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► **To cite this version:**

Michael Saidani, Harrison Kim, Bernard Yannou, Yann Leroy, François Cluzel. Framing product circularity performance for optimized green profit. ASME 2019 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference IDETC/CIE2019, Aug 2019, Anaheim, California, United States. hal-02270135

HAL Id: hal-02270135

<https://hal.science/hal-02270135>

Submitted on 23 Aug 2019

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FRAMING PRODUCT CIRCULARITY PERFORMANCE FOR OPTIMIZED GREEN PROFIT

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ABSTRACT

The purpose of this paper is to develop and discuss a framework aiming at monitoring and optimizing the circularity performance of products for ensuring and facilitating green profit design trade-offs whilst meeting or anticipating end-of-life regulations during the design and development process of industrial products. The proposed framework is used to extend the Green Profit Model – an optimization model to maximize the total profit from the sales of new and remanufactured products, while achieving environmental impact savings – by adding a third dimension to this model, which is the circularity performance. As such, in addition to remanufacturing, it covers a wider spectrum of circular economy practices, leading to additional economic opportunities and environmental trade-offs between maintenance, reuse, remanufacturing and recycling at a product, parts and material levels. A first formulation of this extended optimization model is given and discussed through an illustrative example. By connecting the circularity performance of products with possible economic profit and environmental impact savings, it thus contributes in advancing the understanding and linkages in the area of circular design, life cycle analysis, industrial decision-support tool, and environmental regulations. Concretely, practical implications for both design engineering and green policy making are highlighted.

1. INTRODUCTION

1.1 The importance of product design and end-of-life choices for a sustainable industrial development

Appropriate product design can have a significantly positive influence on sustainability [1]. Most of the environmental impacts are indeed set by choices made in the early stages of product design and development process. While it is estimated that design choices fixe more than 70% of the costs of a product's

development, manufacture and use [2, 3], approximately 80% of a product's environmental footprint is determined as well during the design and development process [4, 5, 6].

Furthermore, product design and end-of-life decisions are closely connected to the environmental regulations [1]. As such, new researches are encouraged to characterize the interactions among regulations, product design, industrial business models, end-of-life pathways, economic and environmental costs. By performing an analysis of barriers for eco-design implementation in industrial companies, Rossi et al. (2016) recommend the implementation of tools allowing a multi-objective analysis, including economic and marketing aspects [7]. In addition, because industry is constrained to respect legislations and standards (e.g., end-of-life regulations), tools and methods (e.g., circularity indicators) should be designed to facilitate their direct control.

1.2 Regulations as a driver to monitor and augment the circularity performance of products

Public policies and regulatory framework, such as extended producer responsibility, are increasingly pushing industrial actors to implement end-of-life management strategies for the products they design, develop and manufacture to ensure proper recovery and recycling. In the meantime, while governments and policy-makers are setting up more and more regulations and guidelines to support the circular economy (CE) transition in various industrial sectors with e.g., mandatory recyclability and recoverability rates for the light-duty vehicles in the European Union, the effective circularity and sustainability performance of a product is often revealed afterwards, depending on real usage, durability and end-of-life conditions [8].

Measuring the circularity potential of product as a means of improvement and optimisation is still in an experimental phase in the CE transition, but is increasingly supported by the recent development of new circularity indicators to be used by

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industrial practitioners during product design and development phases. As discussed in more detail in section 2, the present circularity indicators used in the early stages of a product life cycle can provide a first trend of the circularity performance of a product over its life cycle, but they are not systematically connected to the sustainability impacts of a given circularity [9].

1.3 A need to link the circularity performance of products with sustainability indicators

Interestingly, the adoption of circular economy principles in product design and development is considered as a practical and relevant way of achieving several sustainable development goals [10]. Yet, it is of the utmost importance to measure and monitor the impacts of a transition towards a more circular economy, notably in industrial practices, where trade-offs can occur between circularity and sustainability [11]. The comparison between circularity indicators and life cycle impact assessment results can actually reveal possible trade-offs, for instance, between an improvement of resource circularity and a mitigation of environmental burden [12]. In fact, in some cases, improving the intrinsic circularity performance might result in a negative environmental impact over the entire life cycle [11]. In this line, sound circularity impact measurement represents a key challenge [13] as well-designed indicators can be valuable for managing a sustainable development in industry and providing guidelines to set up circular economy policies [14].

Indeed, life cycle decisions often need to consider trade-offs involving different conflicting parameters. To properly assess the life cycle performance impact for decision-making, when implementing CE principles in product design and end-of-life management of industrial systems, new quantitative analytical tools are needed to connect the potential circularity performance of products and their economic profitability, as well as their environmental impacts all along the life cycle. Actually, taking advantage of the CE to "connect economic and environmental gains" is a key axis of the European Commission Research Agenda [15]. While the European Commission is more focused at a macro level of CE implementation (i.e., reporting on the circularity performance of resources and flows at a country level), this challenge is also true at a micro and more operational level of CE implementation for industry and companies.

