



A sustainability-oriented methodology to compare production strategies: The case of AM-based remanufacturing

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ABSTRACT

The implementation of sustainability principles is becoming fundamental for companies, also for creating added value in the production processes. Production managers should not consider only the economic-financial aspects in their decisions, but also the environmental and social implications to extend the benefits to all current and future world populations. This vision requires to develop and apply sustainability-oriented methodologies to compare alternative production strategies. This paper contributes to addressing this problem by proposing a methodology that allows comparing different production strategies by considering their sustainable impact, starting with the definition of their processes. An aggregated sustainability index has been designed for this purpose. Thus, the paper contributes to the literature on the evaluation of sustainability through the development of a methodology, which can be used by the practitioners as a decision support tool to identify the most sustainable production strategy according to the objective of the company and the specific production process considered. Then, the proposed methodology has been applied to compare two different production strategies, i. e., AM-based remanufacturing and the production of new components. A simulation model has been implemented to reproduce the behaviour of the two competing production strategies. Although the results depend on the utilized data, this application showed that it is possible to distinguish different areas of convenience for each strategy. Moreover, findings revealed that the sustainability of the production strategies is strictly connected to the adopted technology and the importance given to the economic, environmental and social aspects by the company.

1. Introduction

The reduction of industrial pollution is a key factor to preserve nature's wealth. Manufacturing industries are responsible for about 50% of global greenhouse gas (GHG) emissions (Vieira et al., 2021) which are widely recognised as major factors of nature depletion. To mitigate the climate change, excessive waste generation and the scarcity of natural resources, Governments are introducing measures to promote sustainability principles (European Commission, 2015). In such a context, the development and use of sustainable production practices can represent a boost to achieving the goals of climate neutrality and the circularity of resources. For this purpose, it becomes important to assess how much manufacturing paradigms can be considered "environmental-friendly". At the same time, it is equally important to implement industrial practices that guarantee a correct balance between the environmental and economic aspects. The need for integrating and simultaneously

improving such aspects has led many researchers to propose new methodologies for evaluating the green (i.e., economic and environmental) impact of specific technologies in different industrial contexts (Rinaldi et al., 2021a). Such a necessity originated from two important aspects: i) the rise of the fourth industrial revolution (I4.0), which brought high innovation levels in many industrial contexts and ii) the ongoing transition from a linear to a circular economy (CE). In consideration of the first aspect, I4.0 has led to the rise of new technologies which improve the overall performance of the production processes, allowing companies to become more competitive and achieve good economic results (Dalenogare et al., 2018). At the same time, their environmental impact must be carefully evaluated because they are energy-intensive and can contribute to the generation of GHG, CO₂ and other pollutants (Oláh et al., 2020). This is in contrast with the transition towards a CE whose main objective is to reduce the pressure on the environment by extending the useful life of old products and minimising

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the extraction of primary resources, such as raw materials (Neves and Marques, 2022). Different approaches are used to achieve the objectives of a CE plan and most of them are based on the 4R strategies: reduce, reuse, remanufacture and recycle (Bressanelli et al., 2020). Such strategies refer to different ways to approach resource circularity. Product recycling is the best strategy when raw materials must be recovered, while reuse and remanufacturing (RMfg) strategies are supposed to maintain the original functionalities of the resources. In particular, RMfg aims to restore the original quality of the products through an in-depth inspection and maintenance (Ijomah, 2009). It is defined as the process capable of “returning a used product to at least its original performance with a warranty that is equivalent (to) or better than that of the newly manufactured product” (British Standard, 2010). Besides the performance of the remanufactured products, it is important to highlight that RMfg perfectly matches CE principles that companies can adopt to improve their sustainability. The use of remanufactured products has the potential to decrease the use of raw materials and waste disposal by up to 80% if compared to new products and to save up to 87% of CO₂ emissions (Eionet, 2021) providing both economic and environmental benefits for companies and consumers. However, the use of new materials and resources is needed in RMfg processes when there is the necessity to replace a used component because it is non-repairable or when there is no economic convenience in repairing it. To guarantee a high quality of the final product, in some cases, it is needed to employ new components as substitutes for those that can compromise the useful life of the remanufactured product. Moreover, implementing RMfg requires dedicated environments and resources, different from the ones used for manufacturing because of the difficulties in carrying out some processes, such as disassembly, efficiently.

A recent review (Burmaoglu et al., 2022) on the interaction between CE and digitalization revealed that there are four cluster topics to be investigated in the future: sharing economy, additive manufacturing (AM), business models, industrial ecology and remanufacturing. Specifically, AM is an enabling technology of I4.0 which can be used both to produce new products and to remanufacture old products. AM is considered to have a high potential compared to traditional subtractive manufacturing. From the environmental point of view, AM can potentially remove material wastes and drastically reduce material and energy consumption over the product life cycle (Khalid and Peng, 2021).

