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Proposal of a strategic model to unlock the circular potential in industrial practice

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Abstract

Remanufacturing of end-of-life products and parts is seen as a solution in the transition towards a circular economy. There are many proposed tools and methods to facilitate the application of this circular strategy, however, among them, there is a lack of support tools for practitioners that include multiple perspectives related to the value chain and circular economy. In fact, remanufacturing strategy, economic and environmental trade-offs, and circularity indicators are rarely integrated within one framework. In this paper, an approach is presented taking advantage of the state-of-the-art research on green profit model and circularity indicators; in other words, these tools are used together to unlock the circular potential in manufacturing practice. In this way, typical problems of production planning and control in remanufacturing processes are interconnected with the goals of sustainable development, also considering product design and end-of-life strategy choices. The presented framework represents a promising support to be used in industrial practice. A case study based on PV panel infrastructure allows a better comprehension of the research outputs and assesses the validity of the support provided by the framework in the deployment of circular economy strategies.

Keywords: circular economy; remanufacturing; circularity indicators; design for remanufacturing; end-of-life management; optimization; PV racking system.

1. Introduction

The negative effects of the currently dominant production models based on taking, making, and disposing of resources threaten natural ecosystems and affect human health and well-being (1,2). Nowadays, governments and non-governmental organizations (NGOs) stimulate companies to look for new way of producing while meeting environmental goals. In this context, circular economy (CE) has recently been repopularised as both a public policy and business concept (3,4). This strategy allows to address many of the complex challenges of the 21st century, including the loss of biodiversity, climate change, finite resource depletion, conflict over energy and resources (5).

Improvements in terms of circularity performance can be introduced all along the life cycle of products (i.e., design, manufacturing, distribution, usage, and end of life (EoL)). Considering the first life cycle stage, the role of design is crucial in order to reduce the negative effects of economic activity to human health and natural ecosystems, therefore moving towards CE as described by Ellen MacArthur Foundation (EMF). Product design can be considered as the starting point for any circular product or system, since it has been acknowledged that up to 80% of products' sustainability performance can be influenced during the design phase (6). In addition, product design has a significant effect on manufacturing systems since it affects:

- The existing circular economy business options that the manufacturer can adopt (7)
- The selection of the related technological solutions

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- The efficiency and profitability of the remanufacturing process-chain (8).

Among the CE loops, remanufacturing is promising for mechanical and electrical products if some enabling conditions are satisfied (e.g., if products can be easily dismantled by operators). In this way, companies do not face costs to completely produce new goods, instead they takeback products after the customers' use and remanufacture or refurbish them. To guide the transition towards CE, circularity (C-) indicators facilitate the measurement and assessment of the enterprise's performance with respect to CE. In addition, the product centric circularity indicators assess the effective and potential performance of products, parts and components with respect to CE in a concrete manner. Therefore, they can be deployed as a first screening tool in the space of alternative design possibilities when designing for a CE (9).

Overall, CE is a today relevant topic considering the research effort delivered by scholars, but the path is still long for matching academic results with industrial practice. This paper tries to go in this direction taking advantage of state-of-art research on circular tools and indicators. Potential impacts concern the use of the residual value of takeback products, the reduction of supply chain risks and, overall, the adoption of innovative business models.

1.1 Literature review

The literature analysis is performed for each of the pillars of the work: circular economy business model (CEBM), design tools and methods, remanufacturing, decision support models and C-indicators.

Considering the literature review conducted by Geissdoerfer et al. (10), CEBM can be defined as business models that are cycling, extending, intensifying, and/or dematerializing material and energy loops to reduce the resource inputs into and the waste and emission leakage out of an organizational system. This includes recycling measures (cycling), use phase extensions (extending), a more intense use phase (intensifying), and the substitution of products by service and software solutions (dematerializing), as illustrated in Fig. 1.