In this regard, this paper aims to provide a framework to link the circularity potential of a product with the economic profitability and environmental preservation in a circular economy perspective. As a sound basis for further work, the first elements of an optimization model linking circularity, economic and environmental performance of a product are discussed and illustrated. The ultimate goal is to support decision-making during design and development phase to ensure profitability and environmental preservation when designing circular products and associated business models to respect end-of-life regulations, and/or achieve CE-related objectives. More precisely, the main objective here is to help OEMs finding the most appropriate circular business model and associated end-of-life strategies to achieve an optimal green profit under possible regulations enforcing a minimum circularity performance, in

order to both optimize this green profit while satisfying end-of-life regulations (or CE-related objectives on a voluntary basis). An extension of the green profit optimization model is proposed to as a first contribution to this issue we are addressing, by: (i) considering a wider spectrum of circular economy in the economic and environmental optimization model, (ii) adding a third dimension to the Green Profit Model to take into account trade-offs between circularity and sustainability performance.

In the following sections, we provide our inspirations for the proposed framework by reviewing relevant prior research. Then, we unfold the details of our proposed framework, and extend the green profit optimization model to integrate wider CE considerations. Finally, an illustrative example is given to discuss the practical implications in design engineering and green policy making, as well as to orient future research.

2. LITERATURE BACKGROUND

While this literature review section does not claim or mean to be exhaustive, it reports, to the best of our knowledge and research, the latest findings on how the circularity and sustainability performance of technical products can be measured. Several state-of-the-art examples (including, optimization models and decision support tools) showing how it is possible to consider and integrate economic and environmental trade-offs in design engineering are given. Indeed, recent articles, from the fields of industrial engineering, management science and operational research, are providing relevant insights to help industrialists making profitable and environmentally-sound design and end-of-life decisions. Yet, they barely consider in an integrated manner (i) all the different possible CE strategies and related loops, as well as (ii) the possible transfer of environmental impacts between reuse, remanufacturing or recycling scenarios (i.e., global warming potential, calculated in CO₂ eq. emissions, is often the only indicator to assess the environmental savings). The main contributions of each approach in the articles reviewed are synthetically highlighted, as well as the remaining challenges that need to be addressed, such as the relationship between the circularity and the environmental impacts of a product. With all this background, a framework, to link quantitatively the circularity performance of products with their economic and environmental repercussions, is proposed. Concretely, using this framework, a first extension of the green profit optimization model, integrating circularity indicators, is discussed.

2.1 Circularity and sustainability indicators at a product and part level

More than 50 sets of circularity indicators, at all the levels of CE implementation considered, have been reviewed, analyzed, and classified by scholars in 2019 [16, 17]. At a product level, indicators and associated tools aiming at assessing the circularity potential of a product can be used as heuristic instruments to guide circular design and marketing choices (e.g., CE business strategies) during product design and development phases. For instance, the Circular Economy Toolkit (CET) [18], the Circularity Potential Indicator (CPI) [19], the Circular

Economy Indicator Prototype (CEIP) [20], the Circular Material Value Indicator [21], the Material Circularity Indicator (MCI) [22], or the Product Circularity Metric [23], allow to compare design alternatives relatively quickly (e.g., compared to conducting a full life cycle analysis). The underlying assumption of these indicators is that augmenting the circularity scores is the right way forward more sustainable products.

Yet, even if the overall sustainable benefits (economic, environmental and social) offer by the adoption of CE principles are no longer questioned, it remains essential to be able to evaluate quantitatively the economic and environmental consequences of CE strategies, to make informed and unbiased decisions, as well as to select the most appropriate circularity pathway(s) for a given product, associated spare parts and materials, considering e.g., economic and environmental trade-offs between circular economy loops (such as maintenance, reuse, remanufacturing, recycling).

Today, only few frameworks, integrating circularity indicators and associated measurement tools, attempt to provide a holistic approach taking into account both the intrinsic circularity and the effects of products circularity, e.g., on the three pillars of sustainable development. Indeed, so far, few authors have started analyzing the correlation between potential circularity indicators and environmental sustainability indicators, e.g., between life cycle impact assessment midpoint indicators (such as global warming potential) and design for recycling [24], or the results between a conventional carbon footprint assessment and the scores of three circularity indicators (MCI, CEIP, CET) [12].

Actually, circular economy measurement can be improved in several areas. Among the inventory of promising avenues for further research in a wider assessment of the CE, it is suggested that future work should examine the relationship between production costs and circularity [23]. Also, the claim, or underlying assumption, that an increased degree of circularity is a means to make environmental improvements should be systematically analyzed. Another line of investigation would be to examine the association between CE business model characteristics and product circularity performance. In a nutshell, new research is encouraged on the correlation between circularity assessment and life cycle sustainability indicators, i.e., on studying the relationship between an improvement in a circularity score and its impacts on different sustainability indicators [25].

As such, one of the key and remaining challenges, addressed in this paper, is to provide a framework to correlate, in a more systematic manner, the information provided by these circularity indicators to sustainability indicators obtained through conventional industrial ecology tools such as life cycle analysis (LCA) to evaluate the environmental impacts of products, and life cycle costing (LCC) to assess the cost of products throughout their entire lifetime.

2.2 Product design trade-offs and end-of-life optimization for sustainability

Multi-objective optimization involves minimizing or maximizing multiple objective functions subject to a set of constraints [26]. Common problems in design engineering include analyzing trade-offs between mechanical properties (such as young modulus), mass, and cost, in order to select optimal materials and design architecture. Similar approach can be used to any other application, where an optimal solution with compromises between two or more conflicting objectives is sought. Here, we focus on the trade-offs between economic profit and environmental impact savings related to product design and end-of-life strategy choices.

