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

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This thesis represents the end of my university career, a five-years-long journey composed of several experiences which granted me the chance to mature and develop a mindset. I wish to thank all the individuals whose presence and assistance, in different ways and with different roles, were crucial in the completion of this journey, throughout its entirety. Also, being a member in JEMP – Junior Enterprise Milano Politecnico for almost three years allowed me to join an academic association, understanding that the university offering is more than courses, projects and exams. A special thank goes to my Erasmus coordinator professor Mauro Filippini, who simplified my staying abroad from the very beginning. In conclusion, I thank from the hearth my family and friends, who supported me in all the situations and difficulties.
Abstract

English version:
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.

Versione italiana:
La rigenerazione di prodotti e parti a fine vita è vista come una soluzione nella transizione verso un'economia circolare. Ci sono molti strumenti e metodi proposti per facilitare l'applicazione di questa strategia circolare; tuttavia, mancano strumenti di supporto che includano più prospettive relative alla catena del valore e all'economia circolare stessa. Infatti, la strategia di rigenerazione, i trade-off economici e ambientali e gli indicatori di circolarità sono raramente integrati in un unico quadro. In questo lavoro viene presentato un approccio che sfrutta l'attuale ricerca sul green profit model e sugli indicatori di circolarità; ovvero questi strumenti vengono utilizzati insieme per liberare il potenziale circolare nel contesto industriale. I problemi tipici della pianificazione e del controllo della produzione nei processi di rigenerazione vengono interconnessi con gli obiettivi dello sviluppo sostenibile, considerando anche il design del prodotto e le scelte della strategia di fine vita. Il framework presentato rappresenta un supporto promettente da utilizzare nella pratica industriale. L'applicazione in un caso studio basato sull'infrastruttura per i pannelli fotovoltaici permette una migliore comprensione dei risultati della ricerca, e valuta la validità del supporto fornito dal framework nell'implementazione di questa strategia circolare.

Parole chiave: economia circolare; rigenerazione; indicatori di circolarità; design for remanufacturing; gestione della fine del ciclo di vita; ottimizzazione; sistema di fissaggio per pannelli fotovoltaici.
Executive summary

0.1 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;
- 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.

0.1.1 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).

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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 CO2 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).

0.1.2 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.

0.2 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.

0.2.1 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, a concrete comprehension of as-is condition is gained. These findings prepare the ground for using 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.

0.3 Case study

Inside this paper, the authors took advantage of the 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).

0.3.1 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/m². An overview of the structure with its parts is shown in Fig. 4.

![Ground Mount Structure](image)

**Figure 4 Ground mount structure**

0.3.2 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.

0.3.3 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.

0.3.4 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.

<table>
<thead>
<tr>
<th>Indicator</th>
<th>As-is condition</th>
<th>To-be condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>MCI</td>
<td>0.69</td>
<td>0.79</td>
</tr>
<tr>
<td>CPI</td>
<td>28.39</td>
<td>47.13</td>
</tr>
<tr>
<td>CEIP</td>
<td>20%</td>
<td>35%</td>
</tr>
<tr>
<td>CC – circularity</td>
<td>0%</td>
<td>47%</td>
</tr>
<tr>
<td>CC – value capture</td>
<td>0%</td>
<td>22%</td>
</tr>
<tr>
<td>CC – recycled content</td>
<td>0%</td>
<td>27%</td>
</tr>
<tr>
<td>CP Reman/Recycle</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

0.4 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.

0.5 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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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 (Braungart et al., 2007; Stahel, 2016). Nowadays, governments and non-governmental organizations (NGOs) stimulate companies to look for new ways of producing while meeting environmental goals. In this context, circular economy (CE) has recently been (re-)popularized as both a public policy and business concept (EMF, 2012; Voet et al., 2021). This strategy allows to address many of the complex challenges of the 21st century, including the loss of biodiversity, climate change, finite resource depletion, population growth, conflict over energy and resources, human rights and economic failure (Moreno et al., 2016). The CE may be defined as “a regenerative system in which resource input and waste, emission, and energy leakage are minimised by slowing, closing and narrowing material and energy loops. This can be achieved through long-lasting design, maintenance, repair, reuse, remanufacturing, refurbishing, and recycling” (Geissdoerfer et al., 2017). This definition can be considered as a simplified version of the one developed by Kirchherr et al. (Kirchherr et al., 2017) after reviewing 114 definitions of CE:

“A circular economy describes an economic system that is based on business models, which replaces the ‘end-of-life’ concept with reducing, alternatively reusing, recycling and recovering materials in production/distribution and consumption processes, thus operating at the micro level (products, companies, consumers), meso level (eco-industrial parks) and macro level (city, region, nation and beyond), with the aim to accomplish sustainable development, which implies creating environmental quality, economic prosperity and social equity, to the benefit of current and future generations”.

On a practical level, some regulations are now becoming operative therefore companies are obliged to satisfy new requirement in terms of circularity. As an example, the European Commission’s 2015 Circular Economy Strategy emphasized the importance of the revision of the waste electrical and electronic equipment (WEEE) and eco-design directive to set in place regulations that drive businesses towards innovative practices for more circular products (European Commission, 2016). Also, many governments have reviewed available policy options and concluded that placing the responsibility for the post-consumer phase of certain goods on producers could be an option. Extended producer responsibility (EPR) is a policy approach under which producers are given a significant responsibility for the treatment or disposal of post-consumer products. Assigning such responsibility could in principle provide incentives to prevent wastes at the source, promote product design for the environment and support the achievement of public recycling and materials management goals (OECD, 2021). Figure 6 shows the CE loops as described by Ellen MacArthur Foundation (EMF).
At the same time, around the notion of CE many branches of academic research have developed through a considerable increase in articles and journals that cover this topic in the last decade (Geissdoerfer et al., 2017). The CE concept includes many research fields touching environmental, social and economic aspects; this can be understood looking at the five principles stated by the Ellen MacArthur Foundation: design out waste, build resilience through diversity, work towards energy from renewable sources, think in systems, think in cascades (EMF, 2012).

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 EMF. In fact, everything around us was originally designed following different criteria and methods, but recently the attention towards sustainability has increased also in industrial context. 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 (McAlounge & Bey, 2009). 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 (Barker & King, 2007);
- the selection of the related technological solutions;
- the efficiency and profitability of the remanufacturing process-chain (King et al., 2006).

Again, designing products that can easily follow the CE loops allows businesses to create new value for the final customers.

Moving to the end-of-life stage, the first principle suggested by EMF can be pursued taking advantage of the inner loops of circular economy: reuse, remanufacturing and recycle. Among these 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 enterprises take back products after the customers’ use and remanufacture or refurbish them. In order to understand better the concept, here is reported a definition of remanufacturing from (Tolio et al., 2017):

“Remanufacturing includes the set of technologies and systems, tools and knowledge-based methods to systematically restore and upgrade functions and materials from post-consumer products, to support a sustainable implementation of manufacturer-centric circular economy businesses”.

This CE loop encourages companies to reach challenging environmental and economic targets, augmenting the commercial offer at the eyes of the final customer. However, it is not straightforward to measure and assess the enterprise’s performance with respect to circularity. In fact, at the moment many researches are focusing on tools and indicators to measure circularity on the micro, meso and macro level (e.g., Issa et al., 2015; Kravchenko et al., 2019; Saidani et al., 2021; Parchomenko et al., 2019; Saidani et al., 2020). Key performance indicators (KPIs) facilitate the transition toward CE and can guide the design phase looking at the same time at different lifecycle perspectives. Specially, the product centric circularity indicators assess the effective and potential performance of products, parts and components with respect to CE in a concrete manner. They can be deployed as a first screening tool in the space of alternative design possibilities when designing for a CE (Saidani et al., 2020).

1.1 Industrial motivations

Overall, circular economy is a timely topic considering the research effort delivered by scholars, but the path is still long for matching academic results with industrial practice. This thesis work tries to go in this direction taking advantage of state-of-art research on CE tools and indicators.

The thesis has a large-scale scope in industrial practice. In fact, today companies in many industries are facing new upcoming regulations that constraint their usual action range and, even in this new context, the profitability of the enterprise has to be guaranteed. For this reason, in the last years numerous companies decided to target new market shares, especially customers keen to buy environmentally friendly products. Therefore, aside the production of new items, enterprises are now managing reused, recycled and refurbished materials and products to finally deliver to their clients. However, in complex and multi-stakeholders cases, the transition to a more circular way of producing is difficult to manage. Here is the link between the scientific motivations discussed in the previous section and the industrial ones. Additionally, a never-seen-before attention to environmental and climatic issues is raised thanks to high-profile conferences, as United Nations (UN) Climate Change Conference – COP 26 hold in the UK during November 2021. Companies have a relevant influence also in these venues, in fact topics related to carbon emissions and zero waste are more and more discussed today. Lastly, in the post pandemic scenario, firms are reorganizing their supply chain to limit supply risks, in fact it is well known the sharp increase in raw material prices nowadays. Therefore, the thesis work is positioned in this industrial context trying to support industrial players when dealing with complex strategic decisions.
2 Literature review

Circular economy is a broad concept that includes many research areas related to chemistry, political science, industrial engineering and so on. Globally, the thesis’ work considers all the five stages of the product life cycle, even if the steps of design, manufacturing and end of life are majorly addressed within the literature review. These three points together with research about indicators constitute the main pillars of the work. Figure 7, Figure 8 and Figure 9 represent specifically the five life cycle stages using the framework of structured analysis and design technique (SADT). Constraints for the specific step are listed above the box, while the tools and resources needed are written below. The stages addressed within the thesis are highlighted in light green. The three selected boxes represent the most interesting ones from an engineering perspective, in fact they are strongly interconnected among each other and relevant when considering real mechanical products. The underlined words in the following figures are key parameters for the specific life cycle stage (e.g., “dispersion” for the distribution phase).

![Figure 7 Product life cycle: design and manufacturing](image)

![Figure 8 Product life cycle: distribution and usage](image)
In the following sections, a wide literature review is presented for each of the pillars: circular economy business model (CEBM), design tools and methods, remanufacturing, decision support models and indicators.

2.1 Research methodology
The analysis of the state of the art was carried out with the goal of creating a proper background related to the pillars of the work. The review protocol was organized in two main steps: data collection and data analysis. Data collection included the definition of the research goal, search keywords and scientific databases. For each of the pillars of the presented work, the following search keywords were used:

- Circular economy business model: “circular economy business model”; “circular economy business model” AND “literature review”;
- Design tools and methods: “tool” AND “sustainable” AND “design”; “tool” AND “circular” AND “design”; “sustainable” AND “design” AND “principles”;
- Remanufacturing: “design for remanufacturing”; “remanufacturing” AND “environmental” AND “impact”;
- Decision support models: “decision support model” AND “optimization”;
- Indicators: “indicators” AND “literature review”.

The review was conducted in Google Scholar and ResearchGate, due to their wide inclusion of scientific papers coming from different engineering fields. Together with the presented keywords, the works of specific authors were investigated due to their leading role in different research fields: Nancy Bocken for CEBM, Timothy Gutowski for remanufacturing, Daniela Pigosso and Michael Saidani for indicators. Additionally, many references within the articles were analysed to find knowledge falling outside of the database. The study was carried out in March and April 2021 and was limited to research documents in English. In total, 76 articles were initially collected. By applying excluding criteria (i.e., multidisciplinary view of the main research topics and publication within the last two decades), 39 unique papers were selected, based on title and abstract screening process. These excluding criteria are relevant because
the research pillars of the thesis are strongly interconnected among them and this aspect was captured by research only sometimes. Then, since CE related concepts are quite recent, it is reasonable to consider papers published in the last twenty years, considering the technological evolution of industrial products and processes.

Data analysis included the definition of the key information to be extracted and the procedure for the subsequent analysis. In this master’s thesis, the information obtained from the selected papers was classified based on the research topics. The next sections of this chapter synthesize the collected information about the five research topics.

2.2 Circular economy business model
This first branch of the literature review can be considered as an overview on how CE is deployed within companies. In fact, enterprises opt for numerous circular business models that can be clustered following few criteria. In general, the transition to a CE requires not only changes to the way products are designed and manufactured, but also deep changes to how they are put on the market and consumed. Circular business models lie at the core of the CE (Lewandowski, 2016) and constitute a prerequisite for CE spread, because they “enable economically viable ways to continually reuse products and materials” (Bocken et al., 2016).

Boons and Lüdeke-Freund (Boons & Lüdeke-Freund, 2013) identify four elements of a generic business model concept:

- Value proposition: what value is embedded in the product offered by the company;
- Value chain: how upstream relationships with suppliers are managed;
- Customer interface: how downstream relationships with customers are managed;
- Financial model: costs and benefits from the previous elements and their distribution across business model stakeholders.

The four elements constitute the general frame for the definition of a business model (BM) within companies. The concept of circular business model appeared more recently than the circular economy literature as a whole. The term first emerged in 2006 in an article by Schwager and Moser (Schwager & Moser, 2006) that explored business model types for circular value creation. The circular business model concept re-emerged seven years later, coinciding with the broader popularization of the circular economy notion by the Ellen MacArthur Foundation and the World Economic Forum (WEF) (EMF, 2012; WEF, 2014). Since 2015, publications in this field have grown sharply.

Considering the analysis of literature conducted by Geissdoerfer et al. (Geissdoerfer et al., 2020), circular business models can be defined as business models that are cycling, extending, intensifying, and/or dematerialising material and energy loops to reduce the resource inputs into and the waste and emission leakage out of an organisational 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 (dematerialising), as illustrated in Figure 10. These objectives of the circular economy business models are well aligned with the characteristics of CE as described by the European Environment Agency (EEA) (EEA, 2016):

- less input and use of natural resources;
- increased share of recyclable resources and renewable energy;
• reduced emissions;
• fewer material losses/residuals;
• keeping the value of products, components and materials in the economy.

At the end of the cited article, a valuable framework that combines these four circular business model strategies with the three business model elements (i.e., value proposition, value creation and delivery and value capture) is presented. Considering the focus of the thesis on mechanical products used in specific applications, cycling and extending strategies can be considered as more relevant for the subsequent analysis. Therefore, a deeper description of these strategies is presented:

**Cycling strategy:** from a value proposition perspective, take-back is a fundamental element for this strategy enabled by collaborations in the value chain and reverse manufacturing processes (such as repair, remanufacture, refurbishing and recycling). In this case, value capture is mainly related to minimised costs of material acquisition and additional revenues from end-of-life products. As this strategy increases the life of cores and/or materials, it allows to reach environmental goals (i.e., reducing both energy and new materials intake and waste output).

**Extending strategy:** the value proposition is based on long-life products that can create a long-term customer relationship. Therefore, this mechanism generates new revenue streams during the use phase of the products through service packages or ad hoc contracts (e.g., maintenance and repairing practice). The implementation of this strategy lead to reduced need for producing new products, thanks to long-lasting design. One possible drawback of this strategy is the increase in energy consumption as the product becomes timeworn.

In another scientific paper written by Florian Lüdeke-Freund, Stefan Gold and Nancy Bocken (Lüdeke-Freund et al., 2019), the scholars try to categorize CEBM that can support circular resource flows and so allow for business contributions to CE. After a wide literature review about closed-loop supply chain and circular economy business model, a morphology of CEBM is developed to reduce the conceptual lack of clarity around these concepts. The output from the research is the description of six CEBM patterns with the potential to support the reverse
cycles (i.e., repair and maintenance, reuse and redistribution, refurbishment and remanufacturing, recycling, cascading and repurposing, organic feedstock).

For the following development of the thesis, the refurbishment and remanufacturing BM are further investigated. In a general sense, remanufacturing is gaining more and more importance on the industrial and economic landscape, especially for mechanical products. In fact, it has recently been enshrined in US law, which now stipulates the use of remanufactured parts within federal governmental vehicles. Additionally, a 2016 study undertaken by the European Remanufacturing Network (ERN) estimates the value of remanufacturing to the European economy at up to $111 billion (Parker et al., 2015). However today, remanufacturing uptake in Europe is not yet widespread; the remanufacturing intensity (ratio of remanufacturing to new manufacturing) in Europe is estimated at 1.9% (Parker et al., 2015). Refurbishment and remanufacturing require that companies - which can be OEMs (Original Equipment Manufacturer) or third parties as service providers - establish the reverse logistics to access to end-of-life products (e.g., through service models or buy-backs) and that they are capable of improving their physical state. Reverse and forward logistics and the technical know-how about products and how to refurbish or remanufacture them are needed to establish this CEBM. Remanufacturing is more radical than refurbishing and leads to products as good as new, or even better than new. Hence, it involves dismantling, cleaning, checking, testing for compliance, and replacing worn-out parts. Remanufacturing and refurbishment services allow companies to offer greener products, possibly even at lower prices (Vogtlander et al., 2017). There are several cases where third parties perform refurbishment and remanufacturing, this is a widespread practice for technological items. However, it could be argued that OEMs are in a better position to implement design for refurbishment and remanufacturing, having the original design specifications and being able to optimize their product designs considering the business models. In any case, most publications state that reduced or at least slowed streams of waste to landfills and reduced carbon emissions are the most important sustainability contributions of this strategy (Vogtlander et al., 2017). Others argue that energy use in CEBMs is an often-forgotten factor (Cooper & Gutowski, 2017). All in all, a full life cycle perspective that includes all the life phases needs to be considered when assessing the environmental benefit of refurbishment and remanufacturing business models (Cooper & Gutowski, 2017; Gutowski et al., 2011).

At the end of the article by Lüdeke-Freund and colleagues (Lüdeke-Freund et al., 2019), a summarizing table that links the six CEBM patterns with design strategies and resource perspective is shown. The table is particularly useful for connecting business model with design tools and methods as key enablers for the deployment of CEBM into practice.
Finally, Bocken and colleagues (Bocken et al., 2016) define three key strategies for a CE: slowing, closing, and narrowing resource loops. Slowing loops is about extending the life of products to slow down resource usage; closing loops is about recycling to close the loop between post-use and production; and narrowing loops is about using fewer resources per product, such as through light-weight product design and efficient manufacturing processes. The repair and maintenance, reuse and redistribution, and refurbishment and remanufacturing CEBM patterns contribute to slowing resource loops by retaining the product value. Recycling, cascading, and organic feedstock CEBM patterns seek to retain the material value by closing resource loops. Figure 11 summarizes the definitions of slowing and closing resource loops in a graphical way.
As described in (Bocken et al., 2016), business models to slow resource loops encourage long product life and reuse of products through business model innovation. Four key models of BM innovations are described: access and performance, extending product value, classic long life, and sufficiency. The following descriptions are based also on the work of (Matsumoto et al., 2017):

**Access and performance model:** the innovation is about providing the capability or services to satisfy user need without needing to own physical products. The manufacturer or service provider retains ownership of the product and is therefore incentivised to make the product last as long as possible. Examples are laundrettes, bicycle-sharing schemes and printer/copier service/lease contracts.

**Extending product value:** this model is based on exploiting residual value of products - from manufacture to consumers and then back to manufacturing - or collecting products between distinct business entities. In an ideal case, OEMs themselves refurbish or remanufacture, but often other companies see the opportunity first and start these practices (i.e., “gap exploiters”). Examples are companies who collect and sell refurbished electronics (e.g., LEAPP in the Netherlands and Gazelle in the USA). OEMs such as Apple and Dell are selling their own certified refurbished laptops.

**Classic long life:** the business model is focused on delivering long product life, supporting design for durability and repair. To support product long life, design for repair, refurbishment and remanufacturing are essential. Examples are companies who create products that last “beyond a lifetime”, e.g., durable caravans and high-end watches.

**Encourage sufficiency:** the idea is to encourage solutions that seek to reduce consumption through durability, upgradability, warranties, reparability and a non-consumerist approach to marketing and sales. This model follows the classic long-life model. Design for repair, refurbishment and remanufacturing can support slow consumption. Patagonia’s campaign “Don’t buy this jacket” can be considered as an example of this BM innovation.
2.2.1 Circular design and business model strategy framework

Moving towards circular economy requires fundamental changes in the business processes throughout the value chain including product design and development, manufacturing and operations, direct and reverse logistics, consumption patterns, business models (EEA, 2016a) and so on. Integrating circular economy concerns at an early stage in the product design process is important, because once product specifications are being made, only minor changes are usually possible. In fact, it is difficult to make changes, once resources, infrastructures, and activities have been committed to a certain product design (Bocken et al., 2014). Figure 12 illustrates the framework developed by Bocken and colleagues (Bocken et al., 2016) that connects product design with CEBM. Now, the design strategies for slowing and closing the resource loops are discussed.

Table 3 List of design strategies to slow resource loops from (Bocken et al., 2016)

<table>
<thead>
<tr>
<th>Design strategies to slow loops</th>
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<tbody>
<tr>
<td><strong>Designing long-life products</strong></td>
</tr>
<tr>
<td>* Design for attachment and trust</td>
</tr>
<tr>
<td>* Design for reliability and durability</td>
</tr>
<tr>
<td><strong>Design for product-life extension</strong></td>
</tr>
<tr>
<td>* Design for ease of maintenance and repair</td>
</tr>
<tr>
<td>* Design for upgradability and adaptability</td>
</tr>
<tr>
<td>* Design for standardization and compatibility</td>
</tr>
<tr>
<td>* Design for dis- and reassembly</td>
</tr>
</tbody>
</table>

“Designing long-life products” is the first major design strategy to slow resource loops as it ensures a long utilization period of products. Within this categorization, “designing for attachment and trust” refers to the creation of products that will be loved, liked or trusted longer. “Design for durability” relates to physical durability, for example by the development of products that can withstand wear and tear without breaking down. Material selection for durability is an important part of the design process. “Design for reliability” refers to designing for a high
likelihood that a product will operate throughout a specified period without experiencing a chargeable failure.

The second major design strategy to slow resource loops is “design for product-life extension”. This strategy is concerned with the extension of the use period of goods through the introduction of service loops to extend product life, including reuse of the product itself, maintenance, repair and technical upgrading. “Design for ease of maintenance and repair” enables products to be maintained in tip-top condition. Another relevant strategy is designing products to allow for future expansion and modification, taking advantage of upgradability, i.e., the ability of a product to continue being useful under changing conditions by improving the quality, value and performance. In addition, the “design for dis- and reassembly” strategy is relevant within the loop of remanufacturing, it is about ensuring that products and parts can be separated and reassembled easily (Bakker et al., 2014). It is a successful way that can be applied to increase the future rates of material and component reuse (de Pauw, 2013). This strategy is also fundamental for separating materials that will enter different cycles (biological or technological), within the design strategies to close resource loops.

Table 4 List of design strategies to close resource loops from (Bocken et al., 2016)

<table>
<thead>
<tr>
<th>Design strategies to close loops</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Design for a technological cycle</td>
</tr>
<tr>
<td>• Design for a biological cycle</td>
</tr>
<tr>
<td>• Design for dis- and reassembly</td>
</tr>
</tbody>
</table>

Considering the introduction of design strategies related to closing the resource loops, a more detailed understanding of the concept of recycling has been propagated. According to Ayres (Ayres, 1994), there are only two possible long-term fates for waste materials: either recycling and reuse, or dissipative loss (e.g., for lubricants or detergents). Accordingly, McDonough and Braungart (McDonough & Braungart, 2002) developed two distinct strategies for product design within the recycling concept: dissipative losses are to be made compatible with biological systems, fitting the “biological cycle”; whereas other materials are to be completely recycled, fitting a “technological cycle”. Table 4 summarizes the design strategies for closing loops.