In this context, quantitative models and tools to assess the sustainability performance of different manufacturing strategies are needed (Manco et al., 2023). These models should evaluate the most sustainable production strategy according to the company vision, the state of products and processes, and the production technologies adopted. In addition, despite the increasing interest on CE and the open discussion of its impact on economic and environmental performance, the literature analysis highlights the lack of models allowing a comparison between traditional production and 4R strategies, according to the sustainable principles. In light of these considerations, the objective of this paper is to propose a novel methodology to assess the sustainability of different manufacturing strategies. A quantitative model has been developed to be adapted to any need, and then it has been tested and applied for comparing the sustainability of two specific production strategies: the remanufacturing of old products and new productions, considering in both cases AM as production technology.

The remainder of the paper is as follows. Section 2 analyses the literature concerning decisional models and tools used for evaluating different production strategies with a focus on sustainability. Section 3 details the research methodology, then applied in Section 4 to the specific context of remanufacturing and AM. Section 5 shows the results and discusses the theoretical and practical implications of this research and section 6 concludes the paper with the main implications and limitations of the study.

2. Background

2.1. Sustainability and production strategies

Sustainability concerns multiple aspects to consider and, consequently, the scientific literature proposes studies which take different perspectives in terms of the specific dimension of the sustainability they explore, the production strategy or the specific technology targeted for the analysis, as well as the research methodology. Some authors developed general models including sustainable and green aspects and focusing on the comparison among different production technologies or strategies, often considering the entire supply chain (Seuring and Müller, 2008). Cantini et al. (2022) designed a Decision Support System (DSS), based on a decision tree, useful to compare the costs of the supply chain characterised by different degree of centralisation. According to the authors, such a method could be useful to evaluate whether the production of spare parts can be switched from traditional manufacturing to AM. Rinaldi et al. (2021b) proposed a simulation tool for technology selection based on the supply chain configuration. Additive and Traditional manufacturing have been compared testing different supply chains and using a set of strategic metrics. A methodological framework for evaluating the features of sustainability for different production technologies was proposed by (Xia et al., 2017). The authors demonstrated how their method was suitable to be used for many different technologies considering new production processes. Other researches made use of models tailored on the specific use case, such as Vinodh et al. (2014), who developed a decision system for a machinery and automobile parts manufacturing company based on fuzzy logic and different sustainability indicators, with a focus on carbon footprint emissions.

The use of AM machines as an alternative to traditional manufacturing for new production has been widely debated in the literature (Watson and Taminger, 2018). Many papers addressed the sustainability of different production technologies, focusing on the comparison between AM and traditional subtractive technologies. Although AM seems to have not the maturity level for a large production scale (Rinaldi et al., 2022), its environmental and economic advantages are widely discussed in the literature (Attaran, 2017). Recently, Rinaldi et al. have designed a framework to compare AM and traditional subtractive technologies using different key performance indicators (KPIs) related to economic and environmental aspects for identifying the greenest solution in the case of new productions (Rinaldi et al., 2021a). Similarly, Ribeiro et al. (2016) considered economic and environmental factors in comparing a new 3-D production technology to classical production methods by means of life cycle assessment (LCA) tool. The LCA approach was also used to compare AM and CNC technologies (Faludi et al., 2015); findings revealed that the best solution in terms of sustainability strictly depends on the saturation of the machines: when saturation is high or low, AM machines have a lower ecological impact than CNC. Jiang et al. (2019) developed a method based on LCA and reached the same conclusion, but they also considered the social aspect, pointing out that AM has a better social impact than traditional manufacturing. The complexity of the object to produce is also crucial: Paris et al. (2016) developed a LCA model and demonstrated that the production of highly complex parts with the need of high material removal is more sustainable if AM is used.

AM demonstrated to be effective also for RMfg processes (Rahito Wahab and Azman, 2019) because allows regeneration of the original quality of a used component thanks to its high precision, which makes components' remanufacturing through AM feasible in many sectors (Leino et al., 2016). The RMfg of products at their End-of-Life is considered an opportunity for the transition towards a CE and a more sustainable world. For such a reason, decisional models have been developed in the last few years to integrate AM technologies in RMfg processes. Among them, Liu et al. (2018a) considered the sustainability aspects in the RMfg of a crankshaft through AM, showing that the

sustainability of the process is not optimised and needs to be improved. [Kandukuri et al. \(2021\)](#) highlighted the great potential of using AM for RMfg and developed a tool useful to practitioners to increase the AM applications in RMfg. [Wilson et al.](#) proposed a model to test several AM technologies for maintenance during the RMfg process. The laser-engineered net shaping (LENS) has been adopted to repair a turbine blade, highlighting a reduction of 45% of the carbon footprint and a total energy saving of 36% ([Wilson et al., 2014](#)). Laser metal deposition (LMD) was used in the study proposed by [Foster et al. \(2019\)](#), who identified several criteria to investigate the effect of using such a technology for remanufacturing hot forging tools, finding that the mechanical characteristics of the remanufactured components were as good as the new components.