Luglietti et al. (2014) developed a decision support tool to evaluate the environmental and economic implications of three different end-of-life strategies, including remanufacturing, reuse (component recovery), and recycling (material recovery) [27]. The results are shown in a two-dimensional eco-efficiency diagram displaying the three alternatives with their economic revenue and environmental gain (in CO₂ eq. emissions). Ma and Kremer (2015) developed an approach based on fuzzy-logic to determine commendable product component end-of-life options, considering trade-offs between the three dimensions of sustainable development according to the following indicators: the residual value for the economic pillar; the land use and eco-indicator for the environmental pillar; the human toxic potential and job creation for the social pillar [28]. Igarashi (2016) built and applied a multi-criteria optimization model for lower disassembly cost, higher recycling and CO₂ eq. saving rates by an environmental and economic parts selection, and subsequent disassembly line balancing. The results are highlighted on a pareto-optimal frontier through a three-dimension chart with the following axes: recycling cost, recycling rate, CO₂ eq. saving rates [29].

Van Loon and Van Wassenhove (2017) developed a decision-support tool that original equipment manufacturers (OEMs) can use to assess whether remanufacturing is economic and environmentally attractive compared to the production of new components [30]. The decision variables are the twofold: the number of used products, and the number of reused components. The parameters considered are the costs of acquiring used products, the remanufacturing operations and the sale activities. The environmental impact of manufacturing and remanufacturing activities are assessed through the CO₂ eq. emissions of associated operations. In a complementary manner, a total life cycle cost model (TLCCM) for the circular economy has been developed by other researchers [31]. By using this TLCCM, the net life cycle cost benefit for each possible end-of-life pathway is plotted in two-dimensional chart as a function of the percentage of material in any of these recovery streams associated to product's components (recycling, reman, reuse, landfill). The optimized solution is the proper combination of recycling, reman, and reuse ratio that maximizes the life cycle profit. Eventually, a Product Recovery Multi-Criteria Decision Tool has recently been developed to evaluate circularity strategies of a product at the end of its life. Possible end-of-life scenarios (between reuse, remanufacture and recycling) can be compared using environmental (carbon footprint), economic

(total revenue), and societal (exposure to hazardous materials) indicators [32]. Yet, the pre-life and use phases of the product (e.g., design decisions and marketing strategies) are not directly taken into consideration in such approaches.

As aforementioned, to maximize the overall economic profit, design decisions must closely consider both ends of product life cycle, i.e. manufacturing and end-of-life stages. In this line, Kwak and Kim (2015) developed a decision-support model for life cycle design to optimize initial product design (specifications and selling price) and end-of-life options, as well as production strategies, including production quantities (of both new and reman product) and take-back rate [33]. Using mixed-integer non-linear programming, the objective function is to maximize the total life cycle profit, as the sum of the profits from initial manufacturing and end-of-life remanufacturing. Importantly, an update of this model has been made to consider green profit [34]. Using mixed-integer programming, transition matrix and ϵ -constraint approach to consider two objectives simultaneously, the objective is then to maximize the total profit from the sales of new and reman products, while achieving environmental impact saving. With the help of the model, OEMs can identify an optimal line of new and remanufactured products (buyback, sales pricing and production planning) to maximize their total profit while achieving environmental impact saving greater than a target. Yet, in the Green Profit Model: the product design is predefined and fixed; the end-of-life product and remanufactured product have the same design; no upgrade is considered in remanufacturing; environmental impact savings in calculated only taken into account the remanufacture of the whole product; and no other circular economy loops, at a component or material level, are directly considered.

In this line, the foundational work made on the Green Profit Model [34], which is further described in section 3, can serve as a sound basis for modeling the link between the circularity performance of products and their associated economic and environmental repercussions in order to make optimized product design (pre-life), take-back and recovery (end-of-life) decisions. We argue that coupling the Green Profit Model with circularity indicators can facilitate the validation of circular design and business strategies choices (in a time-efficient manner during product development phase), as well as the accomplishment and monitoring of circular economy targets (on a mandatory or voluntary basis).

3. PROPOSED FRAMEWORK

3.1 Framing the circularity performance of products

Before addressing the extension of the Green Profit Model with the integration of circularity indicators, this part aims at framing the relationships between the circularity performance of products with green profit design trade-offs and end-of-life regulations, as illustrated through the Venn diagram in Figure 1.

First, end-of-life regulations (e.g. mandatory take-back, reuse or recovery rates), or voluntary-based objectives to communicate about the sustainable performance of products, are two key drivers for augmenting the circularity performance of products. Then, from a manufacturer perspective, it should

always be checked or proved that the implementation of CE strategies can effectively lead to a viable return on investment. Next, to ensure that moving towards more CE leads also to environmental preservation, avoided impacts allowed by CE loops have to be quantified.