As highlighted within this section, to transform the economy from linear to circular, business model and design strategies will need to go hand in hand. Potentially, companies need multiple business model and design strategies, approaches, methods and tools to support the transition to CE. Therefore, the development of CEBM is intrinsically connected to product design activities. To fulfil longer or multiple use cycles, new products shall be intentionally designed to allow extended lifetime, recyclability and remanufacturability, modularity or other characteristics depending on the strategies of circular economy (Bocken et al., 2016; Lieder & Rashid, 2016).
2.3 Circular design tools and methods

In the last decade, many academic and non-academic discussions have ensued for implementing a different role for design. Terms such as “eco-design”, “green design”, “design for the environment” and “sustainable design” have emerged, looking for alternative ways to deliver less damage to the environment and sometimes to wider society in general (Brezet & Han, 1997; Roy, 2015), moving towards CE.

Previous work from Bocken et al. (Bocken et al., 2016) brings together existing literature on consumer product design and circular business models and develops a framework of strategies. This framework is limited, however, and does not consider the wide and valuable literature on design for sustainability. For the purposes of this thesis, the work of Go et al. (Go et al., 2015) is referenced. In the work, design for X (DfX) is defined as:

“a combination of eco-design strategies including design for environment and design for remanufacture, which leads to other design strategies such as design for upgrade, design for assembly, design for disassembly, design for modularity, design for maintainability and design for reliability”.

DfX strategies can be divided into those that seek to optimize product’s features (e.g., simplicity, functionality, modularity, longevity, reparability, or recyclability) and those that optimize a particular life cycle stage (e.g., manufacturing, assembly, distribution, use, or end-of-life) (Holt & Barnes, 2009). Having in mind the historical evolution of green design to DfX, Pigosso and colleagues (Pigosso & McAloone, 2017) developed a new taxonomy of DfX approaches based on previous work by De los Rios and Charnley (De los Rios & Charnley, 2017). The taxonomy is based on the following DfX approaches:

- design for resource conservation;
- design for slowing resource loops;
- whole systems design.

Figure 13 represents the historical evolution of green design to DfX and describes the focus of each of the design approaches.

![Figure 13 Historical evolution of environmental philosophies applied to design from (Moreno et al., 2016)](image-url)
To deepen the comprehension of DiX method, Table 5 reports the design guidelines for many circular strategies, as identified by Shahbazi and Jönbrink (Shahbazi & Jönbrink, 2020). The black cells indicate a direct connection of the guideline to a specific circular strategy, while the grey cells indicate an indirect connection on a specific circular strategy. Among the circular strategies, remanufacturing is shown in the blue box as a way to recirculate parts and products. The design guidelines related to this strategy are, as an example, “make it easy to inspect the product and components”, “design standardized components across different products and models”, “design in modular construction”, “make spare parts and exchanging components easily available” and “use joints and connectors that can be easily opened and closed multiple time”. It can be understood how the guidelines are broad and general in helping designers. As stated in (Matsumoto et al., 2017), the existing design approaches are quite vague and do not offer the possibility of supporting the actual designer in his task of integrating the aspect of sustainability into the product.
Table 5: Design guidelines from (Shahbazi & Jönbrink, 2020)

<table>
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<th>Design Guidelines</th>
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<td>Focus mainly on functionality and quality performance</td>
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<td>Think about activity supports in the operational stage</td>
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<td>Focus on fulfilling the customer’s requirements and value creation</td>
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<td>Try to use digitalization, ICT and IoT solutions</td>
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<td>Make it easy to inspect the product and components</td>
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<td>Make it easy to clean the product and components</td>
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<td>Make exchanging of faulty components easily accessible</td>
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<td>Make it easy to dismantle the product nondestructively</td>
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<td>Think about incumbent configuration</td>
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<td>Think about complementary capabilities</td>
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<td>Design using renewable materials</td>
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<td>Design using recyclable and secondary (recycled) materials</td>
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<td>Consider toxicity and other environmental aspects of materials</td>
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<td>Favor cleaner production, processes, machines and equipment</td>
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<td>Treat production (pre-consumer) wastes appropriately</td>
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<td>Design for reduced energy consumption and usage of renewable energy</td>
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<td>Design standardized components across different products and models</td>
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<td>Design standardized tools required across different products and models</td>
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<td>Use durable and robust components and materials</td>
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<td>Design in modular construction</td>
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<td>Provide manuals and documentation</td>
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<td>Make spare parts and exchanging components easily available</td>
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<td>Consider timeless design, emotional attachment, and compatibility</td>
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<td>Investigate current and upcoming laws and regulations</td>
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<td>Use joints and connectors that can be easily opened and closed multiple times</td>
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<td>Minimize the number of different incompatible or dissimilar materials</td>
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<td>Make it easy to identify the materials and relevant information</td>
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2.3.1 Combining design strategies with circular economy business model options

Through revisiting the recent literature, a new configuration of the strategies proposed by De los Rios and Charnley (De los Rios & Charnley, 2017) was developed by Moreno et al. (Moreno et al., 2016). This new taxonomy focuses on understanding how the sum of DfX approaches and “systems thinking” can be integrated to change the role of design within circular economy. This taxonomy takes into consideration that design will be mindful and helpful in the transition to CE, according to the chosen business model (EMF, 2012). The move to a CE model requires radical changes, including a new way of thinking and doing business, where a combination of multiple business models and design strategies, approaches, methods, and tools is required (Bocken et al., 2016).

As described in (Moreno et al., 2016), the five identified circular design strategies are:

- Design for circular supplies: this strategy focuses mainly on the biological cycles and refers to thinking of “waste equals food” in which resources are captured and returned to their natural cycle without harming the environment (Benyus, 2002);
- Design for resource conservation: this strategy focuses on both the technical and biological cycles and applies an approach in which products are designed with the minimum amount of resources (Bocken et al., 2016);
- Design for multiple cycles: this strategy focuses on both the technical and biological cycle and refers to design aimed at enabling the longer circulation of materials and resources in multiple cycles (Bakker et al., 2014; Bocken et al., 2016);
- Design for long life use of products: this strategy focuses on the technical cycle and refers to extending the use of a product through extending its life and offering services for reuse, repair, maintenance and upgrade (Bakker et al., 2014), or by enhancing longer-lasting relationships between products and users through “emotional durable design” (Chapman, 2005). Furthermore, changing the ownership of products through services could enhance longer utilisation of products and, therefore, move to a sharing system (Lacy & Rutqvist, 2016);
- Design for systems change: this strategy covers the whole spectrum of value creation for both biological and technical cycles and refers to design thinking in complex systems as a whole and between its parts to target problems and find innovative solutions (Charnley et al., 2011).

A summary was made of five circular business model archetypes:

- Circular supplies: a business model based on industrial symbiosis in which the residual outputs from one process can be used as feedstock for another process (Bocken et al., 2016);
- Resource value: a business model based on recovering the resource value of materials and resources to be used in new forms of value (Bocken et al., 2014; Bocken et al., 2016);
- Product life extension: those business models that are based on extending the working life of a product (Bocken et al., 2014);
- Extending product value: those business models based on offering product access and retaining ownership to internalise benefits of circular resource productivity (Bocken et al., 2014);
- Sharing platforms: those business models that enable increased utilisation rates of products by making possible shared use/access/ownership (Bocken et al., 2014).
For the first time, a framework (illustrated in Figure 14) provides design practitioners with a holistic view of how to approach circular design, not only from a product perspective, but also by considering the relevance and importance of the surrounding business models and how to integrate them with the design process.

Considering as an example the refurbishing/remanufacturing loop as value flow, product life extension is identified as BM position within the framework. Looking at the top part of the figure, it is possible to see how all the five circular design strategies are connected to this positioning within the value chain. However, design for multiple cycles, for long life use of product and for system change strategies are the most relevant for this business model position since they are spread all along the value chain.

By looking at the research conducted by Moreno et al. (Moreno et al., 2016), a set of final recommendations for circular design was generated, with the aim of assisting designers, innovators and decision makers in the consumer goods spectrum, on their way towards circular design. The recommendations are presented below:

1. Design for “systems change” when considering any circular design strategy;
2. Design by identifying the new circular business model that your product/service is being designed for;
3. Design by thinking of revolutionising the world: circular design goes beyond doing less bad;
4. Design for multiple cycles (short and/or long) and not only with end of life in mind;
5. Design by thinking in living and adaptive systems;
6. Design with different participants in the value chain, including your final user;
7. Design by considering value in a broader view, not as a price tag on a shop shelf, but as an asset;
8. Design with failure in mind: it is better to test and prototype as many times as possible;
9. Design knowing where each material and part comes from and where each material and part goes to;
10. Design with “hands on” experiences that foster a call for action.
Nowadays, most DfX approaches and techniques, such as design for product life extension and design for product recycling, are not routinely applied in product development practices (Bakker et al., 2014). Some relevant limitations include the lack of robust DfX guidelines based on life cycle thinking to prevent conflicts between DfX strategies, e.g., remanufacturing versus manufacture and assembly (Hatcher et al., 2011). Additionally, practical design knowledge on product life extension, remanufacturing and end-of-life management is currently underdeveloped (Bakker et al., 2014). Consequently, the isolated application of DfX tools to meet a specific design goal goes against the concepts of concurrent engineering and life cycle thinking. On the other hand, Bocken and colleagues (Bocken et al., 2016) state that companies should define a CE vision before analysing circular business model and product design opportunities in order to fully capture the business potential of pursuing a CE.

The need for integration of life cycle thinking within DfX and more knowledge on design for remanufacturing within the product development process (e.g., comparing key performance indicators and/or design metrics) are aspects to consider when dealing with the definition of a CE strategy, also in industrial context (Matsumoto et al., 2017). Even though a number of seminal papers and key authors have propelled the research forward, remanufacturing research is unsystematic and lacks strategic direction (Matsumoto et al., 2017). In addition, there is a lack of empirical evidence presented in the literature that demonstrates the benefits of design for remanufacturing in practice. More case studies and analysis can effectively demonstrate exactly how and to what degree design for remanufacturing has an impact on the remanufacturing process and the various stakeholders involved. For the further development of the current thesis, the next literature review section is about remanufacturing and clarifies the role of this life cycle stage along the value chain.

2.4 CE loops: remanufacturing

The third pillar of the state of the art is related to the production sphere, especially remanufacturing. This business option is becoming more and more relevant for companies considering public pressure and stricter regulations. In order to set a quantitative context, manufacturers in the US account for 11.39% of the total output in the economy, employing 8.51% of the workforce. Total output from manufacturing was $2,334.60 billion in 2018 (NAM, 2019). Today, many manufacturing companies around the world are assessing remanufacturing as a way to make their business more sustainable. In fact, the growing environmental concerns are fundamentally impacting the way companies design and launch new products across the world (Choi et al., 2008). Therefore, companies are confronted with the responsibility of producing in an environmentally friendly manner (Mihelcic et al., 2008). Additionally, the increasing social concerns on environmental protection and enforcement of environmental regulations of EoL products (i.e., manufacturers take full responsibility for the entire lives of their products including recycling, remanufacturing, and disposal), have also led companies to adopt several product recovery strategies in response to the challenges (Ramani et al., 2010). Remanufacturing can be considered as a sustainable way of dealing with products, considering the definition of sustainable production provided by Alting and Jørgensen (Alting & Jøgensen, 1993) still widely used:
“Sustainable production means that products are designed, produced, distributed, used and disposed with minimal (or none) environmental and occupational health damages, and with minimal use of resources (materials and energy).”

From a business point of view, launching remanufactured products would definitely help companies to access green consumer markets and second markets (also in less developed regions) as well as to improve the company image in terms of social responsibility and environmental friendliness (Aydin et al., 2015). Usually, the first market refers to a developed region where consumers are more interested in and willing to pay for brand new products than remanufactured products. However, some consumers in the first market, who are the supporters of environmental friendliness and/or highly sensitive to price, may be interested in remanufactured products. The second market is normally a relatively less developed region where consumers in general may not be able to afford the purchase of brand new products but they may be interested in remanufactured products because of higher affordability (Aydin et al., 2015).

Looking at the product’s cost breakdown, it is well known that although only 5 - 7% of the entire product cost is attributable to early design, anyway the decisions made during this stage lock in 70 - 80% of the total product cost (Ullman, 2008). As a result, life cycle environmental impacts of a product are largely determined by design. In order to maximize product sustainability, it is more desirable to integrate environmentally conscious manufacturing efforts with design for the environment since the beginning. Additional factors can affect the success of a remanufacturing endeavour such as the demand and the condition of returned products (Goodall et al., 2014). In fact, the product demand can only be satisfied if returned product cores are available. Where the demand and availability of cores overlap, the opportunity for remanufacture to be of value exists (Goodall et al., 2014).

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 (Thierry et al., 1995). 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 (Kerr & Ryan, 2001). Also, the perceived value of remanufactured goods tends to be less than those that have been newly manufactured. This perceived value gap is even greater within the business to customer (B2C) market opposed to the business to business (B2B) (Atasu et al., 2008). This is largely due to B2C products having a considerable fashion emphasis whereas B2B products are purchased predominantly for their functional attributes. Having to invest in additional facilities, equipment, infrastructure and skill base can result in higher costs, which may lead to remanufacturing becoming an unattractive option. The remanufacturing process usually includes 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 (Hatcher et al., 2011). 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 a number of 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 Figure 15.
The product design can have significant impact on the cost of the remanufacturing processes. For example, the ease of separation can be affected by the joining method of internal components. Difficulty in disassembly can increase the process time, number of separating tools and probability of damage to the product, thus increasing the total cost (Sundin & Lindahl, 2008). Design for remanufacture aims to improve the potential for a product to be remanufactured.

Remanufacturing is seen as environmentally preferable to other EoL options such as recycling as not only is the material preserved but also the embodied energy from the initial manufacturing processes. However, when assessing the environmental impacts of remanufacturing, the savings gained over manufacturing from new must be compared to the potential impact in prolonging products where technologies have been substituted with more energy efficient means. In many cases a product's environmental impact can be much greater during the use phase of their life than during the manufacturing stage which is an important factor to consider when evaluating the environmental impact of remanufacturing (Gutowski et al., 2011). In fact, from an energy point of view, from 1998 to 2018, manufacturing energy intensity decreased by 26%. During this same period, manufacturing gross output increased by 12%, implying continued energy efficiency gains (EIA, 2018).

From a consumer perspective remanufacturing can offer low-cost alternatives to many high-quality products. There is also the opportunity of additional job creation as at present remanufacturing tends to be a labour intensive task due to processes such as disassembly being required (Parkinson & Thompson, 2003). The option of remanufactured parts and components can reduce the cost to the customer whilst prolonging the life of the overall product in which the remanufactured component is used. Economically it may be more desirable for the business to sell new products at a higher cost however by sharing the benefits of lower
cost, but high quality products that remanufacturing can offer can lead to strong long lasting customer relations desired by a sustainably minded business (Goodall et al., 2014).

Figure 16 summarizes the decision factors related to remanufacturing, dividing them into three main areas: economic, environmental and social one. Table 6 states the three traditional decision stage, for each of them the remanufacturing decision factors can be evaluated.

![Figure 16 Overview of the remanufacturing decision factors from (Goodall et al., 2014)](image)

**Table 6 Summary of the decision stages for assessing remanufacturing feasibility from (Goodall et al., 2014)**

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<th>Decision stage</th>
<th>Key purpose</th>
<th>Information contained within product description</th>
<th>Potential users</th>
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<td>Strategic</td>
<td>Provide early feasibility analysis of adopting remanufacturing within a business strategy</td>
<td>General Product Type</td>
<td>High level/senior management/middle management</td>
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<td>Tactical</td>
<td>Evaluate a particular product design for remanufacture. Can either be used in the product design phase, or in the operational planning phase.</td>
<td>Specific Model, product structure and BoM may be included</td>
<td>Middle management/operational management/design engineers</td>
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<tr>
<td>Operational</td>
<td>Evaluate a specific product for remanufacture. Can occur remotely using MoL information or during inspections at the remanufacturing facility.</td>
<td>Detailed product structure including information related to condition of the product. Additional process information may also be provided such as inventory levels and facility capacity.</td>
<td>Middle management/operational management</td>
</tr>
</tbody>
</table>

The key factor which complicates remanufacturing decision making relative to traditional forward manufacturing is the high level of uncertainty associated with the return product cores. This uncertainty stems from the lack of information flow between early life cycle phases (in particular the use phase) and the remanufacturer (Goodall et al., 2014). Table 7 summarizes the sources, effects and possible solutions to uncertainty when dealing with remanufacturing in companies.
Uncertainties regarding the condition and product structure can lead to uncertain process routing, as the full set of activities required to complete remanufacture will not be known (Guide, 2000). This can make it difficult to predict performance metrics such as cost, time and environmental impact of remanufacturing. Unknown timings and quantities can cause problems for production planning and inventory control, which can reduce the overall efficiency of the remanufacturing plant through process bottlenecks, unfavourable lot sizing and carrying of unnecessary inventory. All of these uncertainties can therefore make it difficult to predict metrics which are used within remanufacturing decision making.

As explained in (Hatcher et al., 2011), a company is considered as a suitable candidate for remanufacture (and therefore design for remanufacturing) when their products possess certain qualities:

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

As well as the types of products, there has been some consideration of the kinds of companies that would benefit from design for remanufacturing. Lund (Lund, 1984) states that there are three possible remanufacturing scenarios:

- OEM remanufacturing when the original producer is also responsible for the remanufacture of their used products;
- Contract remanufacturing, when a company remanufacture under contract from either the customer or the OEM, who continue to own the product;
- Independent, third-party remanufacturers who buy used products to remanufacture and resell. These companies have no connection with an OEM.

The environmental benefits coming from remanufacturing are the saving of some (usually large) portion of the invested energy used in both the materials production as well as the manufacturing, considering the remanufactured product as a substitute for a new product. However, a study of remanufacturing of eight different products reveals that energy saving may not always be in favour of remanufacturing (Gutowski et al., 2011). The result depends heavily on whether the product has an energy intensive use phase (Gutowski, 2011). Indeed, direct reused and remanufactured products - even if they are as-good-as-new - may be less efficient than brand-new ones due to technological evolution (Stark et al., 2012). However, to
avoid "circular economy rebound" (Zink & Geyer, 2017) where circular economy activities in fact lead to more consumption of materials and products, more drastic changes are needed to the industry and policy landscape. In a general sense, the product manufacturing process is the main stage in the life cycle that consumes resources directly and produces environmental pollution as well as being the main factor that affects the result of enterprise performance in terms of sustainable development (Gutowski, 2004). Efforts to minimize the environmental impacts of manufacturing processes can roughly be classified into three categories, related to the technical sphere:

- process improvement and optimization;
- new process development;
- process planning.

All in all, the main difficulty in the remanufacturing practice is related to the deployment of the strategy *a priori*, so before products have been designed and lived (Hatcher et al., 2011). The use of the precedent design guidelines may allow for partial avoidance of such problems, or at minimum, for identification of the weak points ahead. However, as described in (Stark et al., 2012), when using design for remanufacturing guidelines, a risk arises that designers follow the guidelines without integrating the initial product and process specifications and therein miss out on some crucial points. In fact, guidelines are set up to facilitate the designer’s job according to previous studies. Yet, every product is distinct from the others, so that requiring specific parameters may make one guideline irrelevant and may thus not apply. Finally, the measurement of anthropogenic outputs and economic, ecological and social responses considering the full life cycle of a product is an area of considerable potential for sustainable manufacturing.

2.5 Strategic decision support models for CE
To properly evaluate the feasibility of CE in industrial practice, the use of strategic decision support models is highly recommended due to the complexity of current businesses. These tools usually assess quantitatively the performance of circular strategies considering the context of application. Among many support models available in literature, the green profit model is deployed within the current thesis. The model was first developed by Harrison Kim and Minjung Kwak and they published two scientific papers on it in 2015 and 2017 (Kwak & Kim, 2015, 2017). This chapter aims to introduce and describe the as-is tool and its objectives.

2.5.1 Purpose
The use of the GPM within the thesis is beneficial since it allows to obtain a quantitative simulation of the circular strategy performance. In fact, the GPM describes the case study both from an economic and environmental perspective, considering at the same time multiple actors. It also considers many lifecycle stages (i.e., design, production, distribution, use and end of life) and allows the definition of a CE strategy from the beginning. Figure 17 Overview of green profit model summarizes the extension of the model and its main goals. The combined use of GPM and indicators can be particularly useful considering the lack of support in literature for selecting and applying indicators during the product development process in practice. Furthermore, a consistent and expandable system of indicators is needed in order to support
a targeted top-down approach for the selection of indicators as well as an aggregation from low-level data to high-level indicators and indices (Matsumoto et al., 2017).

Figure 17 Overview of green profit model

Shortly, the GPM is a mixed-integer programming model. Mathematical optimisation and programming are concerned with finding good solutions from a set of available alternatives. This approach is relevant since problems in sustainable manufacturing have in common that there is not only one objective to be considered but several conflicting ones. This is mathematically reflected by considering several objective functions simultaneously. The set of available alternatives and the structure of the considered objective functions can generally be modelled in different ways (Stark et al., 2012). This way of modelling things is different from system dynamics optimisation. In fact, system dynamics is an approach for the modelling and simulation of dynamical systems with a long history rooted in the understanding and teaching of dynamical systems in general, as well as in the field of sustainability. One of the strengths of the system dynamics approach lies in its visual representation of complex systems. This visual approach is essential in the system dynamics modelling process and simplifies access for beginners and users who lack experience with systems of differential equations. All in all, mathematical optimisation can be used as a decision support instrument for a wide range of problems, from scheduling and manufacturing to planning subsidies and exploring dynamical pathways into the future.

Considering the case study under analysis, the green profit model is used to:

- Pre-assess products’ suitability for remanufacturing;
- Simulate the deployment of multiple end-of-life strategies for products (worn parts to be reworked and degraded parts to be recycled);
- Allow a wide comprehension of the case study for deriving further recommendations.

2.5.2 Justification

A number of methods have been developed to achieve an optimal end-of-life strategy, evaluating product redesign. The optimal EoL strategy reveals the maximum recovery potential of the current product design and production processes. The tools listed in Table 8 are focused on EoL management of a single product type. The five papers, with the original paper about green profit model, were selected from the references of the original paper and expanding the research to other pieces of literature. The rationale behind this selection process is to find models and methods similar to the green profit one in terms of objective, so models that pragmatically help company in optimizing CE strategies. Furthermore, the criteria for
comparison are defined in order to assess the models in a complete manner. The criteria can be classified in the following way:

- Strategic perspective: integration of CE strategy from the beginning, ability to reach environmental objectives, ability to model a dynamic behaviour and to consider a multi-period time horizon;
- Operational perspective: possibility to consider indicators, ability to show a brief graphical outcome, test with a case study.

The operational criteria are significant since they assess the wideness of the tool’s modelling capability. Also, considering dynamic parameters and a multi-period time horizon increase effectively the support given to practitioners by the model. Finally, thanks to the test with a case study, the model can be considered valuable also from a practical point of view.