[Jiang et al. \(2011\)](#) designed a multi criteria decision method for RMfg technologies selection, demonstrating that it is fundamental to consider the synergistic effects of the single alternatives under evaluation, concluding that the alternatives that produce more synergistic benefits may be more attractive than those having singular benefits. More recently, [Kerin et al. \(2023\)](#) demonstrated that a combination of digital twin, optimization models and neural network can be beneficial for RMfg activities planning. In this research, authors found that the product quality, location and process costs are the most important factors to evaluate the sustainability of RMfg.

From the above overview it is possible to notice that there is no universally best AM strategy for promoting a CE, but it is necessary to approach the problem through a case-by-case analysis. [Son et al. \(2021\)](#) utilized an integrated sustainability index to contemporary evaluate the cost-effectiveness, the environmental impact, and the manufacturing responsiveness of a conventional product design against a new candidate produced via AM.

The analysis of the existing literature is summarised in [Table 1](#), where each paper is categorised according to the methodology used (qualitative (Q) and/or quantitative(Qt)), the production technology targeted for the analysis, the sustainability aspects considered (economic (E), environmental (Ev) and social (S)) and the production strategy.

Resuming the main findings, it can be stated that models usually combine economic and environmental aspects, but very few papers address the three aspects of sustainability. Papers which deal with the comparison among manufacturing technologies for new production are higher in number, while strategies for RMfg are still less debated. To date, no one proposed a methodology for comparing manufacturing strategies for new production and RMfg, which is the objective of this paper.

Table 1
Summary of the literature analysis.

Paper	Methodology		Technology considered	Sustainability aspects			Production strategy
	Q	Qt		E	Ev	S	
Banerjee and Punekar (2020)	✓		-	✓	✓	✓	Manufacturing
Xia et al. (2017)	✓	✓	Not specific	✓	✓		Manufacturing
Rinaldi et al. (2022)		✓	AM	✓			Manufacturing
Rinaldi et al. (2021a)		✓	AM and subtractive technologies	✓	✓		Manufacturing
Ribeiro et al. (2016)		✓	thermoplastic sandwich structures (t3S), Aluminium hot forging (AHF), Wet lay up (WLU)	✓	✓		Manufacturing
Faludi et al. (2015)		✓	AM and CNC		✓		Manufacturing
Jiang et al. (2019)		✓	AM and CNC	✓	✓	✓	Manufacturing
Paris et al. (2016)		✓	AM and milling		✓		Manufacturing
Kandukuri et al. (2021)	✓	✓	AM				RMfg
Wilson et al. (2014)		✓	AM		✓		RMfg
Foster et al. (2019)		✓	AM				RMfg
Son et al. (2021)	✓	✓	AM	✓	✓	✓	Manufacturing
Liu et al. (2018a)	✓	✓	AM	✓	✓		RMfg
Jiang et al. (2011)	✓	✓	Multiple	✓	✓		RMfg
<i>This model</i>	✓	✓	AM	✓	✓	✓	Manufacturing and RMfg

2.2. Contribution and novelty

This paper aims to contribute to the current literature on the topic of the sustainability of production strategies by proposing a methodology for evaluating the most sustainable solution taking into consideration the environmental, social and economic objectives of a company. The paper aims to respond to the following research questions.

- RQ1: Is it possible to create a methodology, based on sustainability pillars and adaptable to the company needs, to compare different production strategies?
- RQ2: By the application of the methodology, what is the best strategy between AM-based RMfg and new productions through AM?

To the best of the authors' knowledge, past papers dealing with the use of AM for production use mainly quantitative models to assess the benefits of AM. The current literature does not propose any methodology for comparing different production strategies using AM technologies considering all the pillars of sustainability. Specifically, this paper aims to fill this gap by proposing a qualitative and quantitative model for assessing the sustainability of different production strategies, focusing on the specific context of RMfg to compare circular and linear economy. For such a reason, the methodology can also be used as a decision support system for managers who have to choose among different production strategies. Indeed, by identifying the areas of convenience for each strategy according to the company vision, the state of products and processes and the production technologies adopted, this methodology allows evaluating the most sustainable production strategy.