To find the optimum between economic profit and environmental savings, green profit design trade-offs have to be analyzed. Some other trade-offs, not systematically considered when setting up a CE target, between the intrinsic circularity performance of products (i.e., recirculation of parts and materials preventing the extraction of new materials and thus contributing to resource and natural habitat conservation) and the required energy to keep these parts and materials into the value chain (e.g., energy consumed to disassemble and refurbish a component, or emissions due to the collection and transportation to a remanufacturing center), have also be taken into account to define the appropriate circularity strategy and associated end-of-life pathways. The multi-objective problem we set out to formalize is therefore what is the optimal circularity for a given product, or set of products, to achieve greater green profit while satisfying end-of-life regulations.

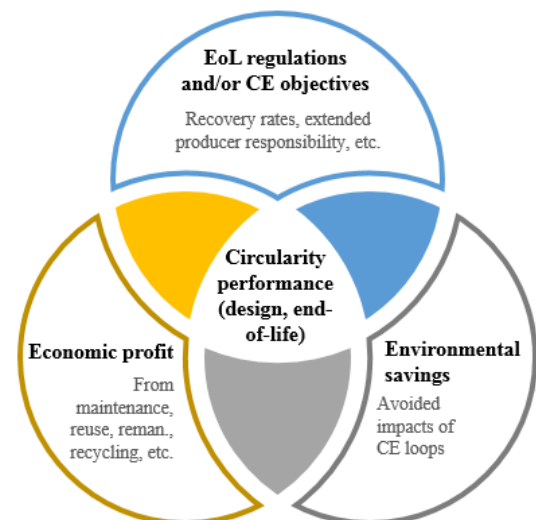


FIGURE 1: FRAMING THE CIRCULARITY PERFORMANCE OF PRODUCTS

In our case, the circularity performance of products can be viewed as a cursor to adjust, regarding the possible modifications in design features, business model offers, market condition and end-of-life capabilities. In accordance with the Ellen MacArthur Foundation [22], the circularity potential of products depends on four building blocks, namely: circular product design, new business models, reverse cycles, and favourable system conditions. Also, as illustrated in Figure 2, forecasting the actual circularity performance if a given product (which is reveals only afterwards, i.e., at the end-of-life stage) during design and development phases is a challenge, given the time gap between the pre-life and end-of-life stages, in addition to the uncertainties related to the usage and location of the product during its lifetime.

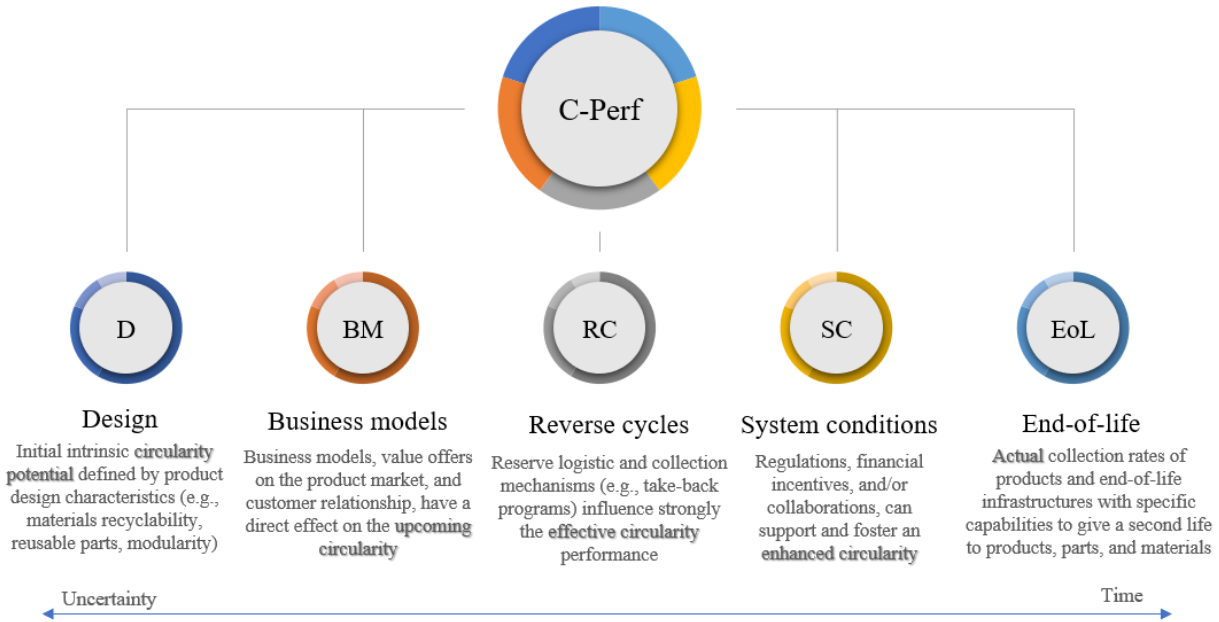


FIGURE 2: FACTORS INFLUENCING THE CIRCULARITY PERFORMANCE OF PRODUCTS

The list of attributes that can influence or contribute to an effective product circularity is quite extensive. First, circular product design (building block #1) is the starting point for any circular industrial eco-system. Appropriate design choices (e.g., modular and maintainable products) can ease the recovery of parts and materials. Second, innovative business models (building block #2) can enable the tracking and collection of products. Third, reverse logistics (building block #3) are needed to effectively recover products from end-users. Fourth, favourable system conditions (e.g., policy frameworks, financial incentives) should act as enablers to catalyze the circular economy transition.