Before discussing Table 8, a brief description of the models considered for the comparison is given:

- (Aydin et al., 2015): a new methodology for simultaneous consideration of remanufactured and new products in product line design is proposed by which profit and market share of the product line can be maximized (by using a multi-objective optimization paradigm). Different research issues are addressed in the development of the methodology: (1) the competition between remanufactured and new products in markets; (2) demand estimation of remanufactured products in markets; (3) downgrading and upgrading the features of remanufactured products and (4) the time of launching remanufactured products in markets. Various issues including consumer preferences, product design attributes, change of product price over time, and cannibalization effect of remanufactured products on the sales of new products are considered in the development of the dynamic market demands;
- (Guide et al., 2003): a simple framework for determining the optimal acquisition prices and selling price (and so maximize the corresponding profit) is proposed. The quantity and quality of product returns can be influenced by varying quality dependent acquisition prices, i.e., by using product acquisition management strategies. Demand can be influenced by varying the selling price;
- (Franco, 2019): this work draws on the system dynamics methodology to capture the complex and systemic nature exhibited by production and consumption systems in CE. System dynamics is a computer simulation methodology that has its roots in the theory
of nonlinear dynamics and feedback control developed in mathematics, physics and engineering;

- (Fukushige et al., 2012): to support the strategy planning stage, this paper proposes a method of describing product lifecycle scenarios by which designers can explicitly determine lifecycle strategies. The lifecycle strategy is defined as a combination of lifecycle options (e.g., maintenance, product reuse, component reuse, closed-loop recycling and cascade recycling) for a product and its components, and the lifecycle scenario is a description of the expected product lifecycle. In other words, by describing the lifecycle scenario, designers can easily identify appropriate lifecycle options and requirements for product and process design in the later stages of lifecycle design. The objective of this study is to develop a management support system for examining various lifecycle strategy possibilities and clarifying requirements for product and process design;

- (González & Adenso-Díaz, 2005): the problem addressed by the model is the assignment of the best EoL strategy for any product. This implies determining the depth of disassembling inside its bill of materials (BOM) hierarchy and the final state for each disassembled part. Given the 3D CAD (computer-aided design) representation of the product, its BOM and some technical and economic data (e.g., component weights and materials, kinds of joint-breaking costs, disposal and recycling rates), the model starts by determining a strategy leading to the lowest cost. For each component or subassembly in the product structure, one EoL strategy must be selected from among the following: disposal, recycling, reuse or remanufacturing, disassembly.

Table 8 shows the comparison among the five selected models and the green profit one. Most of the papers integrates a CE strategy since the beginning and have already been tested thanks to a case study. Also, three models provide a brief graphical output, this can be useful when dealing with trade-off strategic decisions (e.g., maximization of profit and reaching of challenging environmental targets). Only some of the references can take into account S- and C-indicators together with evaluation about environmental objectives. These aspects are quite important when dealing with the definition of EoL strategy since indicators have to be considered at the same time. Additionally, new research is encouraged on the correlation between circularity assessment and life cycle sustainability indicators, therefore on studying the relationship between an improvement in a circularity score and its impacts on different sustainability indicators. Finally, a remanufacturing variable cost (e.g., based on the amount of production operations done or on the quality of the return products) is modelled only in two papers, as reported in the table.

The GPM covers all the criteria except for the modelling of a dynamic behavior (since it is a static and fixed model) and the consideration of a multi-period of time horizon. Anyway, the features can be integrated in future research making the model more helpful for companies. At the moment, the original paper (Kwak & Kim, 2017) propose a linear programming model to achieve an optimal EoL strategy, discussing what insights can be gained for redesigning products. The model fills the gap in the literature of a systemic, integrated, interdisciplinary, and visual tool to support the understanding and performance of CE strategy, from product design and manufacturing up to business models and product return and reprocessing. As explained in (Ramani et al., 2010), collaborations among the various disciplines of product realization (i.e., design, manufacturing, supply chain etc.) are essential to tackle the increasingly challenging task of sustainable development. The GPM optimizes production
planning, take-back and selling strategy, maximizing the total profit and reaching well-defined environmental goals (in terms of kg CO₂ equivalent).

2.5.3 Description
To enable the simultaneous optimization of production planning, take-back and selling strategy, the model considers integrated pricing and production planning in the form of a mixed-integer programming model. The proposed model enables original equipment manufacturers (OEMs) to identify the optimal line of new and remanufactured products that will maximize green profits (i.e., economic profits that accompany positive environmental-impact savings) compared to producing only new products. By setting a target for minimum environmental saving, OEMs can maximize their total profit while achieving greater than the target environmental-impact savings (Kwak & Kim, 2017). Economic profitability is guaranteed since as parts are reused, the same product offering the same quality and performance can be made at only a small fraction of the original cost, with a reduced adverse environmental impact (e.g., natural resource depletion, greenhouse gas emission, and air and water pollution) (Fleischmann et al., 1997; Hatcher et al., 2011). In Figure 18, the links among the three pillars of the model (i.e., product takeback, production and marketing & distribution) and the goal of the model are presented in a graphical way, making explicit some of the variables that will be explained later in detail.

To be clear, the proposed model aims to maximize the total profit from a line of new and remanufactured products. It consists of three components: (1) 'buyback pricing', which determines the buyback prices of end-of-life products and their quantity to take back, which later determines the amount of reusable parts (i.e., supply); (2) 'sales pricing', which determines the selling prices of new and remanufactured products and their quantity to produce (i.e., demand); and (3) 'production planning', which determines the detailed plans for matching the supply and demand, including how the end-of-life products should be disassembled (i.e., disassembly level and sequence) and how many and what kind of parts should be reconditioned, newly procured or recycled (Kwak & Kim, 2017).

![Figure 18 Integrated pricing and production planning model from (Kwak & Kim, 2017)](image_url)
The integrated perspective of the model is one of the main advantages of it. In fact, as an example, most previous studies have limitations with respect to their cost models. Their approaches have been on a simplified cost model, assuming the per-unit production cost of remanufactured products as a constant and average remanufacturing cost. However, such simplification is hard to justify in remanufacturing. As Steeneck and Sarin (Steeneck & Sarin, 2013) pointed out, the per-unit production cost of remanufactured products is affected by not only the quantity and quality of end-of-life products but also the quantity of remanufactured products. Therefore, it should be modelled as a function of both prices. This implies that buyback pricing and sales pricing should be simultaneously implemented and coordinated, but they have been addressed separately in previous studies. Pricing decisions should be made in consideration of possible alternatives to remanufacturing processes (i.e., production plans) and their influences on production costs (Kwak & Kim, 2017).

The proposed model assumes a buyback program as a takeback strategy. According to environmental legislation, consumers can return the end-of-life products to collection sites free of charge in most cases. Without compensation, however, consumers tend to store a product indefinitely even if they no longer use it (Kwak et al., 2011). Buyback price is a means to motivate consumers to return their products early. Although this may increase the takeback cost, a greater number of products with better quality can be secured, which in turn will reduce the production cost at a later stage (Kwak & Kim, 2017). In fact, setting the buyback prices of end-of-life products is an effective means of controlling the quantity and quality of end-of-life products (Guide et al., 2003).

2.6 Sustainability and circularity indicators

Indicators are often used as management tools which provide users a quick and synthesized overview by reducing the complexity of the collected data. An indicator is always a kind of equivalent variable which cannot be measured directly but strongly depends on other measurements (Gladen, 2011). As an indicator presents the trend and degree of fulfilment of a specific objective, it needs a reference value, which distinguishes it from a simple variable (Waas, et al., 2014). Overall 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 (Kravchenko et al., 2019). The sustainability and circularity indicators are presented in the following two subsections.

2.6.1 Sustainability indicators

Sustainability aims at balancing the products’ needs with the social requirements and available natural resources (Matsumoto et al., 2017), since the ecologic system has to be conserved as it supports the basis for human life (Von Hauff, 2014). Measuring and designing sustainability involves a holistic approach spanning the three fields of ecologic, economic and social aspects (Matsumoto et al., 2017). Moreover, performance indicators provide a better insight into strengths and weaknesses of the CE solution, thus enable more informed and balanced decision-making for sustainability (Kravchenko et al., 2019).

Leading performance indicators have the ability to produce simpler measures of environmental (and other triple bottom line (TBL) dimensions: economic and social) performance that can be
effective for driving actions for improving the performance of products (Kravchenko et al., 2019). Leading indicators are considered as simple “input/output” indicators (e.g., material cost per unit of product, take-back offerings for products), and thus offer better measurability and control over effectiveness of proposed actions in the early design stages (Kravchenko et al., 2019; Saidani et al., 2021).

On the other hand, lagging indicators are considered as “outcome/impact” indicators (e.g., global warming potential, customer retention), they provide results about past performance and are often challenging to be interpreted by practitioners into improvement actions, despite having a higher certainty of data (e.g., life cycle assessment (LCA) results) (Saidani et al., 2021). While LCA is a sound approach, its actual applicability in the context of the ex-ante assessment of CE strategies and as a support for early decision-making is often limited (Kravchenko et al., 2019), therefore, LCA can be considered as a lagging assessment tool for existing products.

For a meaningful ex-ante sustainability assessment, leading indicators are preferred over lagging, as they can be used to plan and monitor the effectiveness of proposed actions by focusing on critical areas or resolving some uncertainty early in the planning and development process (Pavlov & Bourne, 2011). In Figure 19, the difference between leading and lagging indicators is highlighted in a graphical way, also considering the temporal axis.

Reading the paper by Kravchenko and colleagues (Kravchenko et al., 2019), a wide analysis about indicators’ application is performed, looking at the business process and TBL dimension. Out of a group of 279 sustainability indicators analyzed, the most extensively covered process is “production and operations”, represented by 76% (211 out of 279) of performance indicators, 65% of which belong to the environmental dimension. This might be, firstly, due to a larger focus in the literature on sustainable manufacturing performance measurements, secondly, due to the expansion of sustainability-related metrics from manufacturing, to supply chain orientation (Kravchenko et al., 2019). The environmental dimension is well covered by performance indicators under “product development”, “after-sales service” and “EoL operations”, while economic and social indicators are lagging behind (Kravchenko et al., 2019). In Figure 20, the distribution of indicators considering business processes and TBL dimensions is evaluated.
At the end of the study of (Kravchenko et al., 2019), some key findings about S-indicators are identified:

- **Sustainability performance indicators**: there is a need for a wider deployment of leading performance indicators assessments. Leading indicators offer useful information about the potential sustainability performance of a solution, hence are effective for early decision-making and management of processes;
- **Sustainability indicators for CE**: leading sustainability-related performance indicators are available for a wide range of CE strategies. Indicators’ classification according to CE strategies and business process allows the configuration of different combinations of circular solutions to be exploited in various business processes.

### 2.6.2 Circularity indicators

During the early stages of product design and development, decisions regarding environmental and circularity aspects, such as the selection of materials, energy consumption, waste handling strategy, material toxicity and hazardousness, use of renewable natural resources and emissions, must be made. Once the product design concept is established, improving environmental and circular performance will lead to time-consuming and excessively uneconomical iterations (Albæk et al., 2020). The importance of metrics for the development of CE concept is highly relevant, as the measured features also shape the thinking and language within the concept and influence its development. Therefore, metrics can promote particular aspects of the CE concept itself (Parchomenko et al., 2019).

To categorize and clarify the positioning of the existing circularity indicators, the publication of (Parchomenko et al., 2019) is considered due to its completeness and rationale analysis. This piece of research is based on the method of multiple correspondence analysis (MCA) applied to assess 63 CE metrics and 24 features relevant to CE. The MCA was used to assess how the different CE features are associated to each other and how they are related with each of the 63 metrics. The analysis identified three main clusters of metrics, as presented in Figure 21 and in the following subsections.
2.6.2.1 Product-centric C-indicators

For circularity at the product concept level, it is important that the tool has a large focus on the product design and can highlight improvement potential in terms of the design and its compatibility for circular economy goals and strategies (Albæk et al., 2020). Some examples of indicators are the following:

- Circular economy indicator prototype (CEIP) (Cayzer et al., 2017): a questionnaire-based tool to score points for different phases of the product lifecycle according to the given answers. The result is shown as a product rating and spider web, which indicate the product score in relation to the total score in different phases of the product lifecycle. This can provide an indication of improvement potential but does not indicate directly what product characteristics should be improved;

- Circular economy toolkit (CET) (Evans & Bocken, 2013): an online questionnaire-based tool concerning the product’s characteristics and its lifecycle. The tool covers a broad range of circularity loops and provides an indication (in terms of opportunity and feasibility) of which areas the product/system perform well in terms of circularity;

- Circularity potential indicator (CPI) (Saidani et al., 2017): an indicator that uses a top-down approach and evaluates the product circularity based on 20 attributes within four aspects: circular product design, new business model, reverse cycles, and favourable system conditions. Each attribute can score up to five points, each building block can obtain a score of up to 25, and the total circularity score can reach 100;

- Circular pathfinder (CP) (ResCom, 2021): an online-based tool to be used during product development to find product strategies for improving circularity. The tool goes through questions relating to product type, product customer interactions, lifetime, and user needs, and eventually, suitable strategies are suggested.
Product-level circularity indicators can provide a practical approach to support the (re-)design of products adapted for a CE (Saidani et al., 2021). Saidani and colleagues (Saidani et al., 2020) provided examples of how C-indicators can support designing circular products by defining CE requirements and comparing the circularity potential of design alternatives. C-indicators can be defined as measuring instruments to quantify the performance and progress of systems in a CE perspective (Saidani et al., 2020), taking previous qualitative design guidelines to the next level (Saidani et al., 2021).

Looking at the MCA map, product-centric C-indicators are represented by the longevity indicator (LONGEVITY-I), which calculates the lifetime of resources in time units. A similar approach is inherent in the product-level-circularity-metric (PCM). It employs monetary units as an alternative measure and has a stronger focus on the CE element of retention, which locates the metric closer to the additionally projected retention element (Parchomenko et al., 2019). The material circularity indicator (MCI) is a nice example of a product-centric metric which combines multiple elements of all three clusters. It considers the amount of virgin feedstock, recycling efficiency and unrecoverable waste, while taking into account the time and intensity of product use.

2.6.2.2 Resource-efficiency C-indicators
The four most frequent CE elements of waste disposal, primary vs. secondary use, resource efficiency/productivity and recycling efficiency characterize the resource-efficiency cluster. As the cluster holds most of those metrics that are applied by governments and their agencies, it can be understood their currently rather narrow focus on a few CE elements. Within the cluster, different methodological approaches are combined together. Examples are input-output (IO) analysis metrics (REG-ENV-IO, AGRI-FOOD-IO), economy-wide material flow analysis metrics (EW-MFA, RE-EW-MFA), LCA-based metrics (IS-LCA, FW-LCI), metrics with a focus on remanufacturing (ECOENV-REMAN-MODEL, GDM-reman) or indicator for the support of investment decisions (ECOENV-INVEST-I) (Parchomenko et al., 2019).

2.6.2.3 Materials stocks and flows C-indicators
Typical associations of materials stocks and flows C-indicators with CE elements are flow destination, waste disposal, stock availability/concentration, downcycling and quality loss, cascading use, and recycling/remanufacturing potential. The material stocks and flows cluster has a strong interaction with the resource efficiency cluster. Examples of metrics belonging to this cluster are materials mixing (SEA), embedded stocks/lifetimes (PRODUCT-ECOSYS-MFA), longevity and downcycling (C-MFA), as well as system stability (Dynamic-SFA) (Parchomenko et al., 2019).

To conclude, there seems to be a significant value opportunity to combine together different types of indicators to overcome the current strengths and limitations of existing LCA, circularity and sustainability indicators (Saidani et al., 2021). There is still room for improving the extent to which sustainability related aspects and associated indicators are considered, when planning, monitoring and evaluating triple bottom line performance of CE solutions on a micro-level. It is important to create more awareness about the expansion of CE measurement scope with inclusion of sustainability-related indicators to ensure the intended sustainability outcomes.
can be planned, measured and realised (Kravchenko et al., 2020). As explained in (Mendoza et al., 2017), there is also a need to develop generic and sector-specific product circularity indicators to help product developers choose appropriate strategies.

2.7 Integration of circularity indicators in decision support models

In sections 2.5 and 2.6, decision support models and circularity indicators are described. Scholars put a lot of effort in developing the state of the art in these two fields, but there is still distance between academic and industrial world. In the near future, companies in many industries will move to CE and they will be able to welcome the change only having the right tools. Up to now, measuring the circularity potential of product as a means of enhancement and optimisation is still in an experimental phase in the CE transition, but is increasingly supported by the development of new C-indicators to be used by industrial practitioners during product design and development phases. Combining indicators with optimization models linking circularity, economic and environmental performance of a product is still researched in academic institutions (Saidani et al., 2019).

Several state-of-the-art optimization models and decision support tools show how it is possible to consider and integrate economic and environmental trade-offs in design engineering. 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 (Saidani et al., 2019). Yet, they barely consider in an integrated manner all the different possible CE strategies and related loops, as well as the actual and potential performance of products measured by circularity and sustainability indicators, as an example global warming potential (calculated in CO₂ equivalent emissions) is often the only indicator to assess the environmental savings (Saidani et al., 2019).

To understand the practicality of the identified gap, a brief overview on the current integration of circularity indicators and decision support models is presented. Luglietti et al. (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). The results are shown in a two-dimensional eco-efficiency diagram displaying the three alternatives with their economic revenue and environmental gain (in CO₂ equivalent emissions). Ma and Kremer (Ma & Okudan 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. Igarashi (Igarashi et al., 2016) built and applied a multi-criteria optimization model for lower disassembly cost, higher recycling and CO₂ equivalent saving rates by an environmental and economic parts selection, and subsequent disassembly line balancing. It is possible to see how CE is an underlying trait to all the three tools, but circular performance is rarely measured with C-indicators, in fact only specific indicators related to environment and human health are used.

An example where C-indicators are actively used is described in (Saidani et al., 2019). The scientific article proposes a timely framework to consider simultaneously the circularity performance and the impacts on sustainability when designing products, associated marketing strategies and meeting end-of-life regulations. The framework is used to extend the green profit
model by adding a third dimension to this model, i.e., the circularity performance. Circularity indicators are inserted in the mixed-integer programming model as additional constraints, so indicators are not used as guidance for unlocking the circular potential of products. Circular indicators, as stated in section 2.6, are the right tools to be used when dealing with CE since they are comprehensive and measure the actual and potential performance of products when CE is envisaged as a promising strategy for industrial practice.

The advantages in coupling strategic decision support models with circularity indicators lies in making easier the validation of circular design and business strategies choices (e.g., 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). 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. More precisely, the ultimate goal is to support decision-making in finding the most appropriate circular business model and associated end-of-life strategies to ensure profitability and environmental preservation to respect end-of-life regulations or achieve CE-related objectives.
3 Outline of the thesis
The current chapter aims to show the structure of the thesis work formulating the research objective of the thesis and illustrating the methodology adopted to fulfil it, along with the tools used. Then, the research contributions are stated.

3.1 Research objectives
Concluded the analysis of the state of the art, some gaps are found in it and now are elaborated and formalized to state the research objective developed in the thesis.

The analysed areas of the literature review are connected among each other. In fact, the sections about circular economy business model, design and remanufacturing can be considered as an introduction in the overall CE strategy, while the sections strategic decision support models and indicators reveal some practical aspect for applying CE concepts into practice. The main research gap identified in the literature is the lack of approaches that have a complete overview on the deployment of CE strategies. As identified in the previous section, frameworks exist for the comprehension of CEBM, design and remanufacturing, while tools that embed all these reasoning in a numerical way are still lacking. The research gap lies in the integration between decision support models and C-indicators for considering multiple aspect of CE within one summarizing framework (also in a numerical way), as stated in section 2.7. 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 is essential for both industrial practitioners (e.g., sustainability managers, product recovery managers, engineers or policy makers). Additionally, indicators’ effectiveness in early decision-making and processes management has to be assessed. In this way, a wider deployment of S- and C-indicators will be possible. In fact, the information disclosed by indicators can effectively guide the design and remanufacturing processes thanks to their ability to summarize knowledge and guide the realization of CE strategies.

Once completed the analysis of the state of the art and in light of the presented gaps, a research question for the thesis’ work is identified:

Can 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 implementing remanufacturing in real practice. It will be assessed whether indicators can properly evaluate the feasibility of remanufacturing strategy looking at the same time at the business model, design and production processes.

3.2 Methodology
Within the current thesis, in order to answer the research question, the green profit model is used and it augmented also following some industrial motivations. To expand the multidisciplinary view of this tool on CE aspects (i.e., business model, design and manufacturing processes), it is supported by circularity indicators mainly. In this way, thanks to the integration of two different tools, indicators’ support will be assessed and a proposition of framework tries to cover the identified literature gap.
3.2.1 Applied tools
The identified research question embraces all the research areas of the literature review. In the following sections, in order to answer to this question, these steps will be covered:

- Augmentation of the green profit model;
- Proposition of a new framework.

Figure 22 provides an overview of the integration of the green profit model with the C-indicators to meet environmental and profit goals. In fact, indicators can lead the transition towards CE through proper target setting. Additionally, indicators can provide a life-cycle view that is fundamental when assessing the environmental benefit of refurbishment and remanufacturing business models (Cooper & Gutowski, 2017; Gutowski et al., 2011).

The need for integration of life cycle thinking within DfX and the acquisition of more knowledge on design for remanufacturing within the product development process (e.g., comparing key performance indicators and/or design metrics) are aspects to consider when dealing with the definition of a CE strategy, also in industrial context (Matsumoto et al., 2017). The idea to include indicators as valuable tools towards CE satisfies the need for a wider deployment of leading performance indicators. Leading indicators offer useful information about the potential performance of a solution, hence are effective for early decision-making and management of processes. Also, C-indicators can be defined as measuring instruments to quantify the performance and progress of systems in a CE perspective (Saidani et al., 2020), taking previous qualitative design guidelines to the next level (Saidani et al., 2021).

3.2.2 Framework assessment
Considering the features of the model and indicators, the case study should be based on a real product. In fact, the GPM relies on the so-called transition matrix which links the structure of the product with the manufacturing operations that can be executed on it. In addition, the GPM has been already tested within a case study considering a smartphone as a reference object, so it is reasonable to think that the model performs well with existing technological products.

For the development of the thesis, the focus is on the racking system for ground mounted solar farms. In fact, solar farms are usually mounted directly on the ground when they are located in desert places, e.g., Arabian Peninsula. Additionally, the ground mounting structure well fits the requirement for the GPM, because it is a real mechanical product with long life span and, in a
general sense, it can be considered as a remanufacturable item, but further analysis follows in chapters 5 and 6. This complex case study is useful to firstly apply the framework and demonstrate how and to what degree indicators support the implementation of remanufacturing processes.

3.3 Synopsis of the thesis

In the core part of the thesis, a proposal of framework 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 scientific and industrial motivations. The goal is to provide companies a useful and easy-to-use approach for reaching economic, environmental and circular objectives. Then, thanks to a representative case study, the framework is tested in real practice and results are discussed.

The architecture of the thesis is now presented. Chapter 4 widely describes the methodology used to answer the research question, while chapters 5 presents the case study provided by TotalEnergies. The framework is applied to the case study in section 6 and the subsequent chapter presents results and sensitivity analysis performed taking advantage of the information disclosed by model and indicators. Chapter 8 explains some conclusion that can be derived from the current project together with future research perspectives. Without any reference to the chapters, Figure 23 shows a graphical synopsis of the thesis.
4 Methodology

In the current chapter, the main research contribution is described. Taking advantage of the state-of-the-art research on green profit model and C-indicators, a new framework is presented. Overall, the author provides an answer to the originally stated research question: “Can indicators provide support for the implementation of remanufacturing as circular business strategy?”

4.1 Augmentation of Green Profit Model

In this section, the GPM is formally described looking at the mathematical model at the basis of it. Then, in order to properly apply the green profit model in industrial practice, further details are included in this tool for a broader view on some economic and environmental aspects.

4.1.1 Overview of main variables and hypothesis

The company produces $Z_n$ and $Z_r$ units of new and remanufactured products, respectively, which are distributed to a competitive market and sold at a price of $P_n$ and $P_r$, respectively. Although the remanufactured product is of the same design and quality as the new product, its label “remanufactured” results in a selling price different from that of the new product (Kwak & Kim, 2017).

In the proposed model, the unused parts are assumed to be sent to recyclers for material recovery. $M$ denotes the number of parts heading to recycling. For the reusable parts to be actually used in remanufacturing, reconditioning operations (e.g., disassembly, cleaning, remachining, lubricating, reassembly, testing) are conducted as needed. After being reconditioned, the parts are reassembled into $Z_r$ units of remanufactured products that provide the same quality and performance as brand-new products. When there is a shortage of parts, new parts can be procured externally, as occurs in new-product production. $N$ denotes the amount of parts newly purchased (Kwak & Kim, 2017).