3. Methodology

The methodology proposed in this study aims to provide a decision-support tool to compare different production strategies considering sustainability aspects. The final output of the methodology is the definition of areas of convenience for two or more competing production strategies according to the strategic vision of the company about the sustainability (RQ1). The areas represent the locus of points where it is convenient to implement a specific production strategy according to the values assumed by a defined number of system's variables, which are crucial for the decision-maker(s).

[Fig. 1](#) shows the framework of the methodology. It consists of one core block (the dotted-line blue block) with 4 inner boxes representing 4 different phases, each one having its inputs (green blocks) and outputs (red blocks). The first phase of the methodology aims to define the

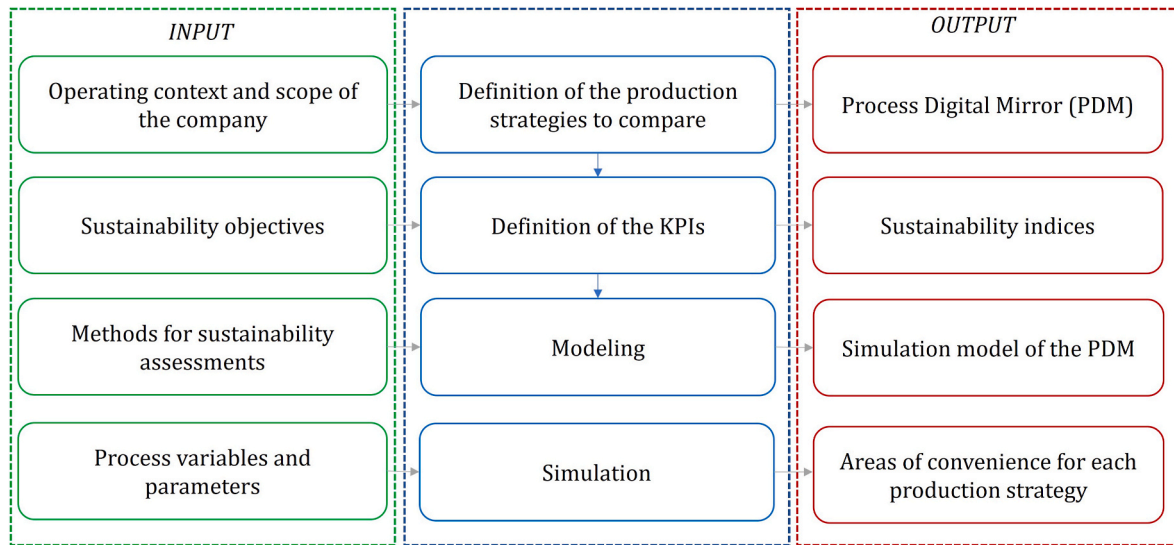


Fig. 1. Framework of the methodology.

production strategies and scenarios to be compared. This phase requires the definition of the boundaries of the production system, the scope of the company and the operating context. This preliminary information is useful to define technologies, flows of resources and materials and other fundamental sustainability-related parameters. The output of the first step is a Process Digital Mirror (PDM), representative of all phases and flows of the alternative production strategies. The second phase aims to define performance metrics to compare the production strategies. According to the framework, the relevant KPIs should be identified to evaluate the performance of the production strategies, mainly related to (Jacobs and Chase, 2018).

- the company's financial payoff, by reducing costs connected to the production;
- the consumer-related payoff, by enhancing customer satisfaction, the company reputation and promoting a new business development;
- the operational payoff, by innovating the production process to increase resource productivity, minimise waste and shorten the lead time.

Since metrics have different scales and units of measurement, a proper approach is to use dimensionless aggregated performance indices as they provide a unique snapshot of the performance (Galar et al., 2014). The choice of adopting an aggregated and unique index rather than considering several unaggregated performance metrics is totally up to the decision-maker. However, if the aim is to focus on a continuous decision space, as it is the case of Multi Objective Decision-Making (MODM) problems, the choice will be the use of a unique target function that aggregates the objectives (Ghaleb et al., 2020).

