur-Foundation_9-Dec-2015.pdf
[42] Schenkel M, Caniëls MCJ, Krikke H, van der Laan E. *Understanding value creation in closed loop supply chains – Past findings and future directions.* Journal of Manufacturing Systems, 2015. **37**: p. 729-745. https://doi.org/10.1016/j.jmsy.2015.04.009
[43] Maginnis MA, Hapuwatte BM, Keown D. *The Integration of True Lean and Industry 4.0 to Sustain a Culture of Continuous Improvement*, in *Product Lifecycle Management in the Digital Twin Era*, C. Fortin, et al., Editors. 2019, Springer International Publishing. p. 336-345. https://doi.org/10.1007/978-3-319-72905-3_48
[44] European Commission. *Directive 2008/98/EC on waste (Waste Framework Directive)*. 2008, European Commission: Luxembourg. https://ec.europa.eu/environment/waste/framework/
[45] European Commission. *Guidance on the Interpretation of Key Provisions of Directive 2008/98/EC on Waste*. 2012, Directorate Environment Brussels, Belgium. http://waste-prevention.gr/waste/wp-content/uploads/2015/10/2012_Guidance%20interpretation%20Directive%2098-2008-EC_EN.pdf
[46] Joshi K, Venkatachalam A, Jaafar IH, Jawahir IS. *A new methodology for transforming 3R concept into 6R for improved sustainability*. in *Proceedings of the 4th Global Conference on Sustainable Product Development and Life Cycle Enginnering, São Carlos, Brazil*. 2006.
[47] Jawahir IS, Bradley R. *Technological elements of circular economy and the principles of 6R-based closed-loop material flow in sustainable manufacturing.* Procedia CIRP, 2016. **40**: p. 103-108. https://doi.org/10.1016/j.procir.2016.01.067
[48] Moreno M, De los Rios C, Rowe Z, Charnley F. *A conceptual framework for circular design.* Sustainability, 2016. **8**(9): p. 937. https://doi.org/10.3390/su8090937

[49] Östlin J, Sundin E, Björkman M. *Product life-cycle implications for remanufacturing strategies.* Journal of Cleaner Production, 2009. **17**(11): p. 999-1009. https://doi.org/10.1016/j.jclepro.2009.02.021
[50] Xu X-h, Song Q-z. *Forecasting for products with short life cycle based on improved BASS model.* Industrial Engineering and Management, 2007. **5**: p. 27-31. http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.646.305&rep=rep1&type=pdf
[51] Geyer R, Wassenhove LNV, Atasu A. *The Economics of Remanufacturing Under Limited Component Durability and Finite Product Life Cycles.* Management Science, 2007. **53**(1): p. 88-100. https://doi.org/10.1287/mnsc.1060.0600
[52] Wang W, Wang Y, Mo D, Tseng MM. *Managing component reuse in remanufacturing under product diffusion dynamics.* International Journal of Production Economics, 2017. **183**: p. 551-560. https://doi.org/10.1016/j.ijpe.2016.06.010
[53] van Loon P, Van Wassenhove LN. *Assessing the economic and environmental impact of remanufacturing: a decision support tool for OEM suppliers.* International Journal of Production Research, 2018. **56**(4): p. 1662-1674. https://doi.org/10.1080/00207543.2017.1367107
[54] Seevers KD, Badurdeen F, Jawahir IS. *Value creation for lifecycle based product development through the sustainable half-life return model.* International Journal of Product Lifecycle Management, 2018. **11**(1): p. 47-65. https://doi.org/10.1504/IJPLM.2018.091656
[55] Badurdeen F, Aydin R, Brown A. *A multiple lifecycle-based approach to sustainable product configuration design.* Journal of Cleaner Production, 2018. **200**: p. 756-769. https://doi.org/10.1016/j.jclepro.2018.07.317
[56] Singhal D, Tripathy S, Jena SK. *Remanufacturing for the circular economy: Study and evaluation of critical factors.* Resources, Conservation and Recycling, 2020. **156**: p. 104681. https://doi.org/10.1016/j.resconrec.2020.104681
[57] Asiedu Y, Gu P. *Product life cycle cost analysis: state of the art review.* International journal of production research, 1998. **36**(4): p. 883-908. https://doi.org/10.1080/002075498193444
[58] Korpi E, Ala-Risku T. *Life cycle costing: a review of published case studies.* Managerial Auditing Journal, 2008. **23**(3): p. 240-261. https://doi.org/10.1108/02686900810857703
[59] Zhang H, Zhu B, Li Y, Yaman O, Roy U. *Development and utilization of a Process-oriented Information Model for sustainable manufacturing.* Journal of Manufacturing Systems, 2015. **37**: p. 459-466. https://doi.org/10.1016/j.jmsy.2015.05.003
[60] Hapuwatte BM, Seevers KD, Badurdeen F, Jawahir IS. *Total life cycle sustainability analysis of additively manufactured products.* Procedia CIRP, 2016. **48**: p. 376-381. http://dx.doi.org/10.1016/j.procir.2016.03.016
[61] Aydin R, Brown A, Badurdeen F, Li W, Rouch KE, Jawahir IS. *Quantifying impacts of product return uncertainty on economic and environmental performances of product configuration design.* Journal of Manufacturing Systems, 2018. **48**: p. 3-11. https://doi.org/10.1016/j.jmsy.2018.04.009
[62] Diaz R, Marsillac E. *Evaluating strategic remanufacturing supply chain decisions.* International Journal of Production Research, 2017. **55**(9): p. 2522-2539. https://doi.org/10.1080/00207543.2016.1239848

[63] Huang A, Badurdeen F. *Metrics-based approach to evaluate sustainable manufacturing performance at the production line and plant levels.* Journal of Cleaner Production, 2018. **192**: p. 462-476. https://doi.org/10.1016/j.jclepro.2018.04.234
[64] Bracquené E, Peeters J, Alfieri F, Sanfélix J, Duflou J, Dewulf W, et al. *Analysis of evaluation systems for product repairability: A case study for washing machines.* Journal of Cleaner Production, 2021. **281**: p. 125122. https://doi.org/10.1016/j.jclepro.2020.125122
[65] Four Elements Consulting LLC. *Life Cycle Environmental Impact Study for North America: HP LaserJet Toner Cartridges vs. Remanufactured Cartridges*. 2019, Four Elements Consulting, LLC. https://www8.hp.com/h20195/v2/GetPDF.aspx/c06433450.pdf
[66] Sahni S, Boustani A, Gutowski T, Graves S. *Cartridge remanufacturing and energy savings*. 2010, Laboratory for Manufacturing and Productivity, Sloan School of Management: Cambridge, MA. http://web.mit.edu/ebm/www/Publications/MITEI-1-b-2010.pdf
[67] Dybå T, Kampenes VB, Sjøberg DIK. *A systematic review of statistical power in software engineering experiments.* Information and Software Technology, 2006. **48**(8): p. 745-755. https://doi.org/10.1016/j.infsof.2005.08.009
[68] Lee JY, Kang HS, Do Noh S. *MAS2: an integrated modeling and simulation-based life cycle evaluation approach for sustainable manufacturing.* Journal of Cleaner production, 2014. **66**: p. 146-163. https://doi.org/10.1016/j.jclepro.2013.11.029
[69] Bradley R, Jawahir IS, Badurdeen F, Rouch K. *A Framework for Material Selection in Multi-Generational Components: Sustainable Value Creation for a Circular Economy.* Procedia CIRP, 2016. **48**: p. 370-375. https://doi.org/10.1016/j.procir.2016.03.247