Optimizing Product Life Cycle Systems for Manufacturing in a Circular Economy

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Abstract. Global population growth and increasing resource scarcity are necessitating sustainable manufacturing and circular economy (CE) practices. These practices require the decisions made at each product life cycle (PLC) stage consider sustainability and circularity implications. We propose PLC system level optimization to identify the most favorable choices, instead of siloed individual PLC stage-specific optimizations. This should yield better circularity by permitting manufacturers to take a more holistic view and identify the areas of highest impact across the PLC. This paper presents initial work towards building a PLC system optimization framework. From an initial review of current circularity metrics, we identify metrics that are suitable for forming the optimization objectives. Second, we identify decision variables available to manufacturers across the PLC that are useful in optimizing the entire system's circularity and sustainability. Finally, we identify limitations of current metrics, and discuss major challenges and potential solutions to PLC system optimization problems.

Keywords: Circular economy · Sustainable manufacturing · Optimization · Metrics · Product life cycle

1 Introduction

Traditional manufacturing exploits economies of scale to mass-produce commodities and meet growing global demands to improve human quality of life. Ironically, the result has been economic considerations take priority over environmental and social ones, thus degrading the environment and compromising quality of life [1]. Alternatively, sustainable development and circular economy (CE) are introduced to enabled the *triple bottom line* (TBL) thinking—the balance between economic, environmental, and social factors that accounts for temporal and spatial parameters [2]. CE more specifically focuses on decoupling economic growth from virgin resource consumption [2].

A system is a collection of elements that work together towards a goal. A CE system orchestrates a variety of stakeholders (incl. manufacturers) that use and manage resources and manufacture products. A *product life cycle* (PLC)-wide [3] CE system is a system viewpoint intended to encompass circularity and sustainability concerns over the PLC stages of *pre-manufacturing*, *manufacturing*, *use*, and *post-use*. In this work, we focus on

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identifying the properties and metrics that make it possible to optimize from this more encompassing viewpoint.

This paper makes two main contributions. First, it provides an initial review of current circularity metrics and identifies metrics for comprehensive PLC evaluation. Equitable quantitative metrics are critical to form objectives of the proposed PLC CE system optimization. Second, we identify potential decision variables available to manufacturers throughout the PLC that help enhance and optimize the circularity and sustainability of entire PLC. Rather than the current siloed approach of optimizing several elements of each PLC stage separately, a PLC system optimization can improve circularity by first focusing on high impact areas [4].

2 Background

The literature presented below proposes metrics for measuring circularity at different stages of the PLC. We considered both recent literature on CE and prior work on sustainable manufacturing. In a recent paper which reviews 114 definitions for CE, Kirchherr et al. [5] raised two major points: 1) only a few definitions address the totality of the TBL and 2) operational level subdivisions are useful for addressing CE. TBL is a foundational tenant of sustainable manufacturing [2]. Yet, several studies flag that TBL is inadequately addressed in CE [5, 6]. While Linder et al. [7] argued circularity should focus exclusively on resource circulation, since higher circularity does not mean better sustainability [8], others recommend [5, 6, 8] complementing circularity with TBL to ensure that sustainability—the goal of CE—is achieved.

Saidani et al. [9] in one of the very few publications on product circularity optimization highlighted the importance of considering both circularity and sustainability metrics, especially during product design, to reveal possible trade-offs. Given this lack of literature on optimizing the PLC for circularity, we review closely relevant literature discussing sustainability optimization at different PLC stages (Sect. 2.1) and the evaluation of circularity in the product context using metrics (Sect. 2.2). Section 3 discusses the integration of decision variables identified in sustainability optimizations with circularity metrics to form PLC system optimizations for CE.

2.1 Current Literature on Optimization for Manufacturing CE

This review summarizes noteworthy literature on PLC activities with a manufacturing-centric point-of-view as described in [2]. Pre-manufacturing stage is broken down to *design* and *acquire material;* manufacturing stage is narrowed to *production*; and post-use stage focuses on *recovery* for circularity. *Acquire material* and *recovery* are considered together for their close relationships in CE. While important, *use* is beyond the scope of this paper's manufacturing-centric view.