For production planning, the proposed model requires a transition matrix as a key input. It represents the relationship between product design and remanufacturing operations in a matrix form, such that the impact of product design can be mathematically reflected in the production planning. If a cell $(i, j)$ has a value of -1, it means that an item $i$ is processed (changed to other item(s)) by operation $j$; alternatively, if a cell $(i, j)$ has a value of 1, it indicates that an item $i$ is generated from operation $j$. If a cell $(i, j)$ has a value of 0, item $i$ has nothing to do with the operation $j$. The transition matrix is useful to deal with a problem that involves complex products having multi-level disassembly structures and is distinguished from other approaches that limit the product structure to be either two or three levels (Kwak & Kim, 2017).

Briefly, the following lists present the input data, the output expected from the model and the hypothesis. Input data required are:

- Product design: in terms of technical drawing and bill of materials;
- Description of the manufacturing process of the product;
- Per-unit variable cost of the new product; cost of new parts’ purchase (i.e., purchasing of components); cost of each manufacturing operation; cost of distribution and transportation;
- Per-unit selling price of the new item;
Environmental perspective: life-cycle analysis (LCA) analysis and calculation of the global warming potential (GWP) of the product; information about the end-of-life strategy;

Market size: amount of product in the market that can be potentially collected by the company.

The model optimizes:

- Takeback strategy: buyback price and the takeback quantity of end-of-life product;
- Profit: selling price and the production quantity of the new and remanufactured product;
- Production plan: number of times of each operation, recycling amount, quantity of new parts to procure.

In a nutshell, the GPM optimizes the green profit opportunities, so where the manufacturing company can achieve profit as well as environmental-impact savings.

The underlying hypothesis are:

- The model considers the case where both new and remanufactured products are offered simultaneously to a competitive market (so no closed loop optimization of new and remanufactured products);
- The remanufactured product is of the same design and quality as the new product;
- The product design is predefined and fixed;
- A single type of product and single-period planning horizon are considered;
- The proposed model assumes a buyback program as a takeback strategy;
- The probability that a component is working and reusable is fixed;
- Fixed cost is not included in the model (consequently, it is assumed that the manufacturer utilizes an existing facility and infrastructure);
- The demand models of the target market and the response functions are assumed to be given.

Finally, in the original paper by Kwak and Kim (Kwak & Kim, 2017), the mathematical model is fully described with the equations that rule the mixed-integer programming model.

### 4.1.2 Overview of mathematical model

#### Nomenclature

**Index**

- **I**: Index set for item (every possible product and part that appears during production), \(i \in I\)
- **J**: Index set for operation, \(j \in J\)
- **K**: Index set for nominal quality level of end-of-life product, \(k \in K\)
- **L**: Index set for market segment, \(l \in L\)

**Decision variable**

- \(X_k\): Amount of end-of-life product with quality level \(k\) to be taken back
- \(Y_j\): Number of times operation \(j\) is executed
- \(N_i\): Amount of item \(i\) to be externally purchased
- \(M_i\): Amount of item \(i\) to be sent for material recovery, respectively
- \(Z_n, Z_r\): Amount of new and remanufactured products to be produced, respectively
In general, the objective function aims at maximizing the total profit from the sales of new and remanufactured products. The profit from new product sales, therefore, can be modelled as the difference between total revenue and total cost, i.e., \( (P_n - C_n) \cdot Z_n \) where \( C_n \) denotes the per unit variable cost of the new product. The variable cost includes the cost of new part purchase, the cost of assembly, and the cost of marketing and distribution. The profit from remanufactured products takes a more complex form, due to its cost structure. The total cost is the sum of five cost components: the cost of material recovery, cost of takeback, cost of remanufacturing operations, cost of new part purchase and cost of marketing and distribution.

**Equation 1 Objective function**

\[
\text{max } (P_n - C_n) \cdot Z_n + P_r \cdot Z_r - \left( \sum_i c_i^M \cdot M_i + \sum_k P_k \cdot X_k + \sum_i c_i^N \cdot N_i + \sum_j c_j \cdot Y_j + c_d \cdot Z_r \right)
\]

The following variables are optimized by the model using mixed-integer programming and have to satisfy non-negativity and integrality constraints:

\[ X_k, Y_j, Z_n, Z_r, N_i \geq 0 \text{ and integer } \forall i, j, k \]

\[ P_k, P_n, P_r, M_i \geq 0 \forall i, k \]

The following equations list the constraints of the model. Constraint \( g_1 \) presents constraints on product takeback, where \( s_k(P_k) \) denotes a response function that gives the takeback rate of end-of-life product \( k \) given the buyback price of \( P_k \). In general, the takeback rate \( s_k(P_k) \) increases monotonically by \( P_k \). The maximum attainable amount of end-of-life product is \( A_k \), and it creates the upper limit for the takeback quantity, \( X_k \). Constraints \( g_2 \) and \( g_3 \) prevent the production quantities \( Z_n \) and \( Z_r \) from exceeding the market demand, where the size of market
segment $l$ is $Q_l$ and the market share of the new and remanufactured products in the segment is given as functions of the selling prices $P_n$ and $P_r$, i.e., $d_{n,l}(P_n, P_r)$ and $d_{r,l}(P_n, P_r)$, respectively. Since they are offered to the same market, the price of one product may affect the demand for the other. The functions can be defined through well-known demand modelling techniques. Constraint $g_4$ requires that $Z_r$ does not exceed $X_k$. Constraint $g_5$ requires the OEM meet the target $\delta$ for environmental-impact saving. The left-hand side formulates the environmental-impact saving. Environmental-impact savings indicates how much environmental impact can be claimed to be avoided by producing $Z_r$ units of remanufactured products, as compared to the reference case when the same amount of equivalent products are newly produced while no takeback is conducted. To be more specific, the environmental-impact saving originates from two sources. First, the amount of waste that must be disposed of is reduced as $X_k$ units of end-of-life product $k$ return for remanufacturing. This is modelled by the first term of the constraint. Second, products in “same-as-new” condition are produced using reduced natural resources and energy, as the parts from the end-of-life products are reused. This is modelled by the remaining terms in the left-hand side.

$$g_1: X_k \leq A_k \cdot s_k(P_k) \quad \forall k \in K$$
$$g_2: Z_n \leq \sum_l Q_l \cdot d_{n,l}(P_n, P_r)$$
$$g_3: Z_r \leq \sum_l Q_l \cdot d_{r,l}(P_n, P_r)$$
$$g_4: Z_r \leq X_k$$
$$g_5: \sum_k (e_w - e_k) \cdot X_k + \left( E_n \cdot Z_r - \left( \sum_i e_i^M \cdot M_i + \sum_j e_i^N \cdot N_i + e_d \cdot Z_r \right) \right) \geq \delta$$

Figure 24 describes an example of response functions (i.e., the term $s_k(P_k)$ within constraint $g_1$). It shows how the takeback rates will change depending on buyback prices. It is assumed that the takeback rates linearly increase according to the buyback price and peak at prices of $180$ (good quality) and $100$ (poor quality). Thus, the OEM can improve the quantity and quality of end-of-life products by paying higher buyback prices.

Figure 24 Examples of response functions from (Kwak & Kim, 2017)
Considering the quantification of the market shares presented in constraints $g_2$ and $g_3$ as $d_{n,l}(P_n, P_r)$ and $d_{r,l}(P_n, P_r)$, it is supposed that the market share of a product in the target market is determined by three factors: product performance, selling price and newness (i.e., whether a product is a brand new or remanufactured). Here, product performance is determined by product design and given as a number between 0 (poorest) and 1 (best performance). Depending on the sensitivity to price and perception of the remanufactured product, consumers in the target market can be clustered into three groups. The critical price $\bar{P}_l$ represents the maximum price that consumers of the segment are willing to consider paying for the product. In other words, if a product is sold at a price greater than its critical value, then no customers will choose that product. Higher critical price implies that the segment is less sensitive to price change. The utility discount factor $\beta_l$ reflects the segment's perception of remanufactured products. If the discount factor is 0.1, the utility is discounted to 10%. In other words, a greater factor indicates that the segment better appreciates remanufactured products.

$$u_{0,l} = u_{0,perf,l} \cdot u_{0,price,l} \cdot u_{0,new,l}$$

where

$$u_{0,perf,l} \in [0,1]$$

$$u_{0,price,l} = \max (0,1 - P_o / \bar{P}_l)$$

$$u_{0,new,l} = \begin{cases} 1 & \text{if choice } o \text{ is a new product} \\ \beta_l & \text{else (choice } o \text{ is a remanufactured product)} \end{cases}$$

$$d_{n,l}(P_n, P_r) = \frac{u_{0,l}}{\sum_{o \in O} u_{o,l}}; \quad d_{r,l}(P_n, P_r) = \frac{u_{r,l}}{\sum_{o \in O} u_{o,l}}$$

The first equation shows the multiplicative utility demand model, where O is the index for choice set $o \in O$, $u_{0,l}$ is the utility of product $o$ in market segment $l$, and $u_{0,perf,l}, u_{0,price,l}, u_{0,new,l}$ denote product $o$’s utility in market segment $l$ with respect to performance, price, and newness, respectively. $P_o$ denotes the price of product $o$. The market share of a product is then obtained last equation.

Constraints $h_4$ through $h_6$ restrain the input-output flow balance in remanufacturing operations. Constraint $h_4$ requires every collected end-of-life product is either disassembled for part recovery or recycled for material recovery. Constraints $h_2$ and $h_3$ ensure the flow balance of parts. If external purchase is available, new parts can be input to the system to address a shortage of parts. All parts remaining after remanufacturing operations are recycled for material recovery. Constraint $h_4$ ensures that the remanufacturing operations produce $Z_r$ units of the remanufactured product. Constraint $h_5$ allows new part purchase only for items with external procurement availability. Constraint $h_6$ removes unrealistic cases in which the remanufactured products are recycled instead of being distributed to the market (Kwak & Kim, 2017).

$$h_4: X_k + \sum_j T_{ij} \cdot Y_j - M_i = 0 \quad \forall i, k$$

$$h_5: N_i + \sum_j T_{ij} \cdot Y_j - M_i = 0 \quad \forall i$$

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4.1.3 Augmentation of model

The state-of-the-art GPM already considers multiple circular loops and integrates different perspectives: product takeback, production and marketing and distribution. Also, the environmental sphere is well considered with the GWP impact factors. Still, in order to properly apply the green profit model in industrial practice, further details have to be included in this tool for a broader view on some economic and environmental aspects. To augment the model, the author reflected on the current limits of GPM, especially in terms of industrial applicability. The augmentation of the model firstly developed by Kwak & Kim is based on:

- Consideration of transportation cost and environmental impact;
- Modification of some inaccuracies in transition matrix;
- Addition of a constraint: economic incentives.

Now these three aspects are described in detail. Firstly, transportation costs and environmental impacts are considered in the augmented version of GPM. This is a key point to evaluate completely the feasibility of the takeback program. In fact, transporting product from and to different locations worldwide means costs and production of greenhouse gases. The objective function is modified as shown in Equation 2: transportation costs (i.e., \( c^t_k \)) are considered through the last term in the equation, while marketing and distribution ones are removed. In this way, the data collection for industrial practitioners is simplified since information about marketing and distribution can be quite difficult to gather when a company produces many products and a blurred distinction among employees’ tasks occur.

Also \( g_5 \) constraint is modified: transportation environmental impact is considered, while marketing and distribution ones are removed together with the term \( \sum_k (e_w - e_k) \cdot X_k \). Therefore, some difficult terms to compute are removed making the tool easier and closer to industrial practice when dealing with strategic decisions. In fact, the terms \( e_w \) and \( e_k \) are cumbersome to compute since they depend on a great variety of factors. \( e_w \) varies if EoL products are landfilled or incinerated when no takeback strategies are deployed and if the products are stocked in customers’ houses for a long time. On the other hand, due to the generic definition of \( e_k \), the term is substituted by \( e^t_k \) which has a practical link with transportation carbon footprint. Overall, a more realistic estimate of environmental impact savings is obtained through the new \( g_5 \) constraint.

\[
\begin{align*}
h_3: & \quad \sum_j T_{ij} \cdot Y_j - M_i = 0 \quad \forall i \\
h_4: & \quad \sum_j T_{ij} \cdot Y_j - Z_r = 0 \quad \forall i \\
h_5: & \quad N_i = 0 \quad \forall i \\
h_6: & \quad M_i = 0 \quad \forall i
\end{align*}
\]

\[
\begin{align*}
\text{max} & \quad (P_n - C_n) \cdot Z_n + P_r \cdot Z_r - \left( \sum_l c^M_l \cdot M_i + \sum_k P_k \cdot X_k + \sum_l c^H_l \cdot N_i + \sum_j c_j \cdot Y_j + \sum_k c^t_k \cdot X_k \right)
\end{align*}
\]
Secondly, some inaccuracies in the T 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 considering their condition. 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, component (remanufactured and new, depending on the availability of core products) are reassembled together and reintroduced in the market. Figure 25 shows the correct version of the T matrix.

\[
g_5: E_n \cdot Z_r - \left( \sum_i e_i^M \cdot M_i + \sum_j e_j \cdot Y_j + \sum_i e_i^N \cdot N_i + \sum_k e_k^T \cdot X_k \right) \geq \delta
\]

Otherwise, “non-working” components also can face the remanufacturing process. Of course, the process requires more materials and/or energy, but in this way the quantity of new parts to purchase is drastically reduced. This aspect is highlighted in the two rows where the costs and environmental impacts of the manufacturing operations are stated. The quantity of components to be recycled decreases too since the residual value in the core product is strongly valorized. In any case, the product design and the feasibility of the remanufacturing processes have to be properly assessed. Figure 26 shows the new version of the T matrix where also “non-working” component can face remanufacturing.
Figure 26 New version of transition matrix: "non-working" components face remanufacturing

The last augmentation introduced in the original GPM is the addition of a profitability constraint for the customer company through incentives (Equation 4). As clear in industrial practice, manufacturers often have a direct contact with final customers, the final owner of the products. Therefore, to stimulate the return of products and so have the possibility to choose remanufacturing, a profitability check for the customer company has to be done. Additionally, the returned core products have a residual value in the materials used and in the energy already spent to manufacture them. So, it is important to add this constraint to properly consider the view of the company that returns the end-of-life products. From the manufacturer point of view, since product takeback determines the quality and quantity of inputs processed later in production, of major concerns are how many products and what quality of products should be acquired. Without compensation, consumers tend to store products indefinitely, even more so the profitability for the customer company has to be guaranteed. Although this may increase the takeback cost, a greater number of products with better quality can be secured, which in turn will reduce the production cost at a later stage (Kwak & Kim, 2017).

\[ \sum_k P_k \cdot X_k \geq \alpha \]

All in all, the augmentation of GPM corrects mistakes, adds details and provides new perspectives to improve the usefulness of the model and to make it more fitting for industrial practice.

4.2 Proposal of framework: combining GPM and C-indicators

Indicators are critical, synthetic and significant tools that allow to measure the company's performance in its most varied aspects. Management makes its choices on them thank to their synthetic nature, in fact they are expressed by a simple or compound variable. Indicators support planning and control cycles at all levels of the firm (strategic, managerial, operational) and they allow to measure the business trend because they are represented by quantitative or qualitative variables that are comparable. Thanks to indicators, management can not only measure business phenomena over time and in space (in relation to competitors, the sector,
etc.), but it can plan company activities (by defining measurable objectives in the short and medium term), measure the deviations (gaps) between expected objectives and obtained results and undertake the necessary actions to correct the gaps.

Generally, the measurement of the performance of business activities and processes requires the definition of a set of indicators that allows to represent, in a unitary and prospective framework, the ability of the company to execute its short, medium and long term objectives. Key performance indicators (KPIs) are a set of indicators that measure:

- Efficiency performance. Measuring efficiency is the primary objective of traditional management control systems, which calculate margin and total costs of activities (i.e., production, purchasing, distribution etc.) and environmental footprint;
- Competitiveness. Competitive results expressed by referring to appropriate indicators that measure the "weight" of the company within the competitive system in which it operates;
- Quality. Indicators measure customers' satisfaction in terms of their requests, time to market and complaints rate; therefore the overall level of service perceived by the final customers.

As it can be understood from this brief overview about indicators, they are a valuable tool in driving strategic decisions looking at the same time at different aspects of the enterprise (i.e., economic, environmental and social). Specially, circularity indicators provide various information about products and companies considering multiple point of views (i.e., CE loops, CE perspectives, format of the CE assessment framework) at the same time. These tools suggest insights for augmenting the circular level of products or industrial facilities usually implementing some strategies suggested by CE practice (i.e., CE loops, DfX, sustainable manufacturing, CEBM, industrial partnerships).

As explained in section 2.5, GPM is a powerful instrument for assessing, also in a preliminary way, the economic and environmental feasibility of remanufacturing and recycling strategy. Undoubtedly, other technical checks have to be made in order to properly consider the product design and manufacturing process. However, GPM can be considered as a useful support for companies entering circular economy perspectives as it satisfies the need for a systematic way of considering multiple life cycles (Ramani et al., 2010). Other optimization models can be used within the framework, making it a flexible and general tool to be used in industrial practice. At the moment, the green profit model has been used alone or with one C-indicator, as in (Saidani, 2019). In this last case, the indicator is used as an additional constraint to be satisfied in the optimization model guaranteeing that a minimum level of circularity is reached. With this modification it is possible to evaluate the performance of a product considering economic, environmental and circular dimensions.

Within the present work, a new way of using optimization models and C-indicators is shown. The new framework allows to validate the supporting capability of indicators in identifying and putting into practice circular strategies. 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 suggestion of the C-indicators and, as a last step, the C-indicators are computed again to quantify (if possible) the gain in performance. Figure 27 depicts the five steps, from left to right, and a brief description is proposed for each of them. An important consideration is that, in this case, indicators are used together to gather multiple views on the problem and the information extracted from them guide the implementation of a CEBM. On the other hand, the model guarantees the consideration of
multiple CE loops at the same time and it allows a feasibility check on economic and environmental dimensions. This framework partially fills the research gap in finding correlation between the scores of C-indicators and economic and environmental performances.

The five steps of the framework represent a logic path for unlocking the circularity potential within a business practice. 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 clear and well-defined criteria related as an example to CE implementation level, CE loops, CE perspective and format of the CE assessment framework. This step is the first block since indicators have to be deployed from the very beginning to acquire knowledge about the current circular performance of business practice and exploit their guidance capability. As an example, using the C-Indicators Advisor web-based tool, specific indicators related to the case study are selected along with others focused generally on business. An estimate of the proper number of indicators to choose is ten, since 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 the 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, 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 to the specificity of the case study and collecting the required data. The use of the optimization model is adequate because it assesses quantitatively the findings obtained from indicators, practically connecting design, production and market information. Therefore, the simulations from the model contain decisive results for understanding the potential improvement in circular performance of the current business practice. Being able to link the potential circularity performances of products with their repercussions on the economic profit and environmental savings, when setting up an end-of-life strategy plan, is essential for industrial practitioners. 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. 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

![Figure 27 The five steps framework](image-url)
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. This last step is relevant for companies to see what the next steps are and move their industrial practice to new circular levels.

As stated in Figure 27, the selection and target step are highlighted as iterative ones because of the presence of human decision making. Criteria for the selection of C-indicators can be refined when more information about the case study are available or when a deeper understanding of the variables involved is obtained. Accordingly, in the target step, only with a good communication and exchanges among the actors involved it is possible to state the best action plan to reach the challenging results identified with the application of the framework.

4.3 Expected results
The outputs from this chapter are the augmentation of the green profit model (as selected optimization tool) and the proposition of a new framework that combines together the new version of GPM and C-indicators. Considering the proposal of framework as the core research contribution from the current thesis project, numerous outputs can be envisaged from the use of it:

- The validation of the supporting capability of indicators in identifying and putting into practice circular strategies;
- Qualitative and quantitative results from the combined use of GPM and indicator, helping company to assess the goodness of circular ways of doing;
- The identification of useful information to find agreements among the players in the supply chain when dealing with circular goals;
- A strategic support for enterprises in order to move from linear to circular economy, in terms of products, production processes, purchasing and distribution.

The validation of the framework occurs in a real complex case study provided by TotalEnergies, French leading company in the oil & gas industry, developed in chapters 5 and 6. With the case study, the approach can be understood in a deeper way and also its flexibility and validity in real practice is tested. The framework discloses various insights about the product under analysis, thanks to its broad scope in industrial practice.
5 Description of the case study

Inside this thesis work, the author took advantage of the collaboration with TotalEnergies, French leader company in the oil & gas industry. In early 2021, the company ratified its name change to TotalEnergies as an intended illustration of its investments in the production of green electricity. In fact, Total Energies believes that renewable energy will soon fulfil its promise and become a key driver of the energy transition that society has to successfully implement in the coming decades. Therefore, TotalEnergies is becoming an international solar energy operator. The organic asset growth, new industrial partnerships, research and innovation are the solid foundations on which the company is building a long-term, profitable solar energy business. As a tangible example, the company is promoting the installation of rooftop solar panels at service stations all around the world, within its existing network and especially at new stations. The panels, which can be installed on shop roofs or integrated in canopies, will offer annual production capacity of 35 - 50 MWh depending on the geographic location.

5.1 TotalEnergies profile

Today the world’s energy future is being shaped by the dual challenge of climate change and rising demand for energy. TotalEnergies’ ambition to get to net-zero emissions by 2050 together with society means taking these realities into account by investing heavily in renewables. The company is focusing on the fast-growing solar, onshore wind and offshore wind segments, leveraging the many advantages that these abundant, clean, flexible, efficient and competitive sources of energy have to offer. To achieve this, TotalEnergies is focusing on:

- Development of large solar and onshore wind plants: TotalEnergies designs, finances, builds and operates large solar and onshore wind plants. Leveraging longstanding presence and deep roots in different parts of the world, the company delivers projects that are both reliable and sustainable over the long term, e.g., the construction of an 800 MW solar plant in Al Kharsaah (Qatar). The facility will meet around 10% of Qatar’s electricity peak demand and will reduce its CO2-equivalent emissions by 26 million metric tons throughout the life of the project;

- Distributed power generation solutions: TotalEnergies provides a range of tailor-made photovoltaic solar systems that can be installed on rooftops, parking lots or vacant land. By enabling customers to produce and consume their own energy, these solutions allow them to make a lasting commitment to fighting climate change while also reducing electricity bill;

- Stationary energy storage solutions: due to the intermittent nature of wind and solar energy, large-scale storage of renewable electricity is critical to ensuring grid stability. For this reason, TotalEnergies is investing in stationary storage capacity, e.g., the company has launched the largest battery storage project in France, with an overall capacity of 61 MWh. In addition, the affiliate Saft designs, produces and sells high-tech batteries for industry, developing solutions that combine superior energy density, longevity and performance to cater to renewable energy applications.

TotalEnergies’ ambition is to become the responsible energy major, providing energy that is more affordable, more reliable, cleaner and accessible to as many people as possible. TotalEnergies’ focus on climate concerns is integral to the four areas of strategic focus: natural gas, electricity generated from renewables and gas, oil products and carbon neutrality. Also, the global energy mix will need to change significantly in order to cut greenhouse gas emissions.
emissions. The company is committed to furthering the sustainable development goals (SDGs) defined by the United Nations (UN), especially in areas related to climate action and the development of energy that is more affordable, more reliable, cleaner and accessible to as many people as possible.

5.1.1 Social impact
From the social side, TotalEnergies is committed to:

- leading the transformation of the energy model to combat climate change and respond to people’s needs;
- being a leading name as an employer and a responsible operator;
- accelerating progress on environmental stewardship;
- generating shared prosperity across regions.