The third step consists of building the mathematical models that steer the behaviour of the production strategies in the PDM. This phase requires knowledge of the technologies used during the production processes, the amount of labour, the material flows, the type of product and, in general, all factors impacting on sustainability. Moreover, the methodology for the sustainability assessment must be set. LCA is among the most used methodology to get the environmental impact of a product or a process. However, the methodology chosen to measure the environmental impact of a production strategy is strongly linked to the environmental impacts of interest, the available data, the geographical region, and the current legislation of the country in which the assessment is done. Furthermore, to consider all the sustainability pillars, also KPIs connected to the economic and social dimensions have to be introduced in the analysis and measured. There are several methods to

estimate costs (Kadir et al., 2020) and to address the role of the manufacturing in affecting the social dimension (Kolotzek et al., 2018). These decisions contribute to define the sustainability model of the PDM which is simulated in the last phase of the framework (fourth blue box). All the processes involved in the production should be considered, from the arrival of the raw materials to the delivery of products to the customers. Simulation is needed because the sustainability of a production strategy can be strongly influenced by several uncertain process variables. The simulation is used to evaluate the performance of the production strategies to identify their areas of convenience, in terms of sustainability, providing the variation of such areas according to the variability of a set of decision variables chosen during the modelling stage. The areas of convenience represent the final output which can be used by the decision-maker to select the best production strategy according to the sustainability vision and goals of the company.

The methodology is a general-purpose step-by-step guide towards building a decision-support tool for the production strategy selection. It requires expertise in the field of industrial, managerial and performance engineering. There are no limits on the number of production strategies to be compared, the number of KPIs to be considered and the type of modelling methods and simulation approaches. However, the methodology only establishes the requirements and the deliverables of each step.

4. Application of the methodology

The methodology has been applied to solve a problem of production strategy selection: "Remanufacturing worn items" and "produce new items". It is assumed that both production strategies adopt AM technologies. This assumption does not affect the generality of the proposed methodology, but it is needed to reduce the complexity of the PDM as adopting similar production technologies allows to reduce the number of processes, parameters, and variables within the system. Fig. 2 is a concise representation of the methodology applied to the case of AM-based manufacturing/remufacturing. The PDM must contain the crucial steps of the RMfg process (green block in Fig. 2) and of the new production process (blue block in Fig. 2). Moreover, some shared steps, such as the raw material and feedstock procurement, have been highlighted (red block in Fig. 2).

Once the PDM of the system has been derived, the decision-maker selects the KPIs in compliance with the company's sustainability goals. In this paper, sustainability has been addressed by considering the economic, environmental, and social impacts of the alternative

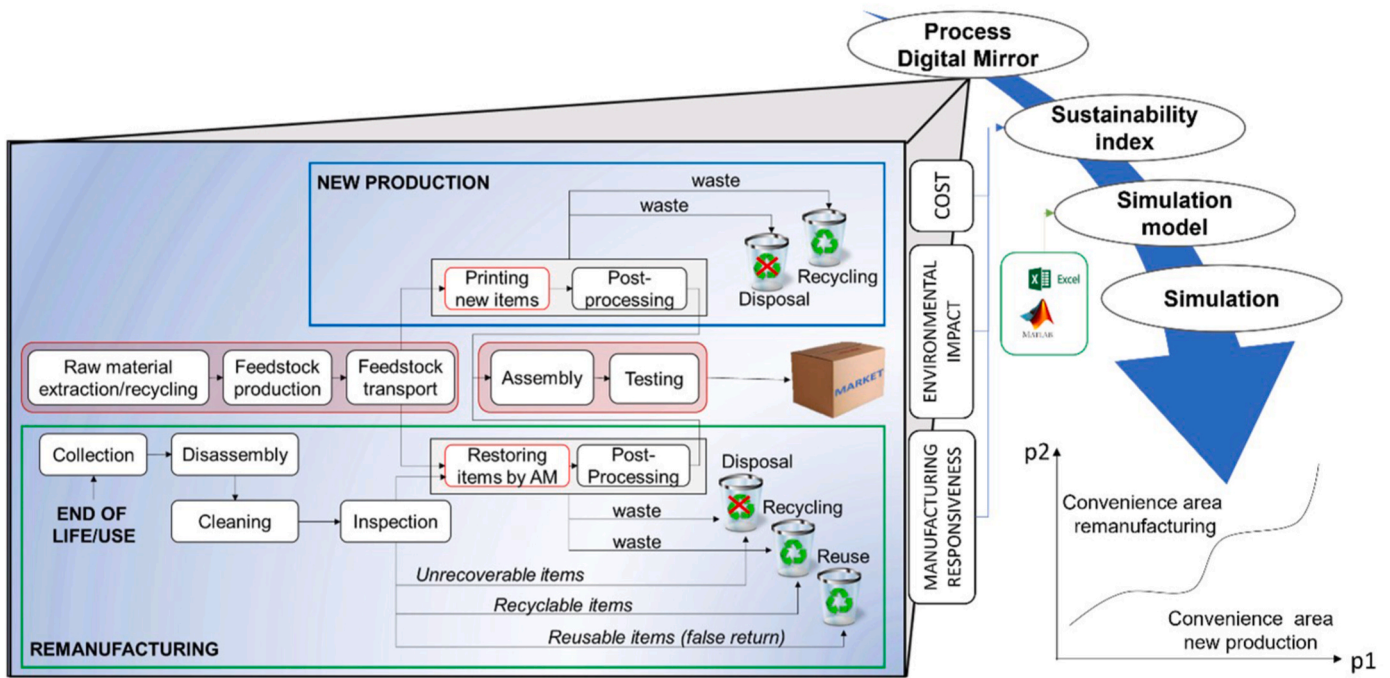


Fig. 2. The PDM: new production vs remanufacturing through AM.