The effective combination of each of these four building blocks are essential to reach an effective circularity and efficient sustainable performance. For example, (i) a well-designed, modular and easy to recycle product, but in a region with no recycle capabilities, would lead to a non-optimal result from a circularity and sustainability perspective; (ii) a modular, easy to disassemble product, in a region with state-of-the-art recycling centers, and under end-of-life regulations, would lead to a way better outcome.

3.2 Extension of the Green Profit Model

The initial Green Profit Model provides a formulation for integrated pricing and optimal production planning for a line of new and remanufactured products in a competitive market [34]. The Green Profit Model combines three main elements and associated parameters for integrated pricing and production planning: (i) product take-back (availability of end-of-life products, response function, buyback price and quantity); (ii) production (product family design, operations, cost and environmental impact, production plan); and (iii) marketing distribution (demand model, selling price, production quantity).

In outputs the initial Green Profit Model, the nine following variables are optimized to maximize the economic profit from sales of new and reman products while achieving a minimum environmental savings target:

P_k, X_k	Buyback price, and takeback quantity of end-of-life products
P_n, Z_n	Selling price, and production quantity of new products
P_r, Z_r	Selling price, and production quantity of remanufactured products
Y_j, M_i, N_i	Number of end-of-life operations, recycling amount, quantity of new parts acquired

The Green Profit Zone is illustrated in Figure 3 for a given product and its associated pricing and production strategy both for the brand-new product and remanufactured one. In this two-dimensional chart, green profit opportunities are revealed compared to a baseline scenario when only newly manufactured product are proposed, and therefore a low circularity performance is achieved. The curve created plotting economic profit against environmental impact savings of the dominating strategies is known as the Pareto frontier. As such, in Figure 3, only the optimized points in terms of Pareto are displayed, showing trade-offs between profitability and environmental savings, based on the adjustment of pricing and product planning both for the new and remanufactured product.

In the proposed extension of the Green Profit Model [34], as described and formalized through the mathematical equations of sub-section 3.3, we are aiming to consider a wider spectrum of circular economy loops, by adding a third dimension, which is the circularity performance at a product, part, and material levels, in the optimization model.

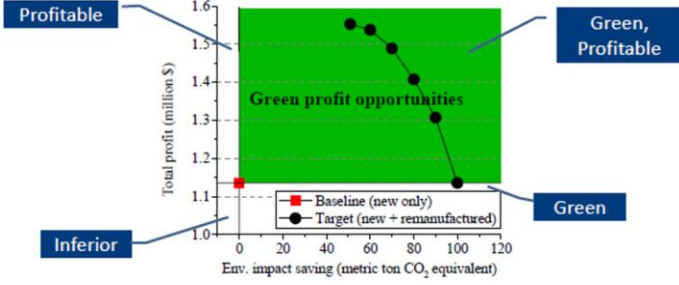


FIGURE 3: GREEN PROFIT ZONE [34]

3.3 Formulation of the optimization problem

An optimization problem is a mathematical model in which certain parameters need to be determined to reach an optimal measurable performance under defined constraints. The optimization problem we are seeking to formulate and to solve here is how to identify and achieve the circularity performance that ensures optimal green profit trade-offs whilst meeting end-of-life regulations. It consists of: (i) decision variables which are the resources that can be used and modified (e.g., design choices, marketing plans, end-of-life pathways); (ii) constraints which represent the resource limitations (e.g., recovery center capabilities) and other imposed restrictions (e.g., regulations); (iii) one or several objective function(s) which is/are the performance indicator(s) to optimize (e.g., circularity performance, economic profit, and/or environmental preservation), as detailed hereafter and further discussed through an illustrative example in section 4.

When designing a product and developing a market strategy, there could be various combinations of designs and business strategies that are some compromises of economic cost, environmental impact savings, and circularity performance. When multiple objectives are conflicting, trade-offs must be analyzed. As in the Green Profit Model, the use of a Pareto front appears as a suitable approach to address this multi-objective optimization problem. It consists at finding non-inferior solutions, that is to say, solutions in which an improvement in one objective does not lead to a degradation in another. In the present case, the set of Pareto solutions are the feasible designs and associated business models, leading to a circularity performance, economic profit and environmental impacts savings, that are not dominated by any other design, business strategy, and forecasted end-of-life scenario. In a three-dimensional graph, displayed in section 4 through an illustrative example, the Pareto frontier provides the decision-maker with the set of optimal solutions.

The challenge here is to integrate both the potential additional revenues and environmental impact savings from other circular economy practices, rather than only remanufacturing at a whole product level, including product life extension thanks to maintenance (e.g., cleaning and refurbishment services, or part replacement), reuse at a spare part level, as well as recycling at a material level. By adding a third dimension to this model, additional variables are incorporated associated to these CE loops at a more detailed level (i.e., including not only the product level but also parts and materials

levels), and thus leading to further opportunities and trade-offs regarding economic profit and environmental impact. To ease reader understanding related to the extension of this model and to ensure consistency with the original model, we use the same terminology and nomenclature as in the Journal of Cleaner Production article introducing, describing and experiencing the initial version of the Green Profit Model [34]. Note that the initial terms of the Green Profit Model are written in black letters, while added decisions variables are highlighted in dark blue:

$$\text{economic profit: } \max (P_n - C_n)Z_n + (P_s - C_s)Z_s + P_r Z_r + \sum_{i \in I} p_i^R Z_i + \sum_{i \in I} p_i^M M_i - (\sum_{i \in I} c_i^R Z_i + \sum_{i \in I} c_i^M M_i + \sum_{k \in K} P_k X_k + \sum_{j \in J} c_j Y_j + \sum_{i \in I} c_i^N N_i + c_d Z_r) \quad (1)$$

$$\text{environmental saving: } \sum_{k \in K} (e_w - e_k) X_k + E_s Z_s + E_n Z_r + \sum_{i \in I} e_i^R Z_i + \sum_{i \in I} e_i^M M_i - (\sum_{i \in I} e_i^R Z_i + \sum_{i \in I} e_i^M M_i + \sum_{j \in J} e_j Y_j + \sum_{i \in I} e_i^N \cdot N_i + e_d \cdot Z_r) > \delta \quad (2)$$

circularity performance (effective):

$$\frac{m_t Z_r + \sum_{i \in I} m_i^R Z_i + \sum_{i \in I} m_i^M M_i}{m_t Z_n} > \gamma \quad (3)$$

circularity performance (potential):

see e.g., the scoring system of the CPI or CEIP (3')

Also, for simplicity purposes and easy reading, below are only described the main terms of the mathematical model for the economic profit depicted in eq. 1. Similar terminology is used to described environmental impacts in eq. 2. Also, as a first attempt to integrate the circularity performance, we used an effective mass-based indicator, as defined in eq. 3, considering the contributions of remanufactured products, reused parts and material recovery:

- I Set of produced items: products, parts and materials
- J Set of end-of-life operations
- K Set of end-of-life products available and recoverable
- $(P_n - C_n)Z_n$ Profit from the new products
- $(P_s - C_s)Z_s$ Profit from the maintenance services
- $P_r Z_r$ Revenue from the remanufactured products
- $\sum_{i \in I} p_i^R Z_i$ Revenue from the recovered spare parts
- $\sum_{i \in I} p_i^M M_i$ Revenue from material recycling
- $\sum_{i \in I} c_i^R Z_i$ Cost of spare parts recovery
- $\sum_{i \in I} c_i^M M_i$ Cost of material recycling
- $\sum_{k \in K} P_k X_k$ Cost of take-back
- $\sum_{j \in J} c_j Y_j$ Cost of remanufactured operations
- $\sum_{i \in I} c_i^N N_i$ Cost of spare parts replacement
- $c_d Z_r$ Cost of marketing and distribution
- $m_t Z_n$ Total mass of newly manufactured products
- $m_t Z_r$ Total mass of remanufactured products
- $\sum_{i \in I} m_i^R Z_i$ Total mass of independently recovered parts
- $\sum_{i \in I} m_i^M M_i$ Total mass of material recycled
- δ Target for the environmental impact savings
- γ Target for the circularity performance

For further information, the entire nomenclature and list of other constraints (i.e., on variables conditions, product take-back, and input-output flow balance in end-of-life operations) of the foundational model are available in Kwak and Kim (2017) [34]. In this initial Green Profit Model, the function objective, aiming at identifying the optimal prices and production plan for a line of new and remanufactured products, is to maximize eq. 1 (i.e., max. economic profit) while ensuring a minimum value for eq. 2 (i.e., environmental savings have to be higher than a certain target δ). In the next section, based on the aforementioned equations, different function objectives and constraints are discussed regarding the needs or preferences of a decision-maker, whether in design engineering or in green policy making.

4. FIRST APPLICATION AND DISCUSSION

4.1 Illustrative example

To illustrate how these trade-offs between circularity performance (eq. 3), economic profit (eq. 1), and environmental impact savings (eq. 2), can be considered and linked all together to provide decision-makers with Pareto-optimal possible solutions, let us take the example of an industrial product with the following characteristics: (i) one out of ten products can properly be maintained during usage and entirely remanufactured at the end of this first life, according to the current usage conditions and continuous exchanges between some customers and the OEM, plus its remanufacturing center;

(ii) up to 25% of the components (spare parts) of the entire product at its end-of-life in terms of mass can be recovered and reused in another products or applications, according to the actual product design and current capabilities of the remanufacturing center; (iii) up to 95% of the materials used in this product can effectively be recycled, according to the actual product design and best available technologies in recycling centers.

As such, in this illustrative scenario, different end-of-life pathways and related CE loops, based on their economic and environmental profiles, can be chosen to reach e.g., whether (i) the minimal circularity performance that is required to satisfy end-of-life regulations and thus maximizing profit under this constraint, or (ii) another Pareto-optimal solution leading to further environmental savings, as illustrated with green dots (dominated solutions) on the charts in Figure 4. Note that on the “environmental savings - economic profit” two-dimensional chart, the green profit zone from the initial model (see Figure 3) can be plotted on the upper right of this graph. The step forward would be to evaluate how possible design changes, as well as other circular business strategies (i.e., implementing design for X strategies like design for ease-of-return take-back management, disassembly, upgrade, reuse, remanufacture, and recycling), can enhance the circularity potential (eq. 3’), and simultaneously affect the associated economic profit and environmental impact savings of this augmented circularity.