These goals can be pursued utilizing the opportunities revealed by solar sector, so expanding access to low-cost clean energy. In fact, community solar is a powerful tool to provide solar benefits to those without easy access to the property or upfront capital needed to install a solar system. Many states have implemented community solar programs but getting beyond the pilot stage and ensuring that these programs are designed to reach underserved communities is critical. In addition, onsite solar creates a pathway for historically disadvantaged communities to reduce monthly energy costs and maintain homeownership, which is critical to building generational wealth. Programs that target these communities to provide incentives for installing rooftop solar systems can provide long-term financial stability and community wealth. Furthermore, increased rooftop solar adoption can reduce overall electricity costs for all ratepayers and help accelerate the retirement of fossil fuel generation facilities, providing environmental and economic benefits to underserved communities. Targeting new solar with storage projects to replace existing peaker plants sited in or near low-income or disadvantaged communities can help reduce pollution and other harmful impacts. By focusing investments in clean, resilient energy projects to intentionally displace dirtier facilities, the industry can proactively address public health and environmental justice1 impacts on frontline communities (SEIA, 2021).

Finally, a key aspect of CE is the financial benefit of remanufacturing the equipment. The 4th industrial revolution results in a huge amount of end-of-life equipment, while at the same time, the gap between the advanced and the developing countries is still growing, not only in terms of production capabilities, but in technological education as well. This becomes even more pronounced in view of the expected pandemic side-effects in global finance and economics. Hence, the volume of retired equipment constitutes an almost unlimited repository of means that could bridge the aforementioned gap. The upcycling, redesigning, remanufacturing and reusing strategies can provide equipment of low cost. In conclusion, the applicability of CE has not only environmental benefits, but financial and societal benefits as well (Rogkas et al., 2021).

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1 Environmental Justice (EJ) is the fair treatment and meaningful involvement of all people regardless of race, color, national origin or income with respect to the development, implementation and enforcement of environmental laws, regulations and policies (SEIA, 2021).
5.2 Overview of photovoltaics sector in US context

In this section, an overview of photovoltaics sector status is provided, specially looking at the US landscape. Additionally, information related to expected growth and installation costs are shown.

In the last decade alone, solar sector has experienced an average annual growth rate of 42% in US. Thanks to strong federal policies, rapidly declining costs, and increasing demand across the private and public sector for clean electricity, there are now more than 100 GW of solar capacity installed nationwide, enough to power 18.6 million homes. Figure 28 shows the historical data and forecast of the US PV installation, from 2010 to 2026. The capacity installed each year is categorized by four segments: the utility one will strongly increase in the near future, making it promising for manufacturers. Figure 29 presents data only for the utility installations, highlighting a positive year-over-year growth for many of the upcoming years. However, the results presented have to face the change introduced by pandemic situation.

As of 2020, more than 230000 Americans work in solar at more than 10000 companies in every US state. The main job categories considering the number of employees are installation & developers, manufacturing and sales & distribution. The cost to install solar has dropped by more than 70% over the last decade, leading the industry to expand into new markets and deploy thousands of systems nationwide. Prices as of the fourth quarter of 2020 are at their
lowest levels in history across all market segments. An average-sized residential system has dropped from a pre-incentive price of 40000$ in 2010 to roughly 20000$ today, while recent utility-scale prices range from 16$/MWh to 35$/MWh, competitive with all other forms of energy generation (Resources, 2021). Figure 30 shows the turnkey installation price (in $/Wdc) for first quarter 2020 and first quarter 2021, looking at three market segments: residential, non-residential and utility. For the utility segment, PV module and structural BOS (balance of system, e.g., racking system) represent the largest cost items.

Figure 30 Turnkey installed price in US by market segment (Q1 2020, Q1 2021) from (Perea et al., 2020)

5.3 Critical raw materials and end-of-life management
Over the last several quarters, critical components for solar equipment – polysilicon, steel, aluminium, semiconductor chips, copper and other metals – have become increasingly supply-constrained. Raw materials are key enablers for all sectors of the economy. Some of the raw materials, in particular those assessed as critical raw materials (CRMs), are essential prerequisites for the development of strategic sectors such as renewable energy, electric mobility, defence and aerospace and digital technologies (Bobba et al., 2020). Figure 31 shows the critical raw materials used in solar PV technologies in red (i.e., boron, germanium, silicon, gallium and indium) and the other materials used in grey.
Even if the dynamics around each commodity are nuanced, the increasing demand for solar, combined with pandemic-related macroeconomic realities (such as increased shipping costs, microchip availability and a residential home renovation boom) have led to increased commodity prices and delivery delays. Additionally, multiple sectors are competing for base metals like copper, aluminium, magnesium, nickel, iron ore and their alloying elements like tungsten, vanadium, manganese and chromium (Bobba et al., 2020). The impacts of these constraints on the solar industry vary. Important raw material inputs to the solar supply chain include steel, aluminium and copper. After the pandemic, price increases for manufacturers may not be felt immediately by customers due to time lags in procuring equipment and long-term supply agreements. Further, manufacturers may still be estimating how much of these price increases they want to pass along to the customer, and how much they decide to absorb (Perea et al., 2020). The price of steel has more than doubled since the pandemic began, which has led to increased prices and lowered availability of solar racking equipment and trackers. To date, this has mostly affected utility-scale solar projects but has also impacted carport installations, which require more steel support structures than other solar projects. Polysilicon supply and demand are barely balanced, so small production errors can make an outsized difference. This has led to stagnant or increasing module costs (depending on the manufacturer), reversing a decades-old trend of module cost declines (Perea et al., 2020). Figure 32 provides quantitative forecasts of the material requirements for PV renewables in 2030 and 2050. For each year, three values are reported corresponding to low, medium and high intensity consumptions respectively (i.e., LDS, MDS and HDS).
The rapid deployment of renewable energy in the EU and worldwide will put some pressure on the supply of certain relevant raw materials used in PV systems. Some of them have a high supply risk and are defined as CRMs for the EU, such as silicon metal, indium, gallium, germanium and borates. On the other side, other raw materials such as copper, cadmium, selenium, silver and tellurium have lower supply risk. The EU supplies 6% of the raw materials used in PV systems. Many countries contribute to the supply of raw materials and therefore the supply risk at this step is considered as medium. As expressed in Figure 33, the most vulnerable step along the supply chain of PV technology is at the component level, for which China dominates the supply market with about 89%. Actually, China dominates nearly all aspects of solar PV manufacturing and use (Bobba et al., 2020). The assessment mechanism of the four supply risks is based on the legend described in Figure 34.

![Figure 33 Solar PV: an overview of supply risks, bottlenecks and key players along the supply chain from (Bobba et al., 2020)](image)

<table>
<thead>
<tr>
<th>Assessed material</th>
<th>Year</th>
<th>LDS [tonnes]</th>
<th>MDS [tonnes]</th>
<th>HDS [tonnes]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>2030</td>
<td>83 000</td>
<td>200 000</td>
<td>520 000</td>
</tr>
<tr>
<td></td>
<td>2050</td>
<td>110 000</td>
<td>410 000</td>
<td>1 300 000</td>
</tr>
<tr>
<td>Cadmium</td>
<td>2030</td>
<td>5</td>
<td>20</td>
<td>220</td>
</tr>
<tr>
<td></td>
<td>2050</td>
<td>1</td>
<td>30</td>
<td>600</td>
</tr>
<tr>
<td>Copper</td>
<td>2030</td>
<td>51 000</td>
<td>120 000</td>
<td>320 000</td>
</tr>
<tr>
<td></td>
<td>2050</td>
<td>60 000</td>
<td>250 000</td>
<td>800 000</td>
</tr>
<tr>
<td>Gallium</td>
<td>2030</td>
<td>0</td>
<td>2</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>2050</td>
<td>0</td>
<td>5</td>
<td>40</td>
</tr>
<tr>
<td>Germanium</td>
<td>2030</td>
<td>1</td>
<td>5</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>2050</td>
<td>0</td>
<td>10</td>
<td>100</td>
</tr>
<tr>
<td>Indium</td>
<td>2030</td>
<td>1</td>
<td>10</td>
<td>60</td>
</tr>
<tr>
<td></td>
<td>2050</td>
<td>0</td>
<td>20</td>
<td>170</td>
</tr>
<tr>
<td>Selenium</td>
<td>2030</td>
<td>5</td>
<td>20</td>
<td>140</td>
</tr>
<tr>
<td></td>
<td>2050</td>
<td>1</td>
<td>30</td>
<td>350</td>
</tr>
<tr>
<td>Silicon metal</td>
<td>2030</td>
<td>23 000</td>
<td>71 000</td>
<td>216 000</td>
</tr>
<tr>
<td></td>
<td>2050</td>
<td>10 000</td>
<td>109 000</td>
<td>399 000</td>
</tr>
<tr>
<td>Silver</td>
<td>2030</td>
<td>50</td>
<td>160</td>
<td>660</td>
</tr>
<tr>
<td></td>
<td>2050</td>
<td>20</td>
<td>110</td>
<td>660</td>
</tr>
<tr>
<td>Tellurium</td>
<td>2030</td>
<td>5</td>
<td>20</td>
<td>280</td>
</tr>
<tr>
<td></td>
<td>2050</td>
<td>1</td>
<td>40</td>
<td>690</td>
</tr>
</tbody>
</table>

*Figure 32 Materials for PV renewables from (Bobba et al., 2020)*

*Figure 34 Legend for supply risk assessment.*
Looking at the end-of-life management topic, over 95% of PV modules deployed in the US have been installed since 2012, and such modules will stay in service for more than 25 years. SEIA’s national recycling program is preparing now for larger volumes of waste to come in future years. Already SEIA’s recycling partners have processed more than 5.5 million dollars of PV modules and related equipment since the program launched (Solar Energy Industries Association, 2020). SEIA’s current partners have prior expertise in recycling glass, polymersics, aluminium, scrap metal and electronics; all of which provide a good foundation for recycling PV modules, inverters, racking systems and other components of a PV system. Like many other durable products and construction materials, solar equipment can last for decades, particularly with proper maintenance. In some cases, PV modules can be reused or refurbished to have a “second life” generating electricity. The other components of solar systems can also be handled responsibly. Inverters can be recycled as e-waste and racking equipment can be reutilized with newer technology or recycled like other metals. SEIA advises manufacturers, system and project owners to consider reuse, refurbishment and/or recycling of first end-of-life PV modules, inverters, racking equipment and associated components when possible (Solar Energy Industries Association, 2020). Also, the European Commission (EC) recommends to recycling and reuse solar systems, even if at the moment the volume of end-of-life products is still low (Bobba et al., 2020).

Other mitigation measures should be put forward by the EU to improving the materials supply chain and the EU’s industrial competitiveness of renewable technologies such as: diversifying the materials supply, promoting research and innovation, sustaining the long-term investments for new mining and refining activities, boosting recycling business and strengthening downstream manufacturing in the EU. Among these measures, research and development efforts to reduce materials use through substitution and increased materials efficiencies will allow the industry to produce and store more renewable energy with less raw materials. Logistic, technological and knowledge efforts will be necessary in the sector to enhance reuse of components and improve collection and recycling of technologies to produce high quality secondary raw materials. The research, development and innovation strategy needs also to consider the improvement of perovskite solar cells or other compounds as substitutes for silicon in solar cells and bringing these concepts to higher technology readiness levels (Bobba et al., 2020).
5.3.1 Overview on aluminium sector
An overview about the aluminium demand and production process is now presented as it is one of the main materials used in ground mount racking systems. It is useful in order to understand the future role of aluminium, even if today it is not yet a critical raw material.

5.3.1.1 Demand
Aluminium is considered a strategic resource in manufacturing industry since it embeds many desirable characteristics, as listed in Figure 35. Global demand for primary aluminium is expected to grow by 50 percent by 2050, approaching 107.8 million tonnes. The most rapid growth will be in Asian countries, although Europe is currently the second-largest user of primary aluminium and is likely to remain so until at least 2050. For the coming decades, Europe will need approximately 9 million tonnes of primary aluminium each year.

Importantly, China is responsible for more than half of all global primary aluminium demand; this is expected to peak around 2035 at almost 50 million tonnes. Subsequently, demand growth in China is expected to stabilise or possibly slightly decline. By 2050, China is expected to have 40 percent share of primary aluminium demand, as shown in Figure 36.

Regarding the generation of greenhouse gas (GHG) emissions, the continuous increase of the recycled production to meet the European demand during the period 2020 - 2050 would avoid between 880 and 1500 million tons of CO₂-equivalent emissions during this period. This is in comparison to a scenario where the recycled production would remain constant (i.e. at current level) until 2050 and the additional demand for metal would be supplied by imports of primary
aluminium from third countries (European Aluminum Association (EAA), 2019). More than 90% of this footprint is from primary production processes, while primary aluminium currently makes up around 70% of annual metal demand. Today, there is still a big difference between the carbon footprint of European and Chinese production of aluminium, as expressed in Figure 37. Chinese carbon intensity is on average about three times the European one.

![Figure 37 Carbon intensity for kg of aluminium produced from](European Aluminum Association (EAA), 2019)

The reduction of direct emissions will depend greatly on the ability of the industry to:

1. Optimize production process efficiency;
2. Capture the CO₂ emissions from the production process;
3. Replace carbon anodes with low-carbon anode technologies.

Today, 75 percent of all aluminium ever produced remains in use. Europe is already the world’s greatest per-capita recycler, as expressed in Figure 38. Over half of all the aluminium currently produced in the European Union originates from recycled aluminium put on the market by refiners and remelters and this is an increasing trend. Yet there is more that can be done to build the circular economy of the future (European Aluminum Association (EAA), 2019). In fact, even with further improvements in collection, considering the long lifetimes of durable aluminium products, a growing population and a broader range of applications mean, there will not be enough post-consumer scrap to meet this demand alone and primary metal will still need to be produced until at least the second half of the century (International Aluminium Institute, 2021). To improve the circularity of aluminium products, the scrap flows need to be better sorted, preferably by specific product and by alloy family in order to satisfy future demands. It is expected that today’s demand for ingots of casting alloys may not remain constant, mainly due to the introduction of electric vehicles. In addition, there will be greater demand for product-to-product recycling. Extra investment in innovative sorting technologies (x-ray, laser, robot, etc.) is considered essential (European Aluminum Association (EAA), 2019).
Opportunities for more productive use of materials has a role to play in the overall decarbonisation challenge, through reducing emission and energy savings. According to the recycling scenario of the study, up to 56% of the carbon dioxide emissions per year caused by the production of steel, plastics, aluminium and cement can be avoided in 2050 if CE strategies are applied, as in Figure 39 (Eddy, 2019). This is particularly true for aluminium production, as highlighted in the material recirculation step (i.e., most of the 178 million tonnes saved comes from aluminium).

5.3.1.2 Production processes
The production of primary aluminium begins with the mining of bauxite ores. Around 5.5 tons of bauxite are required on average to produce one ton of aluminium. The mining process itself is relatively low emitting (compared to other processes in the value chain) representing one
quarter of a percent of total sector emissions, mainly from mobile equipment. Transport of bauxite (and all other intermediate products) amounts to around 3% of emissions. Alumina is extracted from bauxite in the Bayer process, which requires energy in the form of heat and steam, as well as ancillary materials such as sodium hydroxide, all of which come with a carbon footprint. Alumina production represents just under 20% of all sector emissions. The smelting of aluminium currently takes the form of a reduction-oxidation reaction between the raw material, alumina, and carbon anodes, in which three electrons are provided to each aluminium ion to reduce it to its metal form, while the carbon atoms of the anodes are oxidized to form carbon dioxide, according to the reaction:

$$2 \text{Al}_2\text{O}_3 + 3 \text{C} \rightarrow 4 \text{Al} + 3 \text{CO}_2$$

*Equation 5 Smelting of aluminium: reduction-oxidation reaction*

Thus, direct carbon dioxide emissions from this process are proportional to the production of aluminium. This electro-chemical process (electrolysis) requires electricity, carbon anodes and ancillary products, such as cryolite (sodium aluminium fluoride), as well as thermal energy to cast liquid metal into solid products. Electricity-related emissions dominate the 75% of sectoral emissions that smelting represents. And yet, this is the source with the greatest variation across the industry, depending on the smelter power mix – historically dominated by hydropower, but now increasingly by coal and gas combustion. Figure 40 shows five emission intensities considering five power mixes.

Recycling on the other hand, requires much less energy – essentially only that needed to melt the aluminium scrap. It also has no need to reduce aluminium oxide to aluminium metal and so emissions of carbon dioxide from the chemical reaction mentioned above are eliminated (International Aluminium Institute, 2021).

![Figure 40 World average 2018 and power mix cradle-to-gate emissions intensity of primary aluminium from (International Aluminium Institute, 2021)](image)

There are three broad areas that have the potential to contribute to this delinking of growth and emissions, each with distinct innovation, policy and financial drivers, barriers, costs and materiality. The three emission reduction pathways are:
1. Electricity decarbonization;
2. Direct emissions reduction;

The third pathway exploits the high recyclability of aluminium with small loss of properties. This unique benefit makes it an enabling material for circular economies. Current end-of-life (post-consumer) recycling (collection) rates for the metal in its largest market segments (i.e., transport, building and construction) are above 90%. However, these applications tend to have long lifetimes (taking advantage of aluminium’s durability) and so scrap availability is as much constrained by product life as it is by recycling rates. When this metal is not retained in the economy, it must be replaced by primary aluminium. Primary production today has a greenhouse gas emissions profile on average twenty times higher than recovery of metal from scrap. This transformation of the supply of aluminium requires action from all actors along the value chain - including consumers - and policy frameworks that incentivize circularity with investments in scrap recycling capacity, design for disassembly/recycling and novel metal/material joining technologies (International Aluminium Institute, 2021).

5.4 PV racking system
For the development of the thesis, the focus is on the racking system for ground mounted solar farms. In fact, solar farms are usually mounted directly on the ground since they are located in desert places, e.g., Arabian Peninsula. Additionally, the ground mounting structure well fits the requirement for the green profit model, because it is a real mechanical product with long life span and, in a general sense, it can be considered as a remanufacturable item.

In a preliminary discussion, TotalEnergies’ tutors, the supervisor professors and the author discussed about the possibility to select PV panels as the topic of the case study. In fact, the International Renewable Energy Agency (IRENA) estimated that solar panel waste amounted to around 250000 tons in 2016 and could reach a staggering 78 million tons by 2050. The value of recycled waste material could exceed 15$ billion by 2050. It could either be sold on the international markets or used to produce 2 billion new solar panels, securing future raw material supply and creating a circular economy (Weckend et al., 2016). Additionally, waste management firm Veolia launched Europe’s first solar recycling plant in France in 2017, ramping up its capacity from 1400 metric tons of material, in the first year, to 4000 metric tons by 2021. The plant recovers nearly 96% of the materials from a panel. Unfortunately, today it is not possible to image remanufacturing as a feasible EoL strategy for PV panels since some technological constraints still are present. In fact, recycling is the usual loop followed by PV panels at the end of their life, due to their inner structure (most of the time the panels’ components are glued together making the remanufacturing an infeasible technique).

Therefore, the focus of the thesis is on the ground mounting structure as they can be considered as a good match with the green profit model and since their end-of-life management is of the upmost relevance, together with the one of PV panels. At the moment, TotalEnergies does not produce this infrastructure, but it buys the structure from supplier (actually TotalEnergies outsources even the purchasing activity of this structure). For this reason, the data useful for feeding the model comes from different sources: TotalEnergies, websites of manufacturers, reports and scientific paper available in literature. In a general sense, for the company it is important to evaluate the economic and environmental

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performance of this supporting infrastructure since it can contribute to achieve the long-term strategy recently defined by TotalEnergies.

Table 9 Actors within the case study

<table>
<thead>
<tr>
<th>Actor</th>
<th>Brief description</th>
</tr>
</thead>
<tbody>
<tr>
<td>TotalEnergies as purchaser of solar systems</td>
<td>The company targets challenging goals looking at the economic, environmental and social impact of its operations.</td>
</tr>
<tr>
<td>Solar panel suppliers</td>
<td>The PV panel supplier is putting effort in designing more and more recyclable panels, to retain the critical raw materials contained in them.</td>
</tr>
<tr>
<td>Racking system suppliers</td>
<td>The mounting system supplier envisages recycling and remanufacturing as circular strategies for the end-of-life structures, considering also the implementation of a takeback system.</td>
</tr>
<tr>
<td>Distributors</td>
<td>The distributors are keen to diversify their range of products to target new customers' segments with low environmental impact items.</td>
</tr>
<tr>
<td>Metal extruders</td>
<td>Metal extruders are usually in charge of producing basic metal products for racking system suppliers. They face high volatility in raw material prices so they are willing to gain some of the advantages of CE, especially considering circular loops.</td>
</tr>
<tr>
<td>Government’s agencies</td>
<td>There are incentives provided by countries which give support for the solar industry and the adoption of circular strategies.</td>
</tr>
<tr>
<td>Public</td>
<td>The public opinion concerning the use of alternative energy sources, the protection of the environment and the self-sufficiency from fossil fuels has a big impact on the energy industry.</td>
</tr>
</tbody>
</table>

A photovoltaic system consists of three main components: the solar modules (i.e., PV panels), the inverter(s), and the racking and other balance of system equipment. The balance of system is the term used to refer to all the other components in the PV installation besides the modules and inverters. The BOS depends on the type of application and local conditions and includes the structure to support the modules and the installation hardware, batteries to store and deliver energy during load periods, as well as inverters might be necessary if the system is connected to a network that operates with alternate current (AC). Cables to interconnect modules and arrays to batteries are also part of the BOS. Batteries have emission impacts throughout their life cycle and potential disposal concerns at their end of life. Within the BOS, the mounting structure represents the physical anchoring of PV panels to the ground or the roof, also permitting the connection to the electrical grid through inverters and cables. The case study concerns the ground mounted structure displayed in Figure 41 and Figure 42.
5.4.1 Breakdown of balance of systems costs
The balance of system costs can be broken down into three broad categories: non-module hardware costs, installation costs, and soft costs. These three categories can be broken down in more detailed sub-categories, as now explained.

Non-module hardware costs
- Cabling: all direct current (DC) components, such as cables, connectors and combiner boxes and all AC low voltage components, such as cables, connectors and combiner boxes;
- Racking and mounting: complete mounting system including ramming profiles, foundations and all material for assembling. All material necessary for mounting the inverter and all type of combiner boxes;
- Safety and security: fences, camera and security system, all equipment fixed installed as theft and/or fire protection;
- Grid connection: all medium voltage cables and connectors, switch gears and control boards, transformers and transformer stations, substation and housing;
- Monitoring and control: monitoring system, meteorological system (e.g., irradiation and temperature sensor), supervisory control and data system.

Installation costs
- Mechanical installation (construction): access and internal roads, preparation for cable routing (e.g., cable trench, cable trunking system), installation of mounting/racking system, installation of solar modules and inverters, installation of grid connection components, uploading and transport of components/equipment;
- Electrical installation: DC installation (module interconnection and DC cabling), AC medium voltage installation, installation of monitoring and control system, electrical tests (e.g., DC string measurement);
- Inspection (construction supervision): construction supervision, health and safety inspections.

Soft costs
- Incentive application: all costs related to compliance to benefit from support policies;
- Permitting: all costs for permits necessary for developing, construction and operation, all costs related to environmental regulations;
- System design: costs for ecological surveys or structural analysis, costs for surveyors, costs for conceptual and detailed design, costs for preparation of documentation;
- Customer acquisition: costs for project rights, any type of provision paid to get project and/or off-take agreements in place;
- Financing costs: all financing costs necessary for development and construction of PV system, such as costs for construction finance;
- Margin: margin for engineering, procurement and construction (EPC) company and/or for project developer for redevelopment and construction of PV system includes profit, wages, finance, customer service, legal, human resources, rent, office supplies, purchased corporate professional services and vehicle fees.