The cycling strategy is closely linked with repair, remanufacture, refurbish and recycling as CE loops, in fact, takeback is considered as fundamental element for this strategy enabled by collaborations in the value chain and reverse manufacturing processes. In this case, value capture is mainly related to minimised costs of material acquisition and additional revenues from end-of-life products, reaching environmental goals (i.e., reducing both energy and new materials intake and waste output). Designing for dis- and reassembly can ensure that products and parts are separated and reassembled easily (11) and it is a successful way that can be applied to increase the future rates of material and component reuse (12).

Economic savings within remanufacturing, relative to traditional manufacturing, are primarily attributed to reduced material and processing costs. These arise from the reuse of a product which enables both the material content and the embodied energy of the original manufacturing process to be retained (13). However, remanufacturing may struggle to compete with manufacturing on cost as it tends to occur in smaller volumes and includes labour intensive process such as disassembly (14).

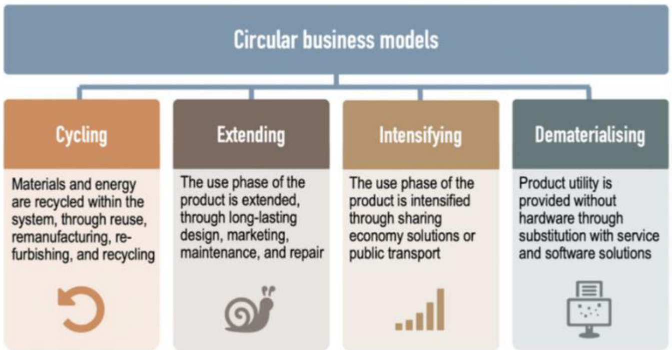

Fig. 1. CEBM: cycling, extending, intensifying, and dematerialising (10).

The remanufacturing processes usually include sorting, inspection, disassembly, cleaning, reprocessing and reassembly, testing and parts which cannot be brought back to original quality are replaced, meaning the final remanufactured product will be a combination of new and reused parts (15,16). Each of the presented steps can be further broken down into generic costs including labour, materials, and overheads. These process and activity costs are by no means fixed and can vary significantly between similar product types for several reasons including the physical EoL condition of the returned product, product design, and overall process efficiency (affected by batch size and inventory control) as highlighted in Fig. 2.

As explained in (15), a company is considered as a suitable candidate for remanufacturing when their products possess certain qualities:

- A reverse flow of used products
- High value and durable parts
- Technological stability
- Potential to be upgraded
- Customer demand for the remanufactured product.

Considering the last pillars of the literature review, decision-makers need adequate support tools when dealing with complex industrial transitions to CE. Among many decision support models available in literature, the green profit model is deployed within the current paper (17) since it is a comprehensive linear programming model. In fact, GPM optimizes production planning, take-back and selling strategy, maximizing the total profit and reaching well-defined environmental goals (in terms of kg of CO_2 equivalent). Additionally, being able to link the potential circularity performances of products with their repercussions on the economic profit and environmental footprint is essential for both industrialists and policy makers. The integration among C-indicators and strategic decision support models can be considered a way to pragmatically help companies in the transition to CE. Overall C-indicators enable detection, monitoring, quantification, assessment, and interpretation of the performance of organizations, operational processes and products in terms of their potential (expected) or achieved (actual) sustainability and circularity impact (18).

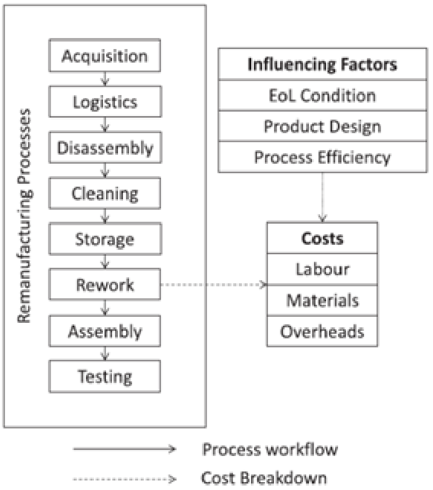

Fig. 2. Remanufacturing processes: influencing factors and costs (16).