Design: Product design disproportionately influences a majority of a product's environmental impact and is crucial in a CE [2]. *Design for sustainability* (DfS) considers environmental impact during design and is the precursor to design for CE. In a recent study Hapuwatte et al. introduced a metrics-based CE product design evaluation framework [2] consisting of 90+ metrics, to be parametrically modeled. Others explored DfS optimization to identify metric models and constraints relevant to CE. For example, Hapuwatte et al. [10] optimized the sustainability performance of multi-generational products by using design configuration choices based on TBL objectives: minimize greenhouse gas (GHG) emissions, maximize profit, and maximize product functionality. Other studies optimized product design by considering trade-offs between life cycle cost and environmental impact [11] and disassemblability [12]. These models are useful for establishing CE metrics linked to other PLC stages.

Acquire Materials and End-of-use (EoU) Recovery: Optimization can be extremely useful for balancing TBL trade-offs [4]. Most work focuses on economic and environmental dimensions. Material acquisition and recovery must be planned considering the range of recovery options—reuse, remanufacturing, recycling, energy recovery, and landfilling [3]. For example, Jiang et al.'s optimization models minimize the environmental impact of remanufacturing [13]. Other studies have explored optimizing disassembly lines from the point of view of profit, disassembly time, and energy consumption [14, 15]. Mathur et al. [16] used a hybrid optimization approach to balance economic and environmental metrics in the context of EoU photovoltaics. These studies flag a lack of standardized methods for determining 1) the ease of EoU material recovery and 2) the suitability of recovered EoU materials as feedstock. Therefore, metrics on topics such as *product disassemblability and modularity*, and *material composition and quality* are needed.

***Production*:** Many production management decisions that tend to have large environmental impact (e.g., manufacturing processes, materials used) now increasingly take into account the sustainability impacts [2]. To balance competing interests, several studies presented the use of optimization models. Atabaki et al. [17] discussed production optimization for CE by considering the decision variables *supplier and location selection*, *transportation mode*, *assembly methods*, and *recovery decisions* and the objectives *cost*, *GHG emissions*, and *energy consumption*. Others modeled manufacturing process and process-condition selection by considering *cost*, *GHG emissions*, and *energy use* [18]. In production planning for CE, Hapuwatte and Jawahir called for considering the entire PLC to avoid TBL burden shifting to other PLC stages [2]. Metrics for production and manufacturing processes are often dependent on the particulars of the individual processes. Work from NIST [19] defined a procedure for selecting process-specific metrics for improving sustainable performance.

In addition to the metrics themselves, it is important to consider the types of classifications available for manufacturing-focused circularity metrics. Recently, Boyer et al. [20] discussed the importance of evaluating the product level circularity in three dimensions: *recirculation* (composition of secondary material), *utilization* (intensity of product usage), and *endurance* (product's ability to retain its value over time). In another comprehensive review [21] discussing CE and its quantification using circularity metrics, Parchomenko presented three major *circularity-metrics clusters* similar to Boyer et al.'s dimensions. The main difference is that Parchomenko combined *utilization* and *endurance* in a *product-centric cluster* and included a separate *material and stock flows cluster*. Their analysis also identified metrics that combine multiple clusters (e.g., Material Circularity Indicator). We use Boyer et al.'s dimensions for our discussion in Sect. 3.2 because it covers the entire PLC and provides more distinct categorization. Metrics capturing *recirculation* dimensions are important. In fact, most circularity metrics focuses

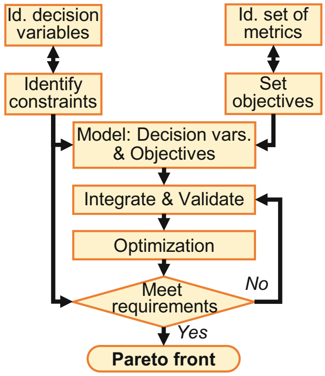

Fig. 1. PLC System Optimization

on this *inherent circularity* (i.e., recirculation of resources) rather than its TBL consequences [9]. Therefore, in parallel to these metrics, it is essential to consider the metrics that address the TBL impacts.

3 PLC System Optimization in a CE

PLC system optimization for a CE requires two components: a framework for performing the optimization and quantitative data for representing the system.

To effectively optimize a PLC system, one needs to identify and quantify the decision variables, constraints, and objectives. We do so from the manufacturer's perspective. Concerns of other stakeholders (e.g., customers, society) are integrated through constraints on the optimization problem. Figure 1 illustrates the basic steps for building a systems optimization framework. Table 1 identifies the major types of manufacturing decisions at each PLC stage. These can be used to determine decision variables in the PLC-system optimization. The decision types were identified from the literature on manufacturing-focused optimizations in Sect. 2.1.