production strategies, by adopting a triple bottom line approach. The economic, environmental and social performance indicators are aggregated into a unique sustainability index to define a continuous problem where the design alternatives (the production strategies) lie in feasible regions (the areas of convenience) bounded by the limit values of the decision variables. The simulation model of the PDM is made up of mathematical relations which link each performance indicators to the steps, flows and parameters that characterize the system. In this phase, some assumptions could be made depending on the available data and the required accuracy of the solution. Finally, the simulation is used to assess the evolution of the sustainability index according to the variation of the set of decision variables. In this study, great attention is given to two uncertain variables of the RMfg system: the return rate (RR) and the quality of the used products that come back to the RMfg site. Both the RR and the quality of returned products are uncertain variables that can strongly influence operations and managerial decisions (Liang et al., 2014). A Montecarlo simulation is finally implemented to generate several scenarios considering the uncertainty about these variables. It is worth noting that all the data introduced hereafter has been taken by the literature.

4.1. Remanufacturing

In this section, the RMfg strategy will be briefly described to highlight its main issues and how they are addressed in this paper.

As described in the introduction section, RMfg represents one of the best expressions of the CE concept because of the potential resource savings it can generate. RMfg aims to restore the original quality of old products by employing few quantities of new resources and protecting the environment while preserving economic growth (Sarkar and Bhuniya, 2022). Both the environmental and economic benefits achieved by RMfg are the leading drivers towards the adoption of this strategy. Many companies need to limit their emissions to reach the carbon neutrality imposed by the European Union by 2050 and this objective can only be achieved by increasingly entering the RMfg market (Eionet, 2021). This is confirmed by the trend of growth that RMfg is having in many sectors, such as aerospace and automotive (where an annual growth up to 3% is estimated in the next years), electric and electronic components (annual

growth up to 5%), marine (annual growth up to 11%) or energy (annual growth up to 9%). Moreover, the reduction of primary resources related to the use of remanufactured products has significant economic benefits, both for companies and consumers. For companies, the production cost of a remanufactured product is 40–65% less than the production cost of a new one and this reduction is also reflected in the price to the final consumers (Nasr, 2019), which is always one of the main aspects related to the willingness of a consumer in buying a product (Aazami and Saidi-Mehrabad, 2021).

Besides the drivers of RMfg, some barriers to its adoption must be considered. Consumers are often not aware of the environmental and economic benefits of the remanufactured products and can be reluctant in purchasing such products because the perceived quality is lower than new ones (Jakowczyk et al., 2017). Companies need to face very important issues for designing RMfg processes; the most important is that (Sundin and Bras, 2005) RMfg processes are completely different from manufacturing ones, and this implies having production environments designed to be dedicated to RMfg, representing a high investment cost. Moreover, there are barriers directly related to the operations carried out during the RMfg process, which is generally carried out in 6 phases (Caterino et al., 2022): product collection; initial inspection; disassembly; remediation of components; reassembly; testing. Each phase consists of different operations and may be characterised by many issues related to the quality of the returned products, which generates uncertainties in the whole RMfg process (Guide, 2000). To assess the quality of the returned product, an initial inspection is needed to classify the product itself as re-manufacturable or as waste. Nevertheless, different qualities of the same type of returned products generate high variabilities in the costs and times for completing the RMfg process even for the same product, in addition to high variability of the components recovered in a returned item. These aspects have been considered in this paper. In fact, only the cost of product collection and first inspection (which allows a company to understand the convenience of remanufacturing a product) have been assumed to be constant, while the cost of the other phases have been considered as depending on the type of process carried out for the specific product. Moreover, to consider that some products could be disposed of or recycled because of the low-quality level of the returned products, this paper introduced the

Return Rate (RR) factor, which represents the percentage of re-manufacturable products. In this paper, the RR will be one of the variable factors of the system in the simulation. It is worth noting that, even if a product is recycled or disposed of, the costs associated with its purchase and transport for collection are sustained by the company operating in the RMfg context. For such a reason, their impacts on economic and environmental pillars have been considered in the proposed model.