1.2 Research question

From the literature review step, the main research gap identified is the lack of approaches that have a complete overview on the deployment of CE strategies, in other words tools that combine decision support models and C-indicators are still lacking. Therefore, a research question is identified: "Can C-indicators provide support for the implementation of remanufacturing as circular business strategy?". The rationale behind this research question is to assess the capability of indicators to capture useful information for guiding the implementation of remanufacturing in real practice. It will be assessed whether indicators can properly be integrated with strategic decision support models (e.g., GPM as optimization model) to link the potential circularity performances of products with their consequences on the economic profit and environmental savings.

2. Methodology

The core part of the work is the presentation of the proposal of framework, which is developed taking advantage of the state-of-the-art research about the green profit model and circularity indicators. The GPM is augmented and modified accordingly to the improvement areas disclosed by C-indicators. The objective is to provide companies a useful and easy-to-use approach for reaching economic, environmental, and circular objectives. A case study allows the validation of the work in industrial context. A leading French company in the renewables industry provided a case study based on the racking system for ground mounted photovoltaic (PV) panels, usually deployed in solar farms.

2.1 Proposition of framework

Within the present work, a new way of using optimization models and C-indicators together is investigated. The framework allows to validate the supporting capability of indicators in identifying and putting into practice circular strategies. Therefore, the key idea of this approach is to use firstly indicators to gain knowledge and insight about the current performance of a specific product, then the optimization model is applied accordingly to the suggestions of the C-indicators and, as a last step, the C-indicators are computed again to quantify (if possible) the gain in performance. In this case, a set of indicators is used to gather multiple views on the problem and the information extracted from them guide the implementation of a CEBM. At the same time, the optimization model guarantees the consideration of multiple CE loops simultaneously, and it allows a feasibility check on economic and environmental dimensions.

The five steps of the framework represent a logic path for unlocking the circularity potential within a business practice, as Fig. 3 shows. In fact, to firstly understand the circularity level of the current industrial practice, a shortlist of C-indicators is selected. The selection process of C-indicators is based on some well-defined criteria, related as an example to CE implementation level, CE loops, CE perspective and format of the CE assessment framework. Using a support tool (e.g., the C-Indicators Advisor web-based tool by Michael Saidani (19)), up to 10 C-indicators are selected because so it is possible to cover well the peculiarity of the case study keeping low the computation effort. In the subsequent "analysis" step, all the selected indicators are computed: some useful insight can be derived looking at performance of the current business practice captured by indicators (e.g., creating new forms of collaboration between manufacturer and customers). In fact, taking advantage of the semi-quantitative nature of indicators,