Since this optimization requires quantitative measurements of the PLC system, the circularity metrics can form that basis. Circularity metrics can be drawn from recent reviews in Sect. 2 and classified. Table 2 summarizes several metrics that are more prominently used in literature; they also represent all three of Boyer et al.'s [20] circularity dimensions (recirculation, utilization, and endurance). As depicted in Fig. 1, an interactive process is used to identify metrics and form objectives for a multi-objective optimization. Table 2 details how extensively the metrics cover each PLC stage, as is needed to ensure a comprehensive evaluation. Table 2 lists the sub-elements of each metric considered at PLC-level. The analysis uncovers some models necessary to relate the manufacturing decisions in Table 1 with the associated optimization objectives. Figure 2 illustrates the complex set of such models, using two metrics as examples. While these models need to be developed (or extended from current TBL optimization work) and validated, understanding the possibilities will help with building a PLC-level optimization framework. A Fig. 2-like diagram is useful for determining a set of metrics-based

Table 1. Decision variables for manufacturers at different PLC activity

PLC activity	Decision Types	Examples of Decisions
Design	Design decisions	Product features (dimensions, mass), Modularity, Design config., Disassemblability, Sustainability
Acquire materials and EoU recovery	Material sourcing dec	Material composition/quality, Collection incentives & ratio, Recyclable/Reused/Remanufactured content
	Material efficiency dec	Recycling efficiency
Production	Process decisions	Process-type selection, Process conditions
	Production decisions	Supplier/production location, Scheduling, Logistics
Use	Utility decisions	Product lifetime/reliability, Functionality/efficiency
	Service decisions	Maintenance/servicing, Product-service model

objectives to find optimal decisions at all levels. Considering the entire PLC as a *system* allows the manufacturer to examine alternative decisions and identify the best option. For example, conventionally to improve the manufacturing circularity of a plastic container, the manufacturing process parameters may be tried to optimize limiting scrap or improving efficiency. With a system view, optimization can consider product design changes necessary to improve material use as well allow altering material composition to higher recycled content.

A considerable number of sub-elements in Table 2 focus on the *recirculation* dimension. Likewise, the metrics in Table 1 are heavily weighted toward decisions in *material acquisition/EoU recovery* and *design* (decisions that influence material options) and highlight the concerns raised in prior publications [20, 21] that current research has an unbalanced view of circularity dimensions. Many constraints and deciding factors of the manufacturing decisions in Table 1 are based on TBL concerns and are predominantly economic (i.e., cost) and environmental (i.e., regulation and value proposition), but rarely social factors. Given the importance of TBL for businesses, incorporating a broad coverage of TBL metrics when optimizing the PLC system is vital (see Sect. 2.1).

3.1 Challenges and Potential Solutions

While the feasibility of applying optimization to improve outcomes has been shown, several factors challenge such models' robustness and suggest a need for standards and guidelines to enable the application of this technology. As Sect. 3.2 identified, modeling PLC decisions relies on many decision variables and constraints. Quantifying the outcomes of those decisions using metrics requires integration of multiple siloed

Table 2. Prominent quantitative circularity metrics and the sub-elements they use to consider for each PLC-stage activity

Metric	**Design**	**Acquire materials/Recovery**	**Production**	**Use**	**Sustainability TBL**
Material Circularity Indicator (MCI) [22]	• Product mass (M)	• Virgin feedstock (V) • Feed recycling efficiency (E_F) • Unrecoverable waste (W) • Energy recovered (E_R)	• Recycling efficiency of component production (E_C) • Energy recovery efficiency (E_E)	• Utility: Product lifetime (L) • Utility: Intensity of use (U)	*(No direct consideration; other than material efficiency)*
Product-Level Circularity Metric (PLCM) [7]	• Indirectly: Number of components	• Cost of all material • Cost of all components • EoU material & compon. Price • Remanufacturing cost	• Value added during production	*(Not considered)*	Economic costs and values are considered
Circularity Index (CI) [23]	• Indirectly informs the availability and feasibility of secondary feedstock	• Material stocks & dissipative losses in recovery proces. (α) • Recovered material quality & energy requirements (β)	*(Not considered)*	*(Not considered)*	*(No direct consideration; other than material losses/degradation, energy intensity)*
Sustainability Performance Indicators (SPI) [24]	• Proportion of linear material flow • Product Mass (M) • Number of components (n)	• Virgin feedstock (V_j) • Waste from production of recycled feedstock (W_{fj}) • Waste from recyc. Parts (W_{Cj}) • Reusable component (M_{ri})	• Unrecoverable waste (W_j) • Efficiency of recycling process (E_i)	• Number of times product is reused (k_i)	• Considers "*Design for Sustainability*" framework
Ease of disassembly metric (eDiM) [25]	• Number of product manipulations • Num. of connectors • Identifiability (qualitative)	• Inefficiency rate • Tool change time • Identifying time • Manipulation time • Removing time	• Component disassembly sequence • Connector disassembly sequence	*(Not considered)*	• Considers "*Ecodesign*" requirements