Another important barrier towards the implementation of effective and efficient RMfg processes is the disassembly phase. Disassembly is not simple the reverse of assembly and products need to be designed for RMfg to facilitate the disassembly operations. Moreover, disassembly is often carried out manually by specialized workers. This results in highly variable processing times that generate further uncertainties in the RMfg process. To address this problem, in this study, disassembly has been assumed to be realised by robots, which allow high repeatability of the operations and reduce the uncertainties in the processing time (Ramírez et al., 2020).

After disassembly, the next phases are remediation, reassembly and testing. The remediation phase consists in repairing the disassembled components to restore their original quality. The impact of this phase on the three sustainability dimensions depends on the specific operations to carry out. In this paper, the remediation consists in adding material to the damaged component by using AM. Thus, the sustainability impact of this phase can be analytically calculated by means of LCA and LCC methods if it is known the quantity of material to add for each component.

After remediation, the last phases of RMfg process consist of reassembling and testing the products. These phases have an impact on sustainability, but they have been neglected in this paper because they must be carried out also in the case of new productions. Since the aim is to compare the production strategies, their evaluation can be avoided because they have the same impact on both strategies.

4.2. Additive manufacturing

Several factors must be considered for comparing two different production strategies using AM. First, the amount of raw material required to satisfy the demand for new and remanufactured items is different. Generally, recovering used products (such as in the case of RMfg) may drastically reduce the consumption of raw material.

The amount of material to add impacts on the times to produce items and the energy consumed. More material requires more production time and, consequently, more energy.

The characteristics of the production processes, such as the product quality, build time and energy consumption, vary according to the machine features (laser power, laser diameter, temperature), part design (material density, volume, surface area, supports) and other parameters such as build orientation, scanning speed, layer thickness and hatch spacing. The microstructure, mechanical properties and residual stresses that characterize the printed part depend on the scanning strategy. The build time depends on the build rate (r_b), which is related to the layer thickness (l_t), the hatch spacing (h_s) and the scanning speed (v_s) through the equation (Shi et al., 2016):

$$r_b = l_t \times h_s \times v_s \tag{1}$$

The build rate is also a parameter to consider, together with the beam power P , for determining the energy input needed for the production, which is quantified by the energy density (E_d).

$$E_d = \frac{P}{r_b} \tag{2}$$

Thus, process parameters should be chosen to get close to the optimal range for the printed material, which are shown in Table 2 for some metals in Selective Laser Melting (SLM) (Liu et al., 2018b).

Without loss of generality, in this paper, an SLM machine has been

Table 2
Optimal volumetric energy density for metal powders.

Material	Optimal Energy density [J/mm ³]
CoCrMo	151
316L	40–90
Ti–6Al–4V	74–93
Zr–1Mo	50.2
IN718	116.7

considered for both strategies. The sustainability analysis of SLM is shown in Fig. 3 as indicated by Torres-Carrillo et al. (2020).

The zoom on SLM in Fig. 3 shows the mass flows over the entire process: after the first job, the mass of powder needed to complete a build is composed of reused and raw material. The ratio between raw material and recycled material is the refresh rate (ref). The suitable value for the ref is usually indicated by the suppliers. However, setting the ref close to the packing rate (the mass fraction of consumed material compared to the total amount required for the print) is a good compromise to avoid excessive process waste. The total mass of raw material required to complete a mission is:

$$m_{mission} = m_b^{in} + (N_b - 1) \bullet ref \bullet m_b^{in} \tag{3}$$

Where m_b^{in} is the mass of material supplied into the chamber for every build, and N_b is the number of builds to complete the mission. The mission is the number of parts to be produced according to the market demand. The total energy consumption (E_b) is the sum of the primary energy consumed during the building phase, e. g the energy required to melt the material, and the second energy required to power all the machine's auxiliary systems such as heaters, chillers and control units (Faludi et al., 2017; Gao et al., 2021) Let T_b be the total build time, the energy consumption of a build is:

$$E_b = \bar{P} \bullet T_b \tag{4}$$

Where \bar{P} is the average power consumption over the entire process (Gutierrez-Osorio et al., 2019). Alternatively, let SEC_p be the Specific Energy Consumption of the generic AM process; the process energy consumption can be calculated by adopting the following equation:

$$E_b = m_p \bullet SEC_p \tag{5}$$

where m_p is the printed mass into the build. The SEC of Laser Powder Bed Fusion (LPBF) technologies, such as SLM, ranges between 80 and 600 MJ/kg depending on the building rate (Liu et al., 2018b). It is connected to the printed material and the process parameters. The need to calculate E_b arises from the fact that energy represents the main source of environmental impact for AM processes (Ma et al., 2018).