Figure 43 shows a detailed breakdown of costs considering hardware costs (i.e., module, inverter and BOS), installation costs and soft costs. The results are divided by country and the reference year is 2019. Among the numerous countries, the costs of modules and racking and mounting represents the bigger cost items when building a utility PV plant. The overall cost strongly varies considering different locations, as an example Russian Federation is more than three times more expensive than India.

![Figure 43 Detailed breakdown of utility-scale PV total installed costs by country from (IRENA, 2020)](image)

Looking at the timeline, the costs for electricity generated from new solar PV farms has fallen by 82% since 2010. The levelized cost of energy generated by large scale solar plants is around 0.068$/kWh, compared to 0.378$/kWh ten years ago. However, what is interesting to see is that these cost reductions were led by hardware components, with modules and inverters accounting for 62% of the global weighted-average total installed cost decline between 2010 and 2019. Balance of systems costs are another contributor to the declining global weighted-average total installed costs with 13% of the global reduction coming from
lower installation costs, 7% from racking, 3% from other BOS hardware (e.g., cables, junction boxes, etc.) and 15% from a range of smaller categories.

Taking a closer look at the data obtained from IRENA (IRENA, 2020), it is possible to draw the next conclusions:

- **Although modules on average mean 30% of total installation costs ($357.9/kW), in some countries these prices might be quite different. In South Africa for instance, on average these costs may reach up to $557/kW which would account to 42.2% of total plant costs;**
- **Installation costs might also see an important deviation from the average depending on the country. Japan has the highest mechanical installation costs ($456.2/kW and 22% of costs) which is more than double the average costs worldwide ($119/kW, 10% of plant’s costs). On the other side of the balance, Indonesia’s mechanical and electrical installation costs only sum up to $41.5/kW and 3.6% of total costs of the plant in comparison to a four times world average of $187.7/kW, 15.8% of costs. This sheds light on Indonesia’s low labor costs;**
- **The margin costs between countries greatly varies, which might go from $260.9/kW in the case of Mexico to as little as $25.6/kW in Indonesia being the world average $132.9/kW.**

The global capacity weighted-average total installed cost of projects commissioned in 2019 was $995/kW (18% lower than in 2018 and 79% lower than in 2010). The total installed cost reductions are related to various factors. Improved manufacturing processes, reduced labour costs and enhanced module efficiency (i.e., introduction of new technologies) are the key drivers of lower module costs. In addition, as project developers gain more experience and supply chain structures continue to develop in more and more markets, declining BOS costs have followed. This has led to an increased number of markets where PV systems are achieving competitive cost structures and resulted in falling global weighted average total installed costs. In 2019, significant total installed cost reductions have occurred across all the major markets such as China, India, Japan, Republic of Korea and the United States (IRENA, 2020). In a general sense, solar has been the renewable energy with the greatest cost reduction of the last decade. The reasons for this can be summarized mainly in competitive pressures, greater installer experience, the spread of best practice installation, module efficiency improvements and digitalization.

5.4.2 **Supplier’s ground mount structure**

Considering the information provided by TotalEnergies and the supplier, the design of the structure is detailed in Figure 44 and Figure 45. 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 on the open area easily. The structure can withstand a maximum of 45 m/s wind speed and a snow load of 1.4 kN/m². The material is Al 6005 – T5 and the expected service life is 25 years.

The supplier is a professional company, engaged in research, manufacturing and marketing of aluminium products for solar mounting system, curtain wall system and other architectural constructions. They have been committed to providing high-level quality products and related technical support service. They provide products with advanced design concepts and good
quality, which not only meet personalized demands of the domestic customers in China, but also are exported to many other countries all over the world. To drive continued success, the supplier invests heavily in the fields of products research, support service system and partner relationship. The company also improves service levels for customers to provide the most professional project solution including a full range of design and installation support services. The company is always a long-term reliable partner with a reputation in the related aluminium sector.

Analysing more in detail the supply chain of the ground mount structures, it is possible that the infrastructures or components are not produced in-house but, following the technical drawings, aluminium extruders manufacture them. So once the products are ready, the supplier sells them to distributors or directly to the final customers all around the world. Finally, customers (e.g., TotalEnergies) can buy the roof or ground mount structures. It is straightforward to understand the complexity of the supply chain for this product since it has a multi-layer structure.

Figure 44 Design of the mounting structure: components
Considering the information related to the case study, the article written by Albaek et al. (Albæk et al., 2020) is particularly relevant for identifying some design guidelines strictly related to the object under analysis and that can be included in it:

- **Environmental profile:** design using recyclable materials, use durable and robust components and materials, minimize the number of different incompatible or dissimilar materials;
- **Re-workability of components and reversibility of assembly/disassembly process:** design in modular construction, make it easy to dismantle the product non-destructively, make it easy to inspect/clean the product and components;
- **Reparability of materials and material recyclability:** minimize the number of different incompatible or dissimilar materials.

### 5.4.3 Overview on competitors

In order to highlight the great innovativeness in the photovoltaic sector, in this section some manufacturers of mounting structures are presented. The description of the players is based mainly on what can be inferred analysing the websites.

- **Wind&Sun – Powering the future:** it is a UK based manufacturing company. Among the ground mounts, the PVMAX ground-mount kits are suitable for mounting to concrete strip foundations and are designed for mounting 2 rows of PV panels with 11 modules each. It is designed for the following maximum admissible loads: wind load 28.0 m/s and snow load of 2.00 kN/m². It is made of steel with a Magnelis® ZM430 coating. The fasteners are made of stainless steel. Magnelis® is an innovative Zinc based composite coating modified by addition of 3.5% Aluminium and 3% Magnesium. It is suitable for protection against corrosion in harsh environment. Otherwise, it is possible to choose galvanised steel;
• K2 Systems: it is a Germany based manufacturer with a global network of local sales partners. The A-rack and P-rack systems are suitable for almost all module types and floors and can be elevated of 15°, 20° or 25°. They are usually mounted on concrete foundations; therefore, no screw or pile foundation is required;

• Tranceria Attrezzeria: it is an Italian company. It produces a solution to improve the price/performance ratio for large photovoltaics systems on the ground or on a flat terrace through the single polar axis TATM1. The product is based on the movement of the modules on a single axis north-south automatically tracking the movement east-west of the sun during the day by solar function. Thanks to the new generation of back-tracking, it controls the possibility of shading a string of panels against the adjacent ones, allowing to reduce the inter-spacing between the various strings, achieving a significant reduction in the use of the land area. The materials used for this structure are aluminium, stainless steel and zinc coated steel. The TATM1 tracker has a 20% higher production index than a stationary tracker;
• Sun-Age PV mounting systems: the company is based in Italy. One of its more innovative products is the mono-axial ground tracker. Mono-axial system consisting of one row of vertical modules, for tables from 18 to 22 modules. The system is designed to adjust to the annual tilt of the installation area. The movement of the modules is operated by an electric motor in low voltage that allows the adjustment of the inclination to be chosen, with re-entry in horizontal at night or in case of windiness exceeding the optimal values of the installation area. The structure uses the international patent for fixing to the ground through cages filled with inert material locally sourced; this facilitates installation and reduces logistics, organizational and special equipment costs. The plant is removable and totally reusable;

![Figure 49 Mono-axial ground tracker by Sun-Age](image)

• Sunsystems: it an Italian company. SunNet Ground is a steel cable-made mounting system for ground photovoltaic plants. Steel wire ropes are anchored at the extremities by anchorages that offer an easy way to tension steel wire ropes. Easels are anchored at the ground and keep steel cables lifted at the desired height. Photovoltaic panels are hooked on the steel wire ropes by special hook that speed up the installation. Both structures and wire ropes are made with hot dip galvanized steel, while screws in stainless steel;

![Figure 50 SunNet Ground](image)

• Mounting Systems: it is a German company. For large solar parks, Sigma Tracker offers an optimal cost-benefit ratio. The system is especially designed for the use of bifacial modules and therefore guarantees minimal rear side shading. The Sigma Tracker was the first tracking system worldwide to offer self-locking properties on each individual system post and is equipped exclusively with standard industrial components
in the drive and control. The structure is made of steel S 355/S 350 GD, while small parts in galvanized steel, stainless steel, geomet-coated steel or extruded aluminum (EN AW 6063 T66).

Figure 51 Sigma Tracker by Mounting Systems

Figure 52 Detail about motor with integrated gearbox and chain drive
6 Application of the framework to the case study
The chapter describes the collected data to feed the model, thanks to the collaboration with TotalEnergies and the supplier of ground mount structures, and the application of the framework to the case study. All the data presented represent a kind of average of the current market condition, so no confidential information is disclosed.

6.1 Data collection
In the following subsections the data useful to compute C-indicators and launch the green profit model are stated. Data concern design of the product, remanufacturing processes, economic information, environmental impact assessment and market insights.

6.1.1 Product design information
The analysis is based on a building block of 20 PV panels, displayed in 2 rows of 10 panels each and producing 8 kWp (1 panel provides 400 Wp), due to the specific nature of the case study since it concerns PV ground mount structures used in solar plants. In fact, respect to the case study about smartphones used to validate the GPM in the article (Kwak & Kim, 2017), within a solar farm the identification of a unitary object is more blurry. Therefore, the idea is to consider a building block of 8 kWp structure made of 20 PV panels as equivalent unitary product. So, considering multiple structures, it is possible to imagine small, medium and big plant of several MWp of capacity. To generate the technical drawing of the ground mounting infrastructure, some preliminary information is stated:

- PV panel size: 1690 x 1046 x 40 mm;
- Wind speed: 45 m/s;
- Snow load: 40 cm;
- Ground clearance: 500 mm;
- Tilt angle: fixed 30°.

Therefore, the technical drawings are defined and showed in the Figure 53, Figure 54 and Figure 55. The full version of technical drawings is reported in 9.3.

![Figure 53 Ground mount structure: rear view](image-url)
Additionally, to give a complete overview of the components of the structure, the bill of materials is hereafter presented (Figure 56 and Figure 57).
<table>
<thead>
<tr>
<th>Photo</th>
<th>Item</th>
<th>Item No.</th>
<th>Spec.</th>
<th>Material</th>
<th>Price/PC (USD)</th>
<th>Qty/Array (PCS)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Rail</td>
<td>YS-19</td>
<td>2900mm</td>
<td>6005-T5</td>
<td>$15.83</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Rail</td>
<td>YS-19</td>
<td>2500mm</td>
<td>6005-T5</td>
<td>$13.65</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Rail Splice Kit</td>
<td>YS-20-Z</td>
<td>200mm</td>
<td>6005-T5 +SUS304</td>
<td>$1.50</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td>Fixing Clamp Kit</td>
<td>YS-FC-01Y</td>
<td>40mm</td>
<td>6005-T5 +SUS304</td>
<td>$0.30</td>
<td>40</td>
</tr>
<tr>
<td></td>
<td>End Clamp Kit</td>
<td>YS-EC1-40Y</td>
<td>L=40mm H=40mm</td>
<td>6005-T5 +SUS304</td>
<td>$0.32</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Mid Clamp Kit</td>
<td>YS-MC1-40Y</td>
<td>L=40mm H=40mm</td>
<td>6005-T5 +SUS304</td>
<td>$0.35</td>
<td>36</td>
</tr>
<tr>
<td></td>
<td>Support Rack Kit</td>
<td>YS-12</td>
<td>2950mm</td>
<td>6005-T5 +SUS304</td>
<td>$23.41</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Al Tube</td>
<td>YS-08</td>
<td>1660mm</td>
<td>6005-T5</td>
<td>$7.72</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>YS-08</td>
<td>420mm</td>
<td>6005-T5</td>
<td>$1.95</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Hex Bolt Kit</td>
<td>YS-OM10-L75</td>
<td>M10X75</td>
<td>SUS304</td>
<td>$0.31</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Diagonal Brace</td>
<td>YS-08</td>
<td>1415mm</td>
<td>6005-T5</td>
<td>$6.58</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Leg Base</td>
<td>YS-11</td>
<td>130mm</td>
<td>6005-T5</td>
<td>$2.59</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Leg Base</td>
<td>YS-11</td>
<td>100mm</td>
<td>6005-T5</td>
<td>$2.03</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Corrugated Gasket Kit</td>
<td>YS-LS-07</td>
<td>L=40mm M10*80mm</td>
<td>6005-T5 +SUS304</td>
<td>$0.41</td>
<td>15</td>
</tr>
</tbody>
</table>

*Figure 56 Bill of materials: part 1*
The ground screws are made of Q235 material. It is an anti-corrosion steel with hot dip galvanization treatment and compatible with screwing machine on open areas.

6.1.2 Remanufacturing process of the product
The manufacturing of the PV racking system is based on several steps, such as extrusion and punching of the aluminium profile, then it undergoes a process of anodization to protect the surface from corrosion. Ground screws are made of steel, which is hot galvanized to protect from corrosion while clamps and screws follow a similar path of the aluminium profiles, Figure 59 summarizes the production flow graphically. The supplier produces only fixed tilt structure even if in the market, as shown in the previous section, for large systems also a one-axis tracking mechanism is deployed, which helps solar panels follow the sun as it moves from east to west. Tracking requires mechanical parts like motors and bearings (Solar Photovoltaic Manufacturing Basics, 2021). Power electronics for PV modules, including power optimizers and inverters, are assembled on electronic circuit boards. This hardware converts direct current electricity, which is what a solar panel generates, to alternating current electricity, which the electrical grid uses (Solar Photovoltaic Manufacturing Basics, 2021).

Considering remanufacturing, at the moment it is not performed by the supplier, therefore the green profit model will help in identifying the feasibility of this strategy. Usually, the remanufacturing activity is based on 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 used components. The T matrix within the model, that links operations with sub-assemblies, focuses on disassembly, reprocessing and reassembly operations (as illustrated in Figure 58).

From an operational point of view, reconditioning represents the most critical part. In fact, depending on the quality of the takeback products, different operations will be deployed to turn the product to the original functionality. The aluminium structure can be scratched or corroded in some areas so numerous operations will be done on the items forming the structure (e.g., polishing the surface or anodization of the components). For ground screws, it can be more difficult since the corrosion agents are even more aggressive, considering also the usual life span of a solar installation of 25 years. Also here, an ad hoc sequence of remanufacturing operations has to be studied on the techno-chemical level to bring the components to the “as new” condition. Additionally, remanufacturing is usually an expensive process due to the difficulty of the tasks and the demand for manual labour, especially in the sorting activity (Tolio et al., 2017). In a general sense, aluminium represents a suitable material also for advanced
manufacturing processes, e.g., additive repair and refurbishment. In fact, material combinations that have been successfully realised in additive repair and refurbishment include, for instance, nickel-based alloys applied to stainless steel and the combination of different aluminium alloys (Ganter et al., 2021). However, in order to select a suitable manufacturing process for refurbishment, the characteristics of the component must be compared with the restrictions of the various processes, e.g., whether the size of the component allows it to be processed within the building space of an laser power bed fusion system (Ganter et al., 2021). The use of additive refurbishment as a maintenance strategy can be suitable for components wherein one area is highly stressed and therefore fails much earlier than other areas. In addition, refurbishment can be predicted during product development when it is known that the state of the art or the requirements for a particular component area change between product generations (Ganter et al., 2021).

<table>
<thead>
<tr>
<th>Transition matrix</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
<tr>
<td>Prod_R</td>
</tr>
<tr>
<td>Prod_Q1</td>
</tr>
<tr>
<td>Prod_Q2</td>
</tr>
<tr>
<td>Subassy1_R</td>
</tr>
<tr>
<td>Subassy1_W</td>
</tr>
<tr>
<td>Subassy1_N</td>
</tr>
<tr>
<td>Part11_R</td>
</tr>
<tr>
<td>Part11_R</td>
</tr>
<tr>
<td>Part13_R</td>
</tr>
<tr>
<td>Part2_R</td>
</tr>
<tr>
<td>Part3_R</td>
</tr>
<tr>
<td>Part11_W</td>
</tr>
<tr>
<td>Part12_W</td>
</tr>
<tr>
<td>Part13_W</td>
</tr>
<tr>
<td>Part2_W</td>
</tr>
<tr>
<td>Part3_W</td>
</tr>
<tr>
<td>Part11_N</td>
</tr>
<tr>
<td>Part12_N</td>
</tr>
<tr>
<td>Part13_N</td>
</tr>
<tr>
<td>Part2_N</td>
</tr>
<tr>
<td>Part3_N</td>
</tr>
</tbody>
</table>

**Figure 58 Transition matrix**

Since TotalEnergies is not the manufacturing company of these structures, the data about costs and environmental impacts of the remanufacturing processes are hypothesized taking advantage some exchanges with supplier, reports and existing literature. The unit of measure of environmental impact is kg of CO$_2$ equivalent, also called greenhouse gas (GHG) emissions. GHG refers to the atmospheric gases that can absorb the solar radiation reflected by the ground that can in turn release some additional gases. The main components of GHG include CO$_2$, CO, NOx, and CH$_4$, and these gases can warm the Earth's surface. The contribution of each gas to the potential greenhouse effect varies. The equivalent factor was used to calculate the potential value of the greenhouse effect, that is, one of the gases is used as a benchmark according to the degree of its influence on the greenhouse effect. Its potential influence is assigned to a value of unity. The equivalent factor of other gases is the ratio of its potential influence to the benchmark gas. Correspondingly, CO$_2$ is considered as the benchmark gas and its potential influence is also assigned to a value of unity, as shown in Table 10.
Three aspects mainly contribute to the carbon emissions in the remanufacturing process of a used product. They are the energy consumption, material consumption, and wastes disposal of the remanufacturing process (Wang et al., 2020).

The usual steps followed by an object within a remanufacturing plant are the following ones. The object is disassembled into several components and parts, the components and parts are carefully inspected along their disassembly process. It is necessary to consider detection results, costs, and the actual conditions together as a whole, to determine the overall replacement, directly utilize or further dismantling repair of the take-back product. Besides, the purpose of the cleaning process is to make the components/parts appearance satisfy the requirements of cleanliness of the remanufacturing process. Subsequently, the disassembled and cleaned components/parts are carefully checked by their surface dimension and performance status, to decide either repair or discard the corresponding sub-assembly components and parts. More importantly, the quality of the repairing process has determined the reusability and performance of the disassembled components and parts. Repair methods of the remanufacturing process, such as brush electroplating, spraying and laser repairing are based on the repair requirement of material, thickness, strength, and durability, etc. of the used object. Besides, the repaired components and parts are reassembled (on the reassembling process) into a qualified remanufactured product in accordance with the technical requirements and product precision. Finally, the remanufactured product is tested with respect to its performance (Wang et al., 2020).

![Figure 59 Production flow of the new mounting structure](image)

Taking inspiration from the paper of Shi et al. (Shi et al., 2019), costs \( (c_j) \) and environmental impacts \( (e_j) \) of remanufacturing operations are shown in Table 11.
In the case where also “non-working” components face remanufacturing, the input data vary as described in Table 12.

<table>
<thead>
<tr>
<th>Component</th>
<th>Code</th>
<th>Material</th>
<th>Cost ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ground screw</td>
<td>YS-GS-03</td>
<td>Q235 Hot Galvanized</td>
<td>165</td>
</tr>
<tr>
<td>Leg Base</td>
<td>YS-11</td>
<td>6005-T5</td>
<td>23,1</td>
</tr>
<tr>
<td>Support rack kit</td>
<td>YS-12</td>
<td>6005-T5 + SUS304</td>
<td>117,05</td>
</tr>
<tr>
<td>Al tube</td>
<td>YS-08</td>
<td>6005-T5</td>
<td>48,35</td>
</tr>
<tr>
<td>Diagonal brace</td>
<td>YS-08</td>
<td>6005-T5</td>
<td>32,9</td>
</tr>
<tr>
<td>Rail</td>
<td>YS-19</td>
<td>6005-T6</td>
<td>235,84</td>
</tr>
<tr>
<td>Fixing clamp kit</td>
<td>YS-FC-01Y</td>
<td>6005-T5 + SUS304</td>
<td>12</td>
</tr>
<tr>
<td>Rail splice kit</td>
<td>YS-20-Z</td>
<td>6005-T5 + SUS305</td>
<td>18</td>
</tr>
<tr>
<td>End clamp kit</td>
<td>YS-EC1-40Y</td>
<td>6005-T5 + SUS306</td>
<td>2,56</td>
</tr>
<tr>
<td>Mid clamp kit</td>
<td>YS-MC1-40Y</td>
<td>6005-T5 + SUS307</td>
<td>12,6</td>
</tr>
<tr>
<td>Hex bolt kit</td>
<td>YS-OM10-L75</td>
<td>SUS304</td>
<td>1,55</td>
</tr>
<tr>
<td>Corrugated gasket kit</td>
<td>YS-LS-07</td>
<td>6005-T5 + SUS304</td>
<td>6,15</td>
</tr>
<tr>
<td>Hex bolt kit</td>
<td>YS-LS-05</td>
<td>SUS304</td>
<td>8,6</td>
</tr>
</tbody>
</table>

Also, the cost of transportation ($c^1_k$) is assumed to be of 200$, considering ocean freight and insurance from Jebel Ali Port Dubai (UAE) to Xiamen (China) and the environmental impact ($e^1_k$) is 50 kg CO2 equivalent. The computation is based on the data from the International Chamber of Shipping (Environmental Performance: Comparison of CO2 Emissions by Different Modes of Transport, 2021).

6.1.4 Environmental impact perspective
The computation of the global warming potential (GWP) is based on the amount of material used in each component times the mass environmental impact specific to the different
materials used. The same computation is performed for the recycling impact. The results of this computation are shown in Table 14. The mass environmental impact factors are derived from reports of World Aluminium (International Aluminium Institute, 2021) and World Steel (“Climate Change and the Production of Iron and Steel,” 2021), so data are based on a global average (especially considering the power mix). Considering that the supplier is based in China, the figures presented in Table 14 are probably underestimated because the Chinese power mix is still pulled today by coal consumption.

<table>
<thead>
<tr>
<th>Material</th>
<th>Environmental impact (kg CO₂ eq./kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Virgin aluminium</td>
<td>11,2</td>
</tr>
<tr>
<td>Recycled aluminium</td>
<td>0,4</td>
</tr>
<tr>
<td>Virgin steel</td>
<td>1,85</td>
</tr>
<tr>
<td>Recycled steel</td>
<td>0,3</td>
</tr>
</tbody>
</table>

Table 14 Mass environmental impact: aluminium and steel

Then, a clustering considering the following object structure is performed: subassembly 1 is made of rail and diagonal brace, aluminium tubes and support rack kit, leg base; part 2 considers ground screw and part 3 the clamp kits. Finally, the residual life price is assumed to be the 10% of the original price. Table 15 summarises all these considerations.

<table>
<thead>
<tr>
<th>Part</th>
<th>Env. Imp. New (kg CO₂ eq.)</th>
<th>Env. Imp. Rec. (kg CO₂ eq.)</th>
<th>Residual life price ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>11</td>
<td>754,37</td>
<td>26,94</td>
<td>26,87</td>
</tr>
<tr>
<td>12</td>
<td>324,90</td>
<td>11,60</td>
<td>16,54</td>
</tr>
<tr>
<td>13</td>
<td>7,65</td>
<td>0,27</td>
<td>2,31</td>
</tr>
<tr>
<td>2</td>
<td>1054,50</td>
<td>171</td>
<td>16,50</td>
</tr>
<tr>
<td>3</td>
<td>23,67</td>
<td>1,27</td>
<td>4,52</td>
</tr>
</tbody>
</table>

Table 15 Environmental impact for new and recycled components and residual life prices

Furthermore, as indicated in (Rogkas et al., 2021), approximately 35% of the world’s steel is currently produced from scrap sources and the smelting processes of scrap steel during the production phase require about one third of the equivalent energy for making steel from virgin ore. Since smelting processes during steel recycling are expensive and energy-consuming, the direct reuse of steel materials without smelting could potentially reduce recycling.