modeling approaches each with differing models, metrics, and data. Standardization of circularity metrics and measurement frameworks will enable integration as well as consistent evaluations [20].

Standardization will be necessary for comprehensibility and usability between PLC stages and the extended supply chain. Even within the metrics in Table 2, some similarly named parameters are defined differently. Most circularity and sustainability metrics identified above do not consider the *dynamic* nature of CE systems, focusing instead

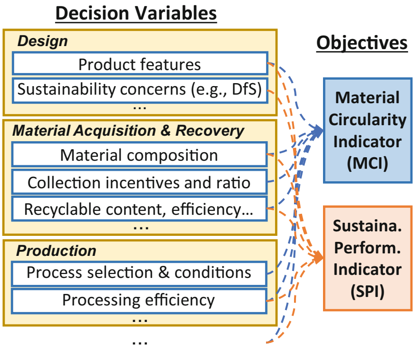

Fig. 2. Relating the decision variables to the metrics (a partial list)

on "snapshots in time" of a production. Certain metric sub-elements (e.g., *virgin feedstock used*, *collection ratio*) can significantly change over multiple productions. Thus, temporal variations are vital to PLC system optimization. A potential solution [26] had employed *demand variation* to model certain elements' temporal changes and suggested use of metrics that consider the entire production timeline to overcome this challenge. In addition, data uncertainty is especially challenging given the number of parameters and sub-models involved in setting up PLC optimization problems. Prior CE production modeling [17] has illustrated techniques to cope with both *randomness* and *epistemic* uncertainty to build robust optimization models. Additionally, to capture these complexities of integrating multiple circularity metrics, others suggest the use of complex system sciences [8].

4 Conclusions

A *system* viewpoint is necessary to make manufacturing decisions in a CE. Given the proliferation and conflicting nature of these decisions and their outcomes, multi-objective optimization is needed to identify optimal choices, considering the trade-offs.

In this paper, we discussed the fundamental considerations for developing PLC system optimization techniques in a CE. We identify potential quantitative metrics that can be used to form the optimization-objectives. Most CE metrics focus on *recirculation* dimension of circularity and exhibit a general lack of consideration for TBL. Thus, the PLC system optimization must account for multiple objectives based on complementing metrics. We also present different types of manufacturing decisions across the PLC and analyze the relationship of the circularity metrics to those decisions. Several prior works provide potential solutions to overcome the challenges in model integration, accounting for the dynamic nature of CE, and data uncertainty in system optimization.

While this work provides an essential first step in realizing PLC system optimization, more work is needed to develop models to relate the decision variables to metrics presented. Although modeling will be specific to each application, studying existing methods can lead to a more standard approach to building the necessary sub-models of PLC. Standardization will especially benefit integration of sub-models into a PLC system-level model. Such a system-level optimization tool can provide crucial decision support for product designers and enable a more effective CE.