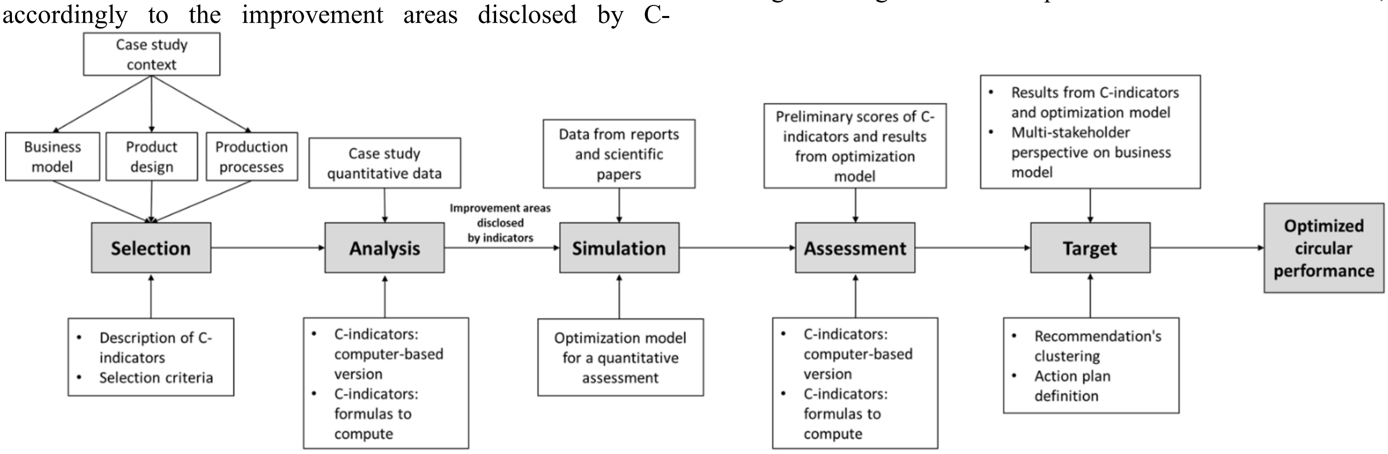

Fig. 3. Proposal of framework to unlock circular potential in industrial practice.

a concrete comprehension of as-is condition is gained. These findings prepare the ground for the use of the optimization model, as it can be launched after fine tuning it and collecting the required data. The use of the optimization model is relevant because it assesses quantitatively the findings obtained from indicators, practically connecting design, production, and market information. The simulations from the optimization model contain decisive results for understanding the potential improvement in circular performance of the current business practice. Also, if the suggestions provided by the first computation of indicators are considered in the optimization model, the overall performance of the business practice will basically be more circular compared to as-is situation. Using the right optimization model (e.g., GPM), the results can disclose information about profit, environmental savings, and production mix. From here the reason to compute for the second time the same shortlist of C-indicators: to check if and how much the circular performance is augmented. Once analyzed the difference in circularity performance between as-is and to-be (obtained from simulations) conditions in the "assessment" step, some recommendations and guidelines can be drawn. In fact, if a tangible increase in the circular dimension is possible, it is important to define the correct action plan to trigger change and close the gap between the as-is and to-be situations. Multiple stakeholders are generally involved when reaching challenging CE goals, so a step-by-step plan is the proper way to pursue the objective.

The selection and target step are iterative because of the presence of human decision making. Criteria for the selection of C-indicators can be refined when a deeper understanding of the relevant variables for the case study is obtained. Accordingly, in the target step, it is possible to state the best action plan only with exchange among the actors involved.

3. Case study

In this paper, the authors took advantage of a new collaboration with TotalEnergies, French leader company in the oil & gas industry. TotalEnergies is becoming an international solar energy operator since it designs, finances, builds and operates large solar plants, delivering projects that are both reliable and sustainable over the long term.

Over the last several quarters, problems in the supply chain were faced by companies in strategic sectors such as renewable energy, electric mobility, defense and aerospace (20). Specially, critical components for solar equipment – polysilicon, steel, aluminium, semiconductor chips, and other metals – have become increasingly supply-constrained. The impacts of these constraints on the solar industry vary. For this reason, Solar Energy Industries Association (SEIA) advises manufacturers to consider reuse, refurbishment and/or recycling of first end-of-life PV modules, inverters, racking equipment and associated components when possible (21).

3.1 PV ground mount racking system

For the development of the work, the focus is on the racking system for ground mounted solar farms. The structure well fits the requirement for the framework because it is a mechanical product made of metallic materials, it has a long life span and, in a general sense, can be remanufactured. Today, TotalEnergies does not produce this infrastructure, but it buys the structure from supplier. For this reason, the data useful for feeding the model comes from different sources: TotalEnergies' experts, websites of manufacturers, reports, and scientific papers available in literature. In general, it is important to assess the feasibility of remanufacturing and recycling with this product to achieve economic, environmental, and circular goals.

The ground screw mounting system is designed to provide an economical and practical mounting solution for large-scale open areas. It is available for both framed and frameless modules and compatible with screwing machine. The structure can withstand a maximum of 45 m/s wind speed and a snow load of 1.4 kN/m^2. An overview of the structure with its parts is shown in Fig. 4.