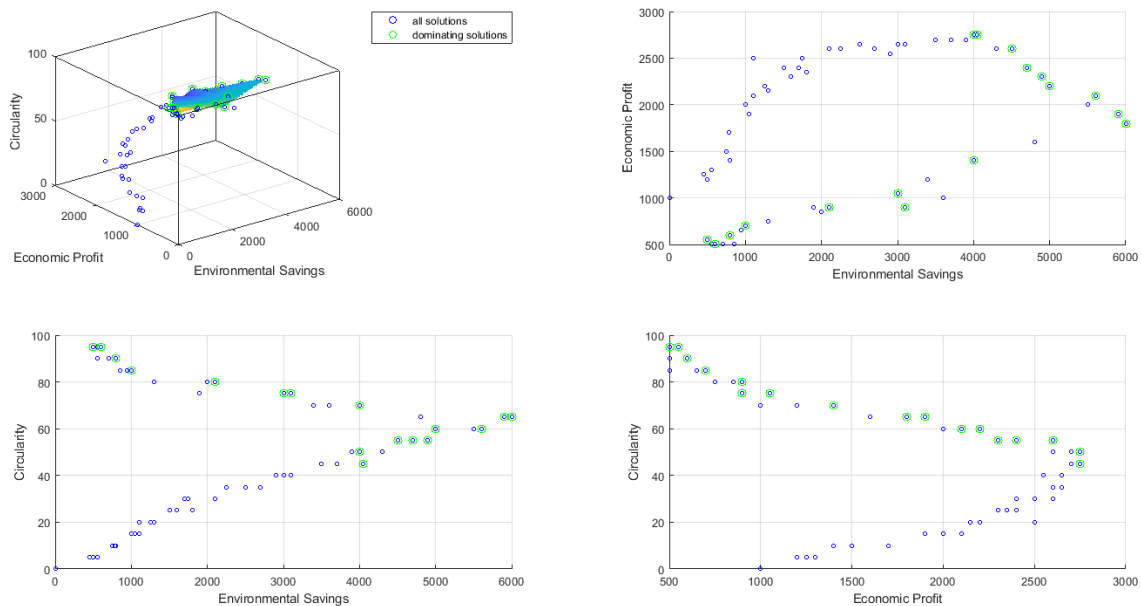


FIGURE 4: ILLUSTRATIONS OF POSSIBLE OUTPUTS OF THE OPTIMIZATION MODEL TO SUPPORT DECISION-MAKING

More precisely, for a given product, each possible solution point, displayed in Figure 4, represents a feasible design (architecture, modularity, bill of materials) associated to a possible business strategy (buyback price, buyback quantity, reman. offers, production plan, selling prices) that leads to an expected end-of-life scenario. As such, it can help (e.g., an OEM) identifying in the early product life cycle phase, what

would be the feasible and optimal CE strategies (between product reman, parts reuse and material recycling) with their associated trade-offs based on product design (part combination and technical specifications), forecasted end-of-life operations (feasibility, cost, impacts, technical issues); market demand for products, parts and materials coming from CE loops).

For graphical purpose, a given end-of-life scenario is represented by an overall circularity score, which is the combination of the contributions of maintenance and whole remanufacturing at a product level, recovery at a spare part level, and recycling at a material level, as defined in eq. 3. This means, in the present case, that a same overall circularity score can have different values for the economic and environmental scores depending on the repartition of maintenance, remanufacture, reuse and recycling contributions. Dominating solutions here are the ones who get the higher values for two parameters out of three Accordingly, for a given circularity (e.g., 60 %), two dots are highlighted as dominating solutions: one with the highest economic profit score, one with the highest environmental savings score, depending of the contributions of reman, reuse and recycling within the overall and single circularity score used here. Also, for illustration purposes, all feasible solutions (i.e., both non-optimal and dominating solutions) of the present example are displayed in Figure 4. By setting a higher target for circularity performance or environmental impact saving, fewer solutions would be displayed to have a focus on the dominating solutions of interest.

For instance, the maximum circularity performance of 95% could be reached by only doing material recovery (i.e., 95% of recycling), or by combining product remanufacturing (e.g., 5%), parts recovery and reuse (e.g., 15%) and recycling (e.g., 80%). Moreover, note that in this illustrative example, the outputs reveal that improving the circularity performance is profitable up to 50%, and augmenting the circularity performance can lead to environmental impact savings up to 65%. In fact, recycling some materials can lead to higher economic and environmental costs than energy recovery or landfill options, considering logistic costs, emissions emitted, and energy used to recycle them. Similarly, giving a second-life to some spare parts can be more expensive or harmful for the environment than making and selling new ones, considering the efficiency of manufacturing process compared to the end-of-life operations, as well as the price difference between brand-new components and second-hand ones.

4.2 Implications for design engineering and green policy making

While it is acknowledged that adding an additional dimension to a two-objective optimization problem can create further complexity, we argue it can bring more relevance and flexibility based on the decision-maker real issues and needs. Practical implications of the proposed approach are discussed both from a design engineering perspective, and from a CE policy making perspective.