References

1. Geissdoerfer, M., Savaget, P., Bocken, N.M.P., et al.: The circular economy – a new sustainability paradigm? J. Clean. Prod. **143**, 757–768 (2017)
2. Hapuwatte, B.M., Jawahir, I.S.: Closed-loop sustainable product design for circular economy. J. Ind. Ecol. **25**, 1430–1446 (2021)
3. Reslan, M., Last, N., Mathur, N., et al.: Circular economy: a product life cycle perspective on engineering and manufacturing practices. Procedia CIRP. **105**, 851–858 (2022)
4. Avraamidou, S., Baratsas, S.G., Tian, Y., et al.: Circular economy - a challenge and an opportunity for process systems engineering. Comput. Chem. Eng. **133**, 106629 (2020)
5. Kirchherr, J., Reike, D., Hekkert, M.: Conceptualizing the circular economy: an analysis of 114 definitions. Resour. Conserv. Recycl. **127**, 221–232 (2017)
6. de Oliveira, C.T., Dantas, T.E.T., Soares, S.R.: Nano and micro level circular economy indicators: assisting decision-makers in circularity assessments. Sustain. Prod. Consum. **26**, 455–468 (2021)
7. Linder, M., Sarasini, S., van Loon, P.: A metric for quantifying product-level circularity: product-level circularity metric. J. Ind. Ecol. **21**, 545–558 (2017)
8. Walzberg, J., Lonca, G., Hanes, R.J., et al.: Do we need a new sustainability assessment method for the circular economy? A Critical Literature Review. Front. Sustain. **1**, 620047 (2021)
9. Saidani, M., Kim, H., Yannou, B., et al.: Framing product circularity performance for optimized green profit. In: ASME 2019 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference IDETC/CIE2019, Anaheim, California, United States (2019)
10. Hapuwatte, B.M., Badurdeen, F., Bagh, A., et al.: Optimizing sustainability performance through component commonality for multi-generational products. Resour. Conserv. Recycl. **180**, 105999 (2022)
11. Ameli, M., Mansour, S., Ahmadi-Javid, A.: A sustainable method for optimizing product design with trade-off between life cycle cost and environmental impact. Environ. Dev. Sustain. **19**(6), 2443–2456 (2016). https://doi.org/10.1007/s10668-016-9864-x
12. Chiu, M.-C., Chang, C.-H., Chen, Y.-T., et al.: Redesign for sustainability and assemblability using particle swarm optimization method. J. Ind. Prod. Eng. **33**, 103–113 (2016)
13. Jiang, H., Xu, L., Li, J., et al.: Energy management and component sizing for a fuel cell/battery/supercapacitor hybrid powertrain based on two-dimensional optimization algorithms. Energy **177**, 386–396 (2019)
14. Ren, Y., Meng, L., Zhang, C., et al.: An efficient metaheuristics for a sequence-dependent disassembly planning. J. Clean. Prod. **245**, 118644 (2020)
15. Wang, W., Zhou, X., Tian, G., et al.: Multi-objective low-carbon hybrid flow shop scheduling via an improved teaching-learning-based optimization algorithm. Sci. Iran. (2022)
16. Mathur, N., Sutherland, J.W., Singh, S.: A study on end of life photovoltaics as a model for developing industrial synergistic networks. J. Remanufact. (2022)
17. Atabaki, M.S., Mohammadi, M., Naderi, B.: New robust optimization models for closed-loop supply chain of durable products: towards a circular economy. Comput. Ind. Eng. **146**, 106520 (2020)
18. Lu, T., Jawahir, I.S.: Metrics-based sustainability evaluation of cryogenic machining. Procedia CIRP **29**, 520–525 (2015)

19. Kibira, D., Brundage, M.P., Feng, S., et al.: Procedure for selecting key performance indicators for sustainable manufacturing. J. Manuf. Sci. Eng. **140** (2017)
20. Boyer, R.H.W., Mellquist, A.-C., Williander, M., et al.: Three-dimensional product circularity. J. Ind. Ecol. **25**, 824–833 (2021)
21. Parchomenko, A., Nelen, D., Gillabel, J., et al.: Measuring the circular economy - A multiple correspondence analysis of 63 metrics. J. Clean. Prod. **210**, 200–216 (2019)
22. Ellen MacArthur Foundation: Circularity Indicators: Methodology - An Approach to Measuring Circularity. Ellen MacArthur Foundation (2019)
23. Cullen, J.M.: Circular economy: theoretical benchmark or perpetual motion machine? J. Ind. Ecol. **21**, 483–486 (2017)
24. Mesa, J., Esparragoza, I., Maury, H.: Developing a set of sustainability indicators for product families based on the circular economy model. J. Clean. Prod. **196**, 1429–1442 (2018)
25. Vanegas, P., Peeters, J.R., Cattrysse, D., et al.: Ease of disassembly of products to support circular economy strategies. Resour. Conserv. Recycl. **135**, 323–334 (2018)
26. Hapuwatte, B.M., Seevers, K.D., Jawahir, I.S.: Metrics-based dynamic product sustainability performance evaluation for advancing circular economy. J. Manuf. Syst. **64**, 275–287 (2022)