6.1.5 Market information

The amount of product in the market that can be potentially collected is assumed to be equal to the one that the company can sell in the future (i.e., a condition of equilibrium is supposed). Considering 3000 \((A_k)\) structures available to collect implies to assume to handle a big solar farm of 24 MWp. The buyback prices \((P_k)\) are set to 150$ and 60$, depending on the quality of the takeback products. In order to consider in the model the competition with other players, data about customers’ preferences and competitors are introduced. The critical price for customers \((\bar{P})\) is 1000$ and the willingness to buy remanufactured products is included in the utility discount factor \((\beta)\), equal to 0.5. At the beginning, the competitor is assumed to produce only new product \((P_o)\) at 850$ each. All these information, together with the demand and takeback response functions, constraint the model for the following optimization procedure.
Practically, the model is an Excel sheet where all the useful data are stocked. The solver, respecting the limits imposed by the constraint cells, modifies the values within the decision cells and produces transient results that allow it to assess the goodness of the results obtained for the target cell. The decision variables are those that represent the decisions that can be taken to achieve the objective. In this case the variables are many and related to the takeback quantities and prices, production mix, pricing of new and reman products and operation decisions. The objective function represents the function that describes the objective. In this case, the objective function is represented by the maximization of the supplier profit. On the other hand, constraints are limitations on what the solver can do to solve the problem, in this case, integrity and positivity of some decision cells and the verification of the relationship among specific cells. The most useful constraints to be modified are the ones related to the environmental saving in kg of CO₂ equivalent and TotalEnergies’ incentives.

The solving technique is the nonlinear generalized reduced gradient (GRG) which is a method suitable for non-linear problems where the functions are sufficiently regular. The gradient method is a local optimisation technique, in fact, given a multidimensional mathematical function, the gradient method allows to follow the descent indicated by the gradient with the aim of finding a local minimum.

6.2 Application to the case study
Chapter 4 sets the background for the application of the above-described method to the case study provided by TotalEnergies. The use of a case study for the validation of the current thesis work represents added value for the experimentation of the tool with real data. A brief graphical representation of the application process is shown in Figure 60. In this section, along the application of the framework to the real case with the five steps, some remarks are stated to underline key aspects. In section 7, results are presented in detail while sensitivity analysis is performed in section 7.1.

![Figure 60 Application to the case study: TotalEnergies](image)
6.2.1 Selection

Scholars made a good effort in the last years in developing new and more effective indicators. Today, this great variety can be however confusing if practitioners are not guided by clear and logic taxonomy of indicators. In the current work, the classifications of (Kravchenko et al., 2019; Saidani et al., 2019) are used for the selection of KPI, mainly related to circularity.

C-indicators can be deployed as a first screening tool in the space of alternative design possibilities when designing for a circular economy. Also, following the scores and potential promising areas of improvement indicated by the C-indicators (e.g., a low score attributed to the "ease of disassembly" criteria), they can orient industrial practitioners to complementary and more in-depth design methods and tools (e.g., design for disassembly guidelines) to fill this gap during the design process (Saidani et al., 2020). This is the main advantage of using C-indicators also in real practice. At the same time, even if adopting CE strategies when developing products contribute a priori to enhance their sustainable performance, it remains of the utmost importance to evaluate systematically if an improvement of the circularity score leads to substantial sustainable benefits (Saidani et al., 2020).

For the selection of indicators, the web-based tool called circularity indicators advisor tool (CIA Tool) and developed by Michael Saidani was used. It was built following the taxonomy developed in (Michael Saidani, Yannou, et al., 2019), so the knowledge captured through this analysis and classification of C-indicators was synthesized in the web-based tool. It has also an Excel-based tool with macro enabled (i.e., it can be download following the instructions contained in (Circularity Indicators Advisor, 2021)) which is linked to the database of 55 sets of C-indicators classified according to the proposed taxonomy. Inside the tool it is possible to select among different options. For the scope of the current thesis, the following criteria are applied:

- CE implementation level: micro;
- CE loops: all the loops;
- CE perspective: actual and potential;
- Format of the CE assessment framework: computer based.

The rationale behind this selection strategy is that the case study is based on a real product so the focus is mainly on the micro level. C-indicators of the micro-level concern organization, products and consumers, otherwise meso-level indicators are related to symbiosis association and industrial parks (Saidani et al., 2019). Secondly, all the CE loops are considered since both reuse, 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. Taking advantage of this selection step and considering the actual computer-based indicators available, the number of eligible indicators was reduced from nineteen to five. Computer-based indicators are preferred to the ones based on formulas to compute since the first ones usually require a lower amount of data and their computation is more straightforward. Therefore, the following indicators satisfy all the four constraints:

- Material circularity indicator (MCI) (Material Circularity Indicator, 2021): a dynamic Excel spreadsheet tool that compute formulas as input information (e.g., lifespan of components, origin of feedstock materials and EoL management of after-use objects) are stated. It is a product-centric metric which combines multiple perspectives, such as
resource efficiency, material stocks and flows and product. It considers the amount of virgin feedstock, recycling efficiency and unrecoverable waste, while taking into account the time and intensity of product use. It measures the extent to which the linear flow has been minimized and the circular flow maximized;

- Circular economy indicator prototype (CEIP) (Cayzer et al., 2017): a questionnaire-based tool to score points for different phases of the product lifecycle according to the given answers. The result is shown as a product rating and spider web, which indicate the product score in relation to the total score in different phases of the product lifecycle. This indicator can provide an indication of improvement potential but does not indicate directly what product characteristics should be improved. It works better with tangible goods that are built from/assembled from other tangible goods where a comprehensive bill of materials is available (Janik & Ryszko, 2019);

- Circularity potential indicator (CPI) (Saidani et al., 2017): an indicator that uses a top-down approach and evaluates the product circularity based on 20 attributes within four aspects: circular product design, new business model, reverse cycles, and favourable system conditions. Each attribute can score up to five points, each building block can obtain a score of up to 25 and the total circularity score can reach 100. CPI aims at providing keys for improvement and monitoring the circularity of products and businesses practices;

- Circular pathfinder (CP) (ResCom, 2021): an online-based tool to be used during product development to find product strategies for improving circularity. The tool goes through questions relating to product type, product customer interactions, lifetime, and user needs and, eventually, suitable strategies are suggested. It comprises qualitative guidance to 8 suitable or optional circular pathways: prolong, upgrade, reuse, repair, refurbish, remanufacture, recycle, biodegrade;

- Circularity calculator (CC) (Circularity Calculator, 2021): the circularity calculator is used to assess the potential value captured by circular business models. It was developed by, with and for designers working on circular products. The tool provides an intuitive and visual way to grasp circularity, showing the flows of reuse, remanufacture and recycling. With a point-and-click dashboard, the circularity calculator represents a fast test for product’s design and business models.

Figure 61, Figure 63 and Figure 62 depict some graphical interfaces of described indicators.
S-indicators are not used within the current work since they are usually related to specific economic, environmental and/or social measures. The data collection for computing some S-indicators is difficult and it strongly depends on the case study’s industry. The information disclosed by these KPI is specific and, in order to have an overview on a case study, numerous indicators have to be used. As an overview, the main phases of the implementation of S-indicators are: the plan stage, data collecting and measuring, checking the performance results and define actions to improve product performance over time (Issa et al., 2015).

6.2.2 Analysis
Starting from the selection of C-indicators, for the purpose of the previously described case study five indicators are chosen: MCI, CEIP, CPI, CP and CC. As written in (Janik & Ryszko, 2019), all indicators except CP include the four core CE principles, i.e., reduce, reuse, recover and recycling, and strongly support the decision-making process. Also, all indicators provide a lifecycle perspective on the product and business model and are computer-based. At the same time, the data needed for feeding the circularity tools are available, while some other indicators
cannot be selected due to the complexity of the data requirements (e.g., Input-Output balance sheet and Resource duration indicator). Reports, scientific literature, data coming from TotalEnergies and supplier, author’s expertise constitute the main source of data for the computation of the five selected indicators.

Now, the five indicators are computed and the data used are justified. MCI focuses on the material dimension of the case study. Steel and aluminium are the main materials used and, as indicated in the state-of-the-art research, metals can be efficiently recycled. In the as-is condition, neither reused nor recycled materials are deployed; while after use about 50% of materials are recycled. The quality of the ground mount structures produces is medium, i.e., the actual lifespan of the structures and their functional units are about one and a half times the industry average. The final synthetic score of MCI is equal to 0.69.

Within CEIP, the information to provide are a mix of quantitative and qualitative ones. Some of the answers are given to the best knowledge and understanding of the author. 15 questions divided in 5 categorized (i.e., design, manufacturing, commercialization, in use, end of use) are necessary to fully run the indicator. Question 3 in the design/redesign section asks if a complete BoM is available for the product and if some critical raw materials are used. Of course, there is a BOM and no critical raw materials are utilized, even if aluminium can be a critical feedstock in future in terms of its availability on the market. For sure, recycling can strongly help in mitigating this problem. In the manufacturing section, it is assessed whether a complete bill of solid wastes is present for the manufacturing process. At the moment, it is present and up to 50% of solid waste is treated for reintroduction in the same manufacturing process (not in terms of energy). Going ahead to the distribution section, a product’s warranty of 3 years is offered. The engineering rationale behind warranty is the manufacturer’s choice to design for durability. In fact, if the producer applies some methods of the design for durability strategy, the warranty can be further extended without losing profit (since statistically the product will be long-lasting). In the “in use” section, it is assessed the possibility to repair the product. Today, the structure can be repaired with standard tools and a repair manual is available. In case of heavy damage to the structure (e.g., due to some extreme weather condition), the substitution of the product is mandatory. In the last section about end of use, question 13 asks if a take-back scheme is available for the ground mount structure. Today, there is not this type of scheme but for sure a formal recovery channel fosters the recovery and reutilization of the product’s materials. Overall, a product rating of 20% is reached, so the final product ranking is classified as “poor”. On the other hand, using some insights disclosed by CEIP, there is room for important improvements in all the five areas.

![Figure 64 CEIP: results](image)
The third indicator used is the circularity potential indicator (CPI) tool. The CPI aims at evaluating the circularity potential of industrial products during design, development or benchmarking phases. The CPI is computed through a guided questionnaire of twenty attributes impacting the circular economy performance of a product. The twenty attributes are based on a literature review and grouped in the four building blocks of the CE defined by the EMF. The first building block concerns circular product design and questions are mainly related to use of DfX practices and end-of-life sorting. The ground mount structure performs quite well in this area even if the modular design level and the material combination compatibility can be increased. In the second part about business model, new forms of collaboration between manufacturers and customers can be exploited, such as with partnership networks, sharing platforms and industrial symbiosis. Additionally, no rental or leasing schemes and take-back offers exist today. The next section concerns reverse cycles, i.e., recycle and reman. Now, these chances are not used so a shared interest among actors for a closed-loop supply chain has to be created. Finally, in the fourth and last part favorable system conditions are investigated. Even though the product conditions at the end of life are quite good (therefore there is a good residual value), there is not financial support, by government or environmental agencies, to foster CE incentives for the structure under analysis. In fact today no policy framework is proposed by institutions, in terms EPR (Extended Producer Responsibility), waste legislation concerning the product or mandatory percentage of reuse or recycling imposed. So, it is necessary to rethink incentives and pro-active attitude from companies to enhance the circular economy with customers. The score obtained by CPI is equal to 28.39 out of 100.

The fourth indicator used is the circular finder. This tool is quite basic and it provides a starting point in the ideation phase of a CE strategy. However, it is quite useful for the present case study since today none of the circular loops are used. Providing some general information already presented in sections 5 and 6.1, it is possible to obtain results from the indicator. Inside the tool, it is stated that the structure is long-lasting and that usually customers replace or discard it because of obsolescence and technological innovation. In fact, looking at innovativeness and competitiveness of solar industry, to extract maximum power from the sunlight, cutting-edge PV panels and mounting structures have to be deployed. The results highlight that upgrade, recycle and remanufacture can be suitable cycles to improve circularity. Therefore, design for remanufacturing can be a relevant design strategy because when the product has broken or degraded visually: its still functioning parts can be used for the production of new products, new product versions and/or for spare parts. Additionally, if it is
possible to collect the durable parts of the product, design for recycling can enable the recovery of the material value of these parts. Furthermore, using recycled materials in these parts helps to truly close material cycles.

The fifth and last indicator used for the preliminary assessment of the case study is the circular calculator. For the use of CC, some numerical data are required, specially: weight of components, costs of raw material and manufacturing processes, price of the finished product and end-of-life waste management information. It is straightforward to understand that the current business practice is linear (as depicted by Figure 67) so a poor circular performance is reached in terms of value capture, recycle content and reuse index.

To sum up, the takeaways that can be derived from the use of C-indicators are:

- To augment the reused and recycled quantity of the deployed materials (i.e., steel and aluminium);
- To extend the lifespan of product and its components, using durable and robust components and materials;
- To foster the recovery and reutilization of the product’s materials, creating new forms of collaboration between manufacturers and customers through formal recovery channel;
- To augment the use of renewable energy in the industrial processes;
- To increase the modularity at the design level;
- To rethink incentives and pro-active attitude from companies to enhance the circular economy practice;
- To foster awareness of environmental issues, sustainability and circularity.
6.2.3 Simulation

After the initial analysis performed by C-indicators, the green profit model becomes the chosen optimization model. Looking at the suggestion extracted from the use of indicators, it is possible to see how many of them are integrated in the GPM. In fact, the model considers recycling and remanufacturing as promising CE strategies for the current case study, therefore fostering the recovery and reutilization of takeback product’s materials. From a business model perspective also, the role of TotalEnergies is considered through an incentive mechanism between supplier and the customer company. In this way, the advantages disclosed from the application of some CE strategies satisfies both the supplier and the customer. Finally, the modularity at design level is introduced as described in section 6.1.1, considering the structure composed by 1 subassembly (of 3 parts) and further 2 parts. The modularity of the product is clear looking at the T matrix. To conclude, the green profit model fosters awareness of environmental issues and circularity just observing the output from it, indeed it is possible to reach profit while achieving significant savings in kg of CO₂ equivalent produced.

Considering the data already presented in section 6.1, the model is directly run. The objective function is the maximization of the profit of the manufacturer of the structures, while the two key constraints are:

- To satisfy the limit in terms of savings in kg CO₂ equivalent (δ), equal to 500000;
- To reach a minimum incentive threshold for TotalEnergies (α), equal to 125000 $.

The optimization results are presented in Table 16.

<table>
<thead>
<tr>
<th>Table 16 GPM: optimization results</th>
</tr>
</thead>
<tbody>
<tr>
<td>GPM</td>
</tr>
<tr>
<td>Total environmental saving</td>
</tr>
<tr>
<td>Take-back products</td>
</tr>
<tr>
<td>TotalEnergies’ incentives</td>
</tr>
<tr>
<td>Remanufactured products</td>
</tr>
<tr>
<td>Recycled products</td>
</tr>
<tr>
<td>New products</td>
</tr>
<tr>
<td>Price remanufactured product</td>
</tr>
<tr>
<td>Price new product</td>
</tr>
</tbody>
</table>

On the other hand, considering the second version of the T matrix, i.e., where also the “non-working” components can face the remanufacturing processes, the results vary. Of course, data and constraint are kept the same as before. Table 17 shows the results.

<table>
<thead>
<tr>
<th>Table 17 GPM: optimization results with second version transition matrix</th>
</tr>
</thead>
<tbody>
<tr>
<td>GPM</td>
</tr>
<tr>
<td>Total environmental saving</td>
</tr>
<tr>
<td>Take-back products</td>
</tr>
<tr>
<td>TotalEnergies’ incentives</td>
</tr>
<tr>
<td>Remanufactured products</td>
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<tr>
<td>Recycled products</td>
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<tr>
<td>New products</td>
</tr>
<tr>
<td>Price remanufactured product</td>
</tr>
<tr>
<td>Price new product</td>
</tr>
</tbody>
</table>
The second table presents preferable results since environmental savings and manufacturer’s profit is higher (500532 $ compared to 383558$). Also, the price for remanufactured products is lower (-8%), so offering the market a more competitive product with good performances. Additionally, with a lower price, it is possible to be closer at the concept that a reman product has to be cheaper compared to the new one, since the target market can be more price sensitive.

6.2.4 Assessment
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 two sections, so now the results are shown. The third column of Table 18 refers to the first version of the T matrix, while the fourth columns to the second version where also “non-working” components face remanufacturing processes. In other words, the third column refers the strategy where both remanufacturing and recycling are performed, while the forth and last column identifies the case where 100% reman is applied.

<table>
<thead>
<tr>
<th>Indicator</th>
<th>As-is condition</th>
<th>To-be condition (1)</th>
<th>To-be condition (2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MCI</td>
<td>0,69</td>
<td>0,79</td>
<td>0,80</td>
</tr>
<tr>
<td>CPI</td>
<td>28,39</td>
<td>47,13</td>
<td>47,13</td>
</tr>
<tr>
<td>CEIP</td>
<td>20%</td>
<td>35%</td>
<td>44%</td>
</tr>
<tr>
<td>CC – circularity</td>
<td>0%</td>
<td>47%</td>
<td>38%</td>
</tr>
<tr>
<td>CC – value capture</td>
<td>0%</td>
<td>22%</td>
<td>22%</td>
</tr>
<tr>
<td>CC – recycled content</td>
<td>0%</td>
<td>27%</td>
<td>0%</td>
</tr>
<tr>
<td>CP</td>
<td>Reman/Recycle</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

In general, the scores of the indicators increase when the two 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, circularity calculator identifies the disruptive change in the case study, moving from a linear to a circular business practice. Looking at the two different strategies, both are beneficial to the current situation; the main difference is in the deployment of a recycling strategy. Only in the first case recycling is used, that is the difference in the “recycled content” item of CC indicator.

6.2.5 Targeting
With the 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. Multiple stakeholders are generally involved when reaching challenging CE goals, so a step-by-step plan is the proper way to pursue the objectives. In fact, looking at the whole value chain, silicon, copper, aluminium, steel and all other materials needed to build a PV panel and its infrastructure are mined and produced using
petroleum and coal derivatives. The electricity to assemble the panel components is partially produced by coal-fired power plants. Finally, the panels are packaged and shipped to Europe or the US on ships powered by heavy fuel oils. Therefore, it is clear that decarbonizing such a complex supply chain is very difficult and will take time.

Supplier's perspective:

The supplier can achieve CE goals thought augmenting the remanufactured and recycled quantity of the end-of-life products (therefore of the materials deployed in them, i.e., 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. Additionally, augmenting the use of renewable energy in the industrial processes and fostering awareness of environmental issues, sustainability and circularity can further help the development of environmentally friendly strategies. In fact, having a closer relationship with customers, agencies and governments sets the proper conditions for important steps towards CE.

TotalEnergies’ perspective:

In order to gain some of the beneficial aspects listed before, TotalEnergies should foster the recovery and reutilization of the product’s materials closing the loop with the supplier of the ground mount structure, therefore creating new forms of collaboration between supplier and TotalEnergies in the long-term.

Government’s agencies:

Financial support by government or environmental agencies, policy frameworks (e.g., in terms of EPR), waste legislation concerning the product and/or mandatory percentage of reuse or recycling can foster CE incentives for the infrastructure under analysis in a complete way, looking equally at all the competitors involved.

Action plan:

1. Technically evaluate the feasibility of the remanufacturing processes;
2. Find an agreement between the supplier and TotalEnergies for developing a takeback system;
3. From the supplier side, start developing a new production mix made of new and remanufactured products;
4. Periodically check the evolution of environmental, economic and circular indexes related to supplier and TotalEnergies respectively, potentially considering policies and/or laws introduced by institutions.
7 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 properly consider the circularity performance and the impacts on sustainability when creating a takeback strategy, evaluating profit trends and deploying a production plan while meeting end-of-life targets. In fact, as described in section 2.5, the green profit model optimizes:

- Takeback strategy: buyback price and the takeback quantity of end-of-life product;
- Profit: selling price and the production quantity of the new and remanufactured product;
- Production plan: number of times of operation, recycling amount, quantity of new parts to procure.

In general, the output 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 produces figures to quantitatively assess the goodness of the identified solution. Indeed, GPM strongly support the understanding of the feasibility of the identified circular strategy with figures about environmental saving, profit, production mix and processes. In the fourth stage of the presented methodology, the use of indicators once again helps in concretely detecting the improvement that can be introduced choosing a circular strategy. Truthfully, the presented indicators have both a qualitative and quantitative basis, so it is reasonable practitioners can compute the indexes in a different way obtaining slightly different results too. For the current case study, only computer-based indicators are used since they are generally easier to compute considering the reduced quantity of data needed.

Coming back to the case study, some remarks about the outputs generated by the two tools are necessary. Looking at Table 18, the increase in value of CPI and CEIP is greater compared to the one of MCI. The results are reasonable if the perspective of the different indexes is assessed. In fact, MCI, as indicated by its name, focuses on the material dimension of the product, both in terms of feedstock and end of life. The change introduced in the case study through reman and recycle as CE strategies involves many areas of the product and business practice, not only the material dimension. Additionally, the choice of metal materials (i.e., aluminium and steel) already guarantees a good environmental performance due to the high recycling rates. These two remarks justify the lower increase in MCI compared to the other indicators.

Moreover, to better understand the role of green profit model, further graphs and details are listed below. In fact, the four graphs are presented for the two versions of the T matrix. Figure 68 shows the profit trend for supplier when environmental goals become more and more challenging. In fact, along the x axis, the savings of metric tons of CO2 equivalent gases increases (i.e., the production of pollutant gases decreases). Therefore, it is reasonable to understand the tendency of the graph and the strong difference with the baseline case (the black point). 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 strategy is added to the production of new product, it is possible to reach green profit opportunities which means higher profit while reducing the environmental footprint.
Figure 69 depicts the trend of incentives coming from the supplier to TotalEnergies with respect to environmental savings. The economic benefit perceived by the customer company goes up when higher savings are achieved. The reason behind this behavior is that when higher amounts of CO2 equivalent gases are saved, the use of remanufacturing strategy becomes more and more wide, so a higher number of end-of-life products is collected.

Figure 70 and Figure 71 are related to the quantity and price of new and remanufactured products produced. Along the x axis, the trends of two items are opposite. For pursuing higher environmental benefits, the quantity of remanufactured products increases and their price goes down. In fact, collecting low-cost end-of-life structures allows to offer the market a cheap remanufactured product, even considering the numerous production processes required.
The following figures refer to the second version of the T matrix, i.e., where also “non-working” components could undergo remanufacturing. The comments about Figure 72 are close to the ones for Figure 68. In general, the profit obtained by the manufacturer and the environmental savings are higher compared to version one of the T matrices. Even when an environmental goal ($\delta$) of more than 3000 metric tons of CO2 equivalent gases, the profit is higher than the baseline case.
Figure 73 shows the increase in the incentive obtained by TotalEnergies when challenging saving are pursued. For the last point shown in the graph (for saving higher than 3200 metric tons of CO₂ equivalent) an unexpected behavior is observed. In fact, moving right on the x axis, the incentives amount decreases. The reason could be related to the optimization model in Excel since it is based on the GRG method. Some influences from the starting point or the detection of a local minimum could have modified the result obtained. In any case, the final decrease in profit is equal to -10.4%.