Actually, in a context of CE transition, being able to link quantitatively the potential circularity performances of products with their repercussions on the economic profit and environmental footprint, during the design and development process and/or when setting up an end-of-life strategy plan, is essential for both industrialists (including sustainability managers, product recovery managers, product designers and engineers) or policy makers. In this line, a first extension of the

Green Profit Model [34] has been proposed to find related Pareto-optimal three-dimensional vectors (circularity performance, economic profit, environmental impact savings).

In design engineering, aligned with the initial aim of the Green Profit Model, the objective function representing product designer or manager preference in order to find the optimal designs and circular business strategies, can be to maximize eq. 1 while achieving minimal target values for eq. 2 and eq. 3. In fact, under the economic profit equation (eq. 1), the objective is to maximize the overall revenue source coming both from the sales of brand-new products and the profit from CE related services (e.g., maintenance, parts replacement) and end-of-life operations (e.g., product remanufacturing, parts recovery, and material recycling) for an OEM and its reconditioning center.

In green policy making, given the actual number of products already designed, currently in the market, and considering the current state-of-the-art recycling facilities, the objective function for a policy-maker to ensure a sound and sustainable end-of-life management of a given line of products (e.g., light-duty vehicles in Europe under the ELV Directive 2000/53/EC) could be to figure out what is the optimal circularity performance (eq. 3) that maximizes the environmental preservation (eq. 2) while ensuring viable profit (eq. 1) both for producers and end-of-life infrastructures.

Also, both for business practices and green policy making, it could be of the utmost significance to simulate and evaluate the repercussions on the economic and environmental profiles of product, when, for example, implementing a take-back strategy ensuring a certain collection rate from the initial sales, or setting up a mandatory recovery rate. This could be envisioned by putting more specific constraints on the circularity performance, and running a more advanced version of this optimization model.

4.3 Conclusion and perspectives for future work

After underlining the stakes of considering design for circularity and sustainability in the early phases of product development, an updated literature review on circularity indicators at a product level has enlightened the lack of systemic correlation with between product circularity indicators and the sustainability performance. On this basis, this paper proposes a timely framework to consider simultaneously the circularity performance and the impacts on sustainability when designing products, associated marketing strategies, while meeting or anticipating end-of-life regulations. Following this framework, a first extended formulation of an existing optimization problem, to link both the circularity and sustainability performance of industrial products, as an extension of the green profit zone, has been developed and illustrated.

As practical implications, this can help decision-makers to consider and avoid negative impact transfers between circularity and sustainability performance when designing a product, defining its associated business model, and forecasting its end-of-life pathways. In fact, we argue that such a framework, optimization tool and graphical visualization could help designers, engineers and managers defining or validating the appropriate circular design, associated marketing strategy and

forecasted end-of-life options to achieve an optimized use of their resources while contributing to environmental preservation. By analyzing such trade-offs in design engineering, business strategies and end-of-life options, decision-makers are more likely to make well-informed and better sustainable choices.

As a current research and operational limitation, the final version of the optimization model is still to be fine-tuned, computed, and tested on a real case study. The present contributions actually include: a framework connecting the circularity performance of products with economic and environmental considerations under constraint of end-of-life regulations; and a first illustrative application of the extended green profit optimization model, integrating a wider spectrum of circular economy opportunities, discussing also the possible implications in design engineering and green policy making. This opens up the door for new contributions and provides a relevant basis to frame and stimulate further research works.

For instance, one promising area of future work would be to correlate the scores given by circularity potential indicators (such as the CPI or the CEIP), with the actual economic and environmental profiles of different products. Interestingly, if more advanced and systemic correlation can be validated between acknowledged life cycle impact assessment indicators (from LCA or LCC), and circularity indicators (i.e. proving that augmenting the circularity score to a certain extent lead to actual economic and environmental benefits), the use of such indicators could be practical to improve the sustainability performance of products during design and development stages. Actually, using life cycle assessment software is often time-consuming during the product design and development process, which is a hindrance to their effective adoption and use [7, 25]. If such circularity potential indicators, considered as time-efficient heuristic tools, can be associated with tangible and positive sustainability impacts, they could be used to help designing greater circular and sustainable products.

Next steps, and relevant areas for pushing this framework and model to the next level, also include:

- The explicit integration, in the optimization model, of how the four building blocks (e.g., product design variables) are linked to the circularity performance. For instance, a product can be modelled as a set of attributes, including functionality, producibility, usability, maintainability, possibility of recycling, reuse, remanufacturing, and can be characterized by materials, architecture, and production technology. The interest would be to analyze how design choices affect the circularity performance, in order to know what circular design strategies are preferable in a green profit optimization perspective.
- In other words, based on the graphical outputs illustrated in Figure 4, a designer would figure out what are the product features that make the curves shifting towards an ideal circularity performance zone, and/or what can be done to reach that ideal area. Through this proposed extended Green Profit Model, incorporating a more detailed characterization of the product circularity

performance (considering entire product, spare parts, and parts levels, and associated end-of-life options), it will make easier for future works to integrate the impact of design alternatives of the circularity performance.

- The need to perform real-world case study in order to validate, and fine-tune the model, based on the data required and actually available to compute the model, as well as to interact with industrialists, discuss their interests, and analyze informed actions taken as a result.
- The modeling (and automation) of this trade-off analysis in a user-friendly environment, so that it can be easily integrated and effectively used by decision-makers (designers, engineers, managers) during the design and development process of products.

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