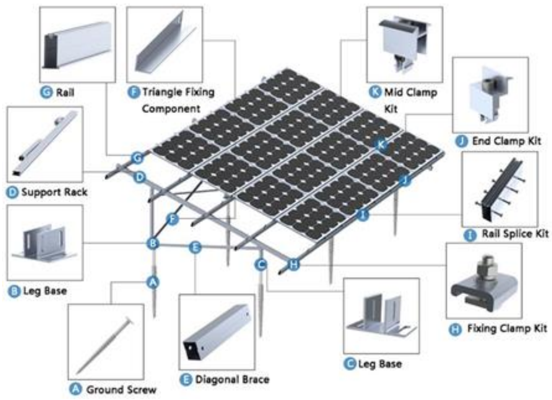

Fig. 4. Ground mount structure.

3.2 Framework: selection and analysis

Circularity indicators provide various information about products and companies considering multiple points of view (i.e., CE loops, CE perspectives, format of the CE assessment framework) at the same time. Usually, all the information processed by indicators is summarized in scores that allows a clear understanding of the actual level of circularity and provides insight for augmenting the circular level of products or industrial facilities.

For the scope of the case study, the following five C-indicators are selected thanks to the C-Indicators Advisor (19): material circularity indicator (MCI), circular economy indicator prototype (CEIP), circularity potential indicator (CPI), circular pathfinder (CP), circularity calculator (CC). The rationale behind this selection is that the case study is based on a product, so the focus is mainly on the micro level (i.e., organization, products, and consumers) (22). Secondly, these indicators consider all the CE loops since both remanufacturing and recycling are envisaged as credible strategies. Thirdly, to make a comparison between the current and future situation, both actual and potential circularity performance have to be used. Finally, computer-based indicators are preferred for their simplicity and need for a lower quantity of input data, compared to the formulas-based indicators.

From the analysis step, the takeaways, derived from the use of C-indicators, to be applied in the optimization model are:

- To augment the reused and recycled quantity of the deployed materials (i.e., steel and aluminium)
- To foster the recovery and reutilization of the product's materials, creating new forms of collaboration between manufacturers and customers
- To increase the modularity at the design level
- To rethink pro-active attitude from companies to enhance the circular economy practice.

3.3 Framework: simulation

The green profit model, firstly developed by Kim and Kwak (17), is deployed within the current case study. The use of the GPM within the case study is beneficial since it allows to obtain a quantitative simulation of the circular strategy performance, from an economic and environmental perspective. The model supports the understanding and performance of CE strategies, from product design and manufacturing up to business models and product return and reprocessing.

To augment the model, the authors reflected on the current limits of GPM and were inspired by industrial motivations. Some inaccuracies in the transition matrix are solved. In fact, the logic flow of the remanufacturing process has to be respected: when a product is disassembled, components are categorized into "working" and "non-working", then the "non-working" parts are usually sent to a recycling facility while the "working" ones are reconditioned. These components can be cleaned or reworked, depending on the feasibility of the manufacturing processes and on some possible changes in the product design. Then, after a testing phase, components (remanufactured and new, depending on the availability of core products) are reassembled together and sold.

Another improvement introduced in the original GPM is the addition of a profitability constraint for customer company (i.e., TotalEnergies) through incentives. In fact, TotalEnergies owns the ground mount structures used in solar plants so, to assess positively remanufacturing practice with a supplier, a profitability check has to be made. Also, the returned core products have a residual value in the materials used and in the energy already spent so it is important to add this constraint to properly consider the view of the customer.

3.4 Framework: assessment and target

The fourth step of the presented procedure is the re-calculation of C-indicators to assess whether the improvements in the circular performance of the product and business practice introduced produce beneficial effects. The novelties for the case study in terms of circular strategy are well detailed in the previous sections, so now the results are shown in Table 1.

In general, the scores of the indicators increase when the new CE business strategies are applied. The increase in score is different among the C-indicators, for MCI is lower (about +16%), while for CPI and CEIP is stronger (more than +70%). On the other hand, CC identifies the disruptive change in the case study, moving from a linear to a circular business practice.