Figure 74 and Figure 75 shows once more how the production mix should be varied to achieve higher environmental goals. In other words, remanufactured products are produced in bigger quantities and their price is reduced along the x axis, which means higher incentives for TotalEnergies but lower profit for the supplier company.
Looking at the graphs in their entirety, the results are consistent with reasonings already made: remanufacturing and recycling can be considered as a promising strategy for the case study, referring to both C-indicators and GPM. An evident outcome from the graphs 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 communicate to general public and stakeholders. Respectively, the amount of profit and incentives achievable are selected.

Instead, comparing the performance of the two different versions of T matrix, the main difference concerns the possibility to extract all the residual value from end-of-life products. In fact, considering the same takeback product, in the second version also the “non-working” components can undergo some production processes to build the final remanufactured structure. In other words, the incentives are higher in version one while the profit for the
supplier company is superior in version two. The graphs are therefore consistent with the remarks stated in the previous sections and with the original paper by Kwak and Kim (Kwak & Kim, 2017).

To conclude, together with the benefit listed above, also some procurement advantages are gained with the use of reman and recycle as CE strategies. In fact, specially looking at the relationship between the supplier of the ground mount structures and TotalEnergies, there is the possibility to enhance the connection among them through a long-term contract. When looking at circular practices, it is important to look at the future, for example when the structures will be takeback by the supplier for the remanufacturing processes. The link among the two parts involved is not only due to the purchase agreement when the products are bought as new, but also for the future circular strategy. On one hand, TotalEnergies will gain some economic incentives thank to the takeback program, while the manufacturer will face reduced costs for reman processes and will have for sure work order considering the flow of core products. Additionally, both the parts will have environmental and social advantages specially looking at the value retention of the core products. In fact, savings in terms of production of pollutant gases are reached and this valuable goal can be communicated to shareholder and general public to highlight the reduced impact of industrial companies.

As a final remark, considering aluminium as relevant part of materials’ consumption, supply risks will be limited. Even if today aluminium is not a critical raw material, in the future it could be because the use of this material is increasing worldwide. Also, the performances of virgin and recycled aluminium are similar, so decide to lock-in the aluminium content of the ground mount structures can be a successful strategy for both OEM and TotalEnergies (meaning reduced prices).

7.1 Sensitivity analysis
In the following section, the results from the sensitivity analysis are shown. The analysis is useful to understand the performance of the circular strategy when some modifications of the input data are introduced. The first version of the T matrix is used since it represents a common situation in industrial practice: only the “working” components undergo remanufacturing. As stated previously, a check of the feasibility of the remanufacturing strategy has to done in any case, specially looking at the technical side of the production processes.

The first results from the sensitivity analysis are presented in Figure 76 and Figure 77. Here, it is modified the ratio of “working” components extracted from the subassembly operation of sub-assembly 1. That is to say, when dissembling sub-assembly 1, 10% of the resulting components are still working while the other 90% do not work anymore. In this case, operation number four (in the T matrix) is performed in order to retain the residual value of this 10% of working components. In the graphs, the described case is plotted referring to the baseline case where only “non-working” can be collected from the disassembly operation of sub-assembly 1. The supplier profit and the incentives for TotalEnergies are depicted in the two following graphs.
The results are consistent with the tangible meaning of the optimization model. In other words, when 10% of parts are found working the supplier reduces the amount of end-of-life structure to takeback, therefore the incentives obtained by TotalEnergies are reduced. Additionally, the supplier does not buy the corresponding part of new components, when 10% are found working.

The second part of the sensitivity analysis is related to the production costs ($c_j$). The goal is to understand whether modifying the costs of the production processes there are still green profit opportunities. Figure 78 is the most relevant graph since it highlights that increasing the production costs there are again green profit chances for the supplier. In fact, augmenting the costs from 100% to 150 and 250%, the profit of the supplier company remains higher than the baseline case (i.e., 241154 $).
A similar reasoning can be for Figure 79. TotalEnergies envisages a profitable economic flow coming from incentives even if the production costs strongly increase. Of course, increasing the costs, the supplier profit and TotalEnergies incentives shrink, guaranteeing however green profit opportunities.

The last part of the sensitivity analysis is related to the market conditions. In fact, introducing the profiles of two competitors is possible to see how the market shares of new and remanufactured products can vary. Table 19 describes synthetically the characteristics of the two competitors. Instead, the supplier provides a performance ($u_{o,perf}$) of 0.7 out of 1, the price of new and remanufactured products varies according to the selected optimization point. Once the two competitors are introduced, the model is launched several times to obtain the optimization graph and Figure 80 is plotted.
<table>
<thead>
<tr>
<th>Competitor</th>
<th>Performance</th>
<th>Price</th>
<th>Newness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Competitor 1</td>
<td>0.5</td>
<td>$800</td>
<td>New</td>
</tr>
<tr>
<td>Competitor 2</td>
<td>0.7</td>
<td>$700</td>
<td>Remanufactured</td>
</tr>
</tbody>
</table>

Increasing the threshold related to the environmental savings, the market share of remanufactured ground mount structures increases at the expenses of new items. The market shares of the other two competitors remain approximately constant. So, a redistribution within the supplier company is faced: progressively the share of reman products increases, while for new product the trend is the opposite one.

7.2 Validation of the proposal of framework: interviews
To have a validation, at least partial, of the framework, some interviews were conducted. Looking at the partner of TotalEneries in the ground mount structures field, K2 Systems stated its availability for interviewing some employees. With the support of Claudia Vannoni (country manager for the Italian market), Simon Globig (supplier manager) and Matthias Reutschler (product manager) were interviewed. In this section, K2 Systems is briefly described and some highlights from the interview are commented.

K2 Systems is a German company founded in 2004 operating in the renewables sector. The company has been developing pioneering and functional mounting system solutions for photovoltaic installations around the world. The products are designed in K2 Systems’ product development department where they are continually optimized and adapted to the ever-changing market. K2 Systems stands for worldwide power generation from solar energy for a sustainable future, in fact the heart of the company is the development of installation-friendly mounting systems that are tailored to the needs of our customers. The focus of the company is on roof mounted structures; however, they produce also ground mounting systems.

K2 Systems does not own a production site where the structures are produces, in fact the company has a wide network of aluminium extruders in Europe. However, proprietary warehouses are positioned in strategic location to effectively supply local markets. The warranty duration for the products starts from a baseline of 12 years, but it can be extended
up to 15 and 20 years. The customers for K2 Systems are the installers and engineering - procurement - construction (EPC) of solar plants, but also the distributors. The size of the solar plants installed can be up to 12 MWp. K2 Systems invested a lot in the last years in the digital transformation, supporting in a more efficient way the installers of structures. In fact, only with a good installation, the products can well perform in terms of durability and strength. K2 Systems developed an application for properly training installers (usually coming from small and medium enterprises (SMEs) or they operate as freelancers) and EPC. The app supports the planning, installation and maintenance phases of roof and ground mount structures sold by K2 Systems.

From the interview, many aspects emerged about the framework and its applicability in the case study (for further information, the full transcript of the interview is reported in section 9.2). As a general validation of the proposal of framework, the approach is considered logic and well presented. The interviewees recognize in it many keywords relevant for their jobs (e.g., KPIs and simulation model). The effective applicability of the framework in their industry was however questioned, therefore the author tried to investigate better this aspect. In fact, in the interview, Simon Globig explained the actual position of K2 Systems in the supply chain of supporting structures for solar installations. Actually, K2 Systems design the infrastructures and, following the technical drawings, European extruders manufacture them. Today K2 Systems does not have a production plant since big investments are needed to enter the manufacturing world of aluminium. So once the products are ready, K2 Systems sells them to distributors and freelancers all around the world. Finally, customers (e.g., TotalEnergies) can buy the roof or ground mount structures. So, a meaningful question for the use of the framework in real practice is: which decision-maker has to be targeted? In the current thesis, both supplier and customer are targeted (i.e., K2 Systems and TotalEnergies) even if the production side is only seen by the extruders of aluminium profiles. Additionally, the communication among the supply chain becomes complex due to the multi-layer structure of it: extruders, K2 Systems, distributors and TotalEnergies. It is clear that extruders do not have contact with the final customers for concretely developing a takeback scheme.

Another remark from the interview concerns the supply risk experienced today in companies. In fact, due to the pandemic and climatic condition, an energetic and supply crisis is changing the way companies are working and the prices of products for customers. As Simon Globig confirmed, remanufacturing and recycling are a way to limit supply risks of raw materials, since the residual value of takeback products is considered. Also, from the regulatory side, in Germany there are not governmental policies that constraint the action range of K2 Systems, in terms of product design and production processes. Only recycling is advised as good practice with metal materials, in fact the European extruders recycle aluminium and steel accordingly to availability. The regulations that K2 Systems is actually following today are related to the connection between the roof mount structures and the roof of the house, in order to guarantee safety and insulation of the dwelling.
8 Conclusions

This work had the target of investigating the supporting role of C-indicators for the deployment of remanufacturing as a circular economy strategy. Through the proposal of a framework that connects C-indicators and an optimization model, the use of indicators in industrial practice can be enhanced.

The first step of the research consisted in the literature review, which had the aim of setting the proper background about the topics and describes their state of the art. The analysis was conducted via deep research for scientific papers taking advantage of keyword selection. At the end of the process, 39 unique publications were selected and they cover widely the state-of-the-art research about circular economy business model, circular design tools and methods, remanufacturing and indicators.

What in general emerged from the analysis is a research gap in the consideration of multiple aspect of CE within one summarizing tool. In fact, scholar put effort in designing classification and framework about circular business model, design tools and indicators but a complete view on the whole business practice is missing. Sometimes only a connection among these research areas all related to CE is identified. Additionally, indicators’ effectiveness in early decision-making has to be firstly assessed. In this way, a wider deployment of C-indicators will be possible, in fact, the information disclosed by indicators can effectively guide the definition of the design and manufacturing processes of industrial products thanks to their ability to summarize knowledge and guide the realization of CE strategies.

The results of the literature review part were used to set the direction of the second part of the current thesis. In particular, in order to contribute to the available research area identified, the main research question addresses remanufacturing as a specific circular economy strategy and was formulated as follows:

*Can indicators provide support for the implementation of remanufacturing as circular business strategy?*

This question was investigated combining green profit model (as selected optimization model) with circularity indicators. In other words, to assess quantitatively the feasibility of circular strategies in a real context, an optimization model is chosen as useful tool besides the semi-quantitative evaluation provided by indicators. Therefore, a new framework was born from the need to properly answer to the research question and, at the end, it integrates two promising tools in a structured approach. The framework consists of five steps: selection, analysis, simulation, assessment and target. The selection of C-indicators is the first step and the rationale behind it is the definition of a set of criteria that guide the process (e.g., related to CE implementation level, CE loops and/or CE perspective). Therefore, the computation of C-indicators is useful to understand the potential increase in circularity of products and business models. Valuable insights are extracted from the information disclosed by indicators. Taking advantage of it, the optimization model is adjusted and launched: a simulation of profit, environmental savings and production mix is obtained. The effective improvement in circularity performance is assessed by a new computation of indicators. Further remarks can be made looking at the same time at the information provided by them and the optimization model. Finally, 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.
The first innovation point consists in the integrated use of C-indicators and GPM as optimization model. In fact, till today, C-indicators were embedded inside the GPM as an additional constraint for finding an optimal solution, i.e., they were a way to assess the circular dimension of a product and/or business practice. With the current work, indicators play an active role for guiding the development of circular strategies and the subsequent monitoring of environmental, economic and social benefits introduced. Secondly, another innovation lies in the augmentation of the GPM following industrial motivations. In fact, GPM has not been used as described in its original paper. The application field has been augmented considering the use of industrial practitioners: transportation costs and environmental impact is taken into account along the introduction of an active role for customer company through the incentive’s mechanism.

Finally, the framework was assessed with the data collected within the case study provided by TotalEnergies. Also report, scientific publications and author’s expertise allowed the testing of the framework in real practice. The topic of the case study concerns the ground mount structures for PV panels and the possibility to recycle/remanufacture them. In this way, the validation of the approach was possible and results were obtained. In particular, considering aluminium as key material for the systems, supply risks will be limited since the residual value of takeback products is preserved. This is a relevant result taking into account the pandemic and climatic condition, where an energetic and supply crisis is changing the way companies are working and the prices of products for customers. Also the performances of virgin and recycled aluminium are similar, so decide to lock-in the aluminium content of the ground mount structures can be a successful strategy for both manufacture and TotalEnergies.

To conclude, this thesis work presented a framework for developing CE strategies in real practice taking advantage of state-of-the-art research on green profit model and C-indicators. Such framework acts as a way to connect typical problems of production planning and control in remanufacturing processes with the goals of sustainable development, also considering product design and end-of-life strategy choices. The presented framework can be considered as a promising support to be used in industrial practice. The case study assesses the validity of the support provided by indicators in the deployment of circular economy strategies. Thanks to some interviews hold with experts in the field, the approach is considered logic and well presented, even if it has to be tested more generally.

8.1 Industrial limitations
Critically reviewing the thesis project with TotalEnergies’ experts (and particularly with Sara Aid and Etienne Drahi), the author had the possibility to see some limitations looking at the industrial applicability of the research outputs. The key points from the exchange with experts are provided here with additional remarks.

- **Ownership of solar farms**: lately TotalEnergies has decided to share the ownership of solar plants with other companies, once it is completely installed, for financial issues. In fact, to reduce the economic indexes in the financial statements, it is reasonable to split the solar installation with other enterprises to have some financial benefits. Usually, the operation and maintenance (O&M) agreements still remain under the responsibility of TotalEnergies as long as the plant is used. Splitting the property of the solar farms makes harder the identification of the decision-maker to target with the proposal of framework. In fact, TotalEnergies is not the final customer of the PV ground mount structures, but other companies play a significant role looking at EoL.
management. Envisaging EPR as possible strategy, it is straightforward to see how complex is recognizing the player that allows the takeback of products, since different companies can have various ways to manage end-of-life items even in the same solar plant;

- **Long-term commitment**: the average lifespan for PV racking systems is 25 years, as described in the previous sections. In this timeframe, the industrial world is used to powerful disruptions therefore it is logic to ask ourselves about the changes that renewables industry will face soon. For sure, a change in the design of PV modules will occur (looking at the past years, the size of modules is increasing), but also partnerships will expire and maybe they will not be signed again. All in all, imagining a more circular way of doing for racking systems is complex looking at the long-term perspective between installation and buyback. Finally, a legal check has to be done since setting an agreement among companies with a long timeframe is delicate, so it needs the appropriate countermeasures.

8.2 Further research
The work presented has possible investigation lines which could be expanded in future studies. In particular, the main ones individuated are:

- **Optimization models for circular economy**: new optimization tools can be used within the framework besides green profit model. The key requirement for these tools is a quantitative nature to properly simulate the deployment of one or more circular strategies. Regarding GPM, it can be further augmented in the future specially looking at the possibility to consider multiple periods of time at the same time and the possibility to upgrade the design of product(s) over the time. In fact, developing a time perspective, additional reasoning could be made about capital expenditures (so considering fixed costs and their depreciation), modification in the design of components and product, change in market conditions and customers’ preferences, integration of governmental policies;

- **Application of circularity indicators**: scholars researched a lot in the last years about the role of C-indicators for the development of circular practices. A critical step for the current framework lies in the correct selection of indicators, in fact numerous indexes are available today and choosing among them can be difficult. Developing criteria and approaches for their selection and the subsequent creation of a web-based tool can be a promising investigation line. Consequently, the application of indicators is fostered as in the way suggested by the current work, i.e., through a framework. As highlighted through the thesis, C-indicators can properly support the development of CE so easing the selection step can further facilitate the use in industrial practice. Finally, as stated in other pieces of research, the actual sustainability of circular economy strategies has to be properly assessed, also through real case studies;

- **Testing phase of the framework**: the proposal of framework discusses in the current work has to be further tested. Also considering the cases study based on PV panels ground mount structures, it is possible to improve the quality of input data trying to collect them all directly from the supplier company. However, this is not an easy task since some of them has to be derived directly from scientific publications or agencies’ reports. Additionally, the framework can be 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 framework is tried in different conditions in terms
of industrial practice. Finally, the framework has to be tested using various optimization models and selecting the cluster of C-indicators with different rationales.
### 9 Appendix

#### 9.1 Appendix A

Transition matrix of the ground mount structure: version one

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<th>Reconditioning</th>
<th>Reassembly</th>
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Transition matrix of the ground mount structure: version two

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Cost ($) and environmental impact (kg CO₂ equivalent) parameters regarding part procurement, transportation and recovery

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Operational cost and environmental impact: version one

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9.2 Appendix B

Transcript of the interview had with Simon Globig (supplier manager at K2 Systems) and Matthias Reutschler (product manager at K2 Systems). The interview was held on Zoom the 28th October 2021 and lasted 45 minutes. During the call, also Claudia Vannoni took part as country manager at K2 Systems for the Italian market.

Luca Benini: Welcome Matthias and Simon, thank you for your availability. The aim of the meeting is to conduct an interview related to K2 Systems and the proposal of framework I am developing. So, starting with the first question… How is K2 Systems moving towards circular economy today? Looking at products, materials, energy. Just to have an overview.

Matthias Reutschler: So, if we think about products, let’s start with that first topic, they are most made of metal. From my perspective, in the metal area, meaning aluminium, steel and so on, the circularity is already quite good implemented. So, most of the metal parts are reused at least if they are big as we use today, so no mobile phones or something else. We do not have so small parts and most of the components are good to be reused. Our aluminium companies for example used up to 80, 90, 100% of recycled aluminum. So, in that case we are already quite good, without we need to do a lot because it is already implemented. So, thinking about taking back, which can be as well interesting, we think we are too young to think really in detail about it because mostly of PV installation is 25, 30, 35 years on a roof or on site and K2 Systems is only 17 years old, founded in 2004. And so, we have to think about it, but we are in quite an early stage, out of my perspective to go really into detail of bringing back our products. It will be on our list in the next 5 to 10 years I think because during that time hopefully our products are still on site and are still working that would be the idea behind.

Luca Benini: Okay, I see. That are also the reasoning that PV module manufacturers are doing, even if the module are more easily recycled, because all the components are glued together. In fact, for different components, different circular paths can be selected. Simon, would you like to add something?

Simon Globig: Let me comment a bit in the direction of the suppliers, as Matthias already said, like we have the advantage that most of them are caring about the issue generally. Coming from the market situation, it is even a bigger advantage to use recycled aluminum and that is the main positive aspect that you have from aluminium because it is 100% recyclable. Our suppliers already do, some are doing more, some are doing less in the topic; but everybody is caring about accordingly to availability. So not only on kind of sustainability and environmental questions, but also based on availability.

LB: Yeah, do you think that remanufacturing can be a way to limit supply risks? Because I know that many companies and industries are facing problems with purchasing of raw material. Maybe already recycling is easing this aspect but remanufacturing even more.

SG: Definitely, it would help and I think for the next months and years it will be even more important, not only to think about but also to care about and work on this… This situation will constantly be like it is now not maybe in every aspect that we see right now, not maybe in every effect that we see right now, but it will go on more or less like it is now and that is why we have to do our calculations based on.

LB: Okay, I see. Now I would like to ask you feedback about the framework you have seen before. Because I had the chance to apply it to a real case study, what do you think about it?
Can it be useful to you? Maybe for unlocking the circular potential of your products or to see new circular goals.

SG: My question related to the “target” step in the framework: what targets do you have? What targets do you follow? Cause what you are writing here makes sense but that is why we are also asking about your background of companies. Discussing it with you, applying on a real case study is good, but I do not know how it will work in the practical phase.

LB: The case study was not only driven by company, but was a mixture of company data, reports… For example, targets can be to understand better the technical knowledge in order to pursue remanufacturing production processes, but also try to be closer to customers to takeback the products. So, target can be on different aspects but also with different timelines, so try to be closer to customers, to suppliers than just the technical feasibility of the processes. The aim of the framework is to allow to have a better comprehension of the products, the production process and then to put into practice this with a good communication among the stakeholders; since this is the basis for circular economy, as written in the scientific literature.

SG: I mean, only if our suppliers that we have are carrying about that topic, we as customers for them do not automatically do what they want and think of course. So it is really a question, as you described, of communication among the supply chain, of course the general aspect or maybe also marketing aspects that is behind that makes sense for everybody, but the real practical use of that question of circularity I think can only work if the supply chain cares about it together.

MR: I think so as well. Because if we are closer to our customers and we are quite specific area because our products have a 25/30/35 years of life. So, they are not sold, installed and 2 years later changed. It is different from mobile phones or cars, where they have 6/7/8 years of lifetime, but we think and talk about at least in the PV branch of 30 years lifetime. And to bring the products back would be more difficult to use the circle we have already implemented, so if we have metal products you can just bring them back and they are sold to our suppliers (so to manufacturers): there is already a circle in Germany for the metal industry. So, I think it is already quite good, but I am not sure that could help us as PV mounting systems and manufacturers in the future.

LB: Your product is not changing over the years; the design is quite similar. Maybe the performances are enhanced, some details and features are augmented, but I think that having a quite constant product all along the years can also be a good starting point for you relating to remanufacturing because you can takeback the product, change something and then be able to sell them to developed or underdeveloped countries, so other markets.

SG: It could be, it could work. But as Matthias has described, it is in a lifetime we have to calculate things, so 25/30 years. That is something we have not had experience with it, and during that time many things are changing, so many requirements, circumstances are changing that I am not really positive about that idea, because for example the modules are changing during the years several times. It is an idea, but I think it will not work. To use it in the same way as it used before, not based on recycling the material itself.

LB: Why do you think so? Is it about changing conditions in the renewables field?

SG: Yes, that it is. You know, also political requirements are changing. Just physical requirements are changing as I described based on the modules for example, the roofs will be
similar to today situation but the other thing around that will constantly lead to adaption of products in some way.

LB: Up today, do you already face some rules or regulations coming from government in Germany?

SG: In which aspect?

LB: About the products, about sustainability and environment. I know that you do not have a production plant, but usually you have a supplier that manufacturers the components even if you design the systems, so what is the relation with government and rules that can constrain a bit your way of doing.

SG: Related to products yes, if this is a question on how you are allowed to build a house and build the PV construction on the house and on the roof, so that is in my opinion the main aspect that governmental rules are looking for and they are not based on environmental up to now.

MR: I would like to add that it is not about the products, since governments are not regulating so far. But what we see for the future, they are pushing us to sell our carbon footprint, so it would be a topic for the future, and we are working on that already, but there is still not a regulation.

LB: Okay, and about the design of products, do you use some techniques for design for X, so trying to make the components last longer or to have a good communication with the producers of PV modules, inverters…

MR: Sure, we are always in contact with the manufacturers of modules, because if they change something, we have to change consequently. We are not in contact so often with frequency converters companies. We design our products thinking that they have to last on the roof for 35 years, so our problem is not that we have to design a product that lasts longer, because it is already long lifetime. What we are trying to do at the moment is to save material and still have a strong product. In fact, as Simon already mentioned, the environmental regulations are not impacting our products.

LB: My last question is related to the framework. Focusing a bit more on it, what are your feelings about it? Is it complete or not?

MR: As I already mentioned, I see a lot of good things in the diagram and for me it is logic. I still do not know if we are the right company for that since out of the long lifetime for our product, it is getting quite difficult. And I really like the idea and the clarity of the framework, and I would like to use it, but I think that for our company can be a bit far, compared to smartphones and tech devices industries. At the moment, I do not have a clear idea of where we can use the framework and what can be the right indicators for our products. To be honest with you, if we now use some indicators, in 25 years you can see how indicators are developing and for us it is more difficult and harder to think in that lifetime. In general, the framework is quite good, and it looks quite well.

LB: That was my last question, thank you Matthias and Simon for your time.
9.3 Appendix C
Technical drawings of the ground mount racking system.
10 References


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*Resources*. (2021, August 9). SEIA. https://www.seia.org/resources