With the positive results obtained from C-indicators and the optimization model, it is possible to define some recommendations for the stakeholders involved and identify an action plan. In this way, the framework is linked with industrial practice. Looking at the supplier perspective, it can achieve CE goals through augmenting the remanufactured and recycled quantity of the end-of-life products (therefore of the materials deployed in them: steel and aluminium), creating new forms of collaboration between manufacturer and customers through formal recovery channel and rethinking incentives to enhance the circular economy practice. Of course, firstly it has to be evaluated the technical feasibility of the remanufacturing processes. Instead, TotalEnergies should foster the recovery and reutilization of the product's materials closing the loop with the supplier of the ground mount structures. Finally, financial support by government or environmental agencies, policy frameworks (e.g., in terms of extended producer responsibility (EPR)), and waste legislation concerning the product can foster CE incentives for the structure under analysis in a complete way, looking equally at all the competitors involved.

Table 1. Assessment step: C-indicators.

Indicator	As-is condition	To-be condition
MCI	0,69	0,79
CPI	28,39	47,13
CEIP	20%	35%
CC – circularity	0%	47%
CC – value capture	0%	22%
CC – recycled content	0%	27%
CP	Reman/Recycle	-

4. Results and discussion

In the previous sections, the new way of using C-indicators and green profit model together is presented and discussed taking advantage of the case study. Overall, the new framework proposes an innovative path to combine circularity indicators and decision support models, e.g., the green profit one.

Fig. 5 shows the profit trend for supplier when environmental goals become more and more challenging. The baseline case represents the situation where only new ground mount structures are produced and environmental saving are not pursued. On the other hand, when remanufacturing and recycling strategies are added to the production of new products, it is possible to reach green profit opportunities, i.e., higher profit while reducing the environmental footprint. Fig. 5 also depicts the trend of incentives flowing from the supplier to TotalEnergies. The economic benefit perceived by the customer company increases when higher savings are achieved since the use of remanufacturing strategy becomes wider, so more of end-of-life products are collected.

Looking at the graphs in their entirety, the results show that remanufacturing and recycling can be considered as promising strategies for the case study. An evident outcome is the trade-off situation between the profit for supplier and incentives for TotalEnergies. For moving forward this condition, it is important to find an agreement on the desired reduction of environmental footprint to share with public and stakeholders.

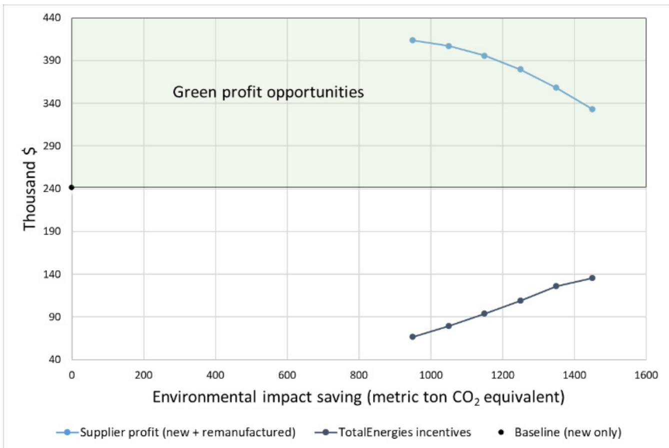

Fig. 5. Results from GPM.

5. Conclusions

The outputs from GPM and C-indicators can be considered complementary: the indicators help in a better goal definition while disclosing some insight on the problem, at the same time the green profit model (as selected optimization model) produces figures to quantitatively assess the goodness of the identified solution.

Looking at the case study, the high recyclability of aluminium with small loss of properties is a pathway to be exploited. This benefit makes it an enabling material for CE in order to limit supply risks, in fact deciding to retain the value of core products can be a successful way of reaching green profit opportunities, for both manufacturer and TotalEnergies.

Looking at further steps, the framework has to be further tested in multiple industries to check the goodness of the five steps, attempting to target the right decision-maker in the supply chain. In this way the flexibility of the approach is evaluated, also using different optimization models and selecting the cluster of C-indicators with different rationales.

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