4.3. The sustainability index

After the definition of the strategies to compare and the system's PDM, KPIs must be identified. In this paper, a sustainability index (SI) has been defined, aiming to identify the areas of convenience for the competing strategies. The three dimensions of sustainability have been considered for the index (Son et al., 2021): economic sustainability (CSI), environmental sustainability (ESI) and order response sustainability (RSI); the last one is usually assumed as the lead time from the product design to the delivery and its social value is linked to the customer satisfaction. CSI is referred to the cost of the mission (MC) for producing the planned amount of products. Likewise, ESI and RSI refer respectively to the mission environmental impact (MEI) and the mission order response time (MT). The sustainability index defined in this paper is an aggregated metric based on the evaluation of MC, MEI and MT for the two production strategies and it is expressed as follows:

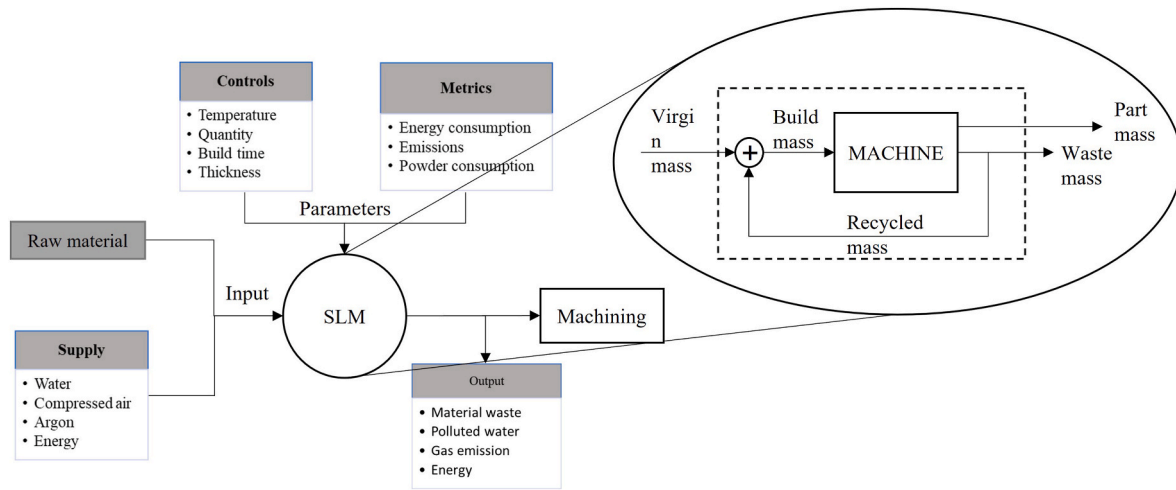


Fig. 3. Sustainability analysis of the SLM process (Torres-Carrillo et al., 2020).

$$SI = w_c CSI + w_e ESI + w_r RSI = w_c \frac{MC^{new} - MC^{RMfg}}{MC^{new}} + w_e \frac{MEI^{new} - MEI^{RMfg}}{MEI^{new}} + w_r \frac{MT^{new} - MT^{RMfg}}{MT^{new}} \quad (6)$$

$$w_c + w_e + w_r = 1 \quad (7)$$

The parameters w_c , w_e and w_r are the weights of the sustainability dimensions, set by the decision-maker according to the sustainability goals of the company. It is worth noting that each metric (MC, MEI and MT) assumes positive values and small values are preferred in the view of sustainability. By looking at eq. (6), the higher the SI (at most equal to one), the more the RMfg strategy is sustainable. Negative values of the SI represent a situation in which producing new items is more convenient than RMfg. However, whatever value SI takes, the single performance related to costs, environment or responsiveness could be different from the SI.

Evaluating the three sustainability performances implies collecting

data related to the production processes. The main processes impacting the sustainability of the RMfg strategy are: i) the collection of the products because it requires transports; ii) the inspection of the products to understand their quality; iii) the disassembly of the products; iv) the production phase, intended as the phase of restoring the original quality of the products by adding materials through AM processes.

In view of the comparison, some common phases of the alternative strategies, such as the reassembly and final testing can be neglected. Viable formulations to measure the MC, MEI and MT for RMfg can be expressed as follows:

$$MC^{RMfg} = C_{collecting} + C_{cleaning} + C_{inspection} + C_{disassembly} + C_{material} + C_{recovery} \quad (8)$$

$$MEI^{RMfg} = EI_{collecting} + EI_{disassembly} + EI_{inspection} + EI_{material} + EI_{cleaning} + EI_{recovery} \quad (9)$$

$$MT^{RMfg} = T_{collecting} + T_{disassembly} + T_{recovery} + T_{cleaning} + T_{inspection} \quad (10)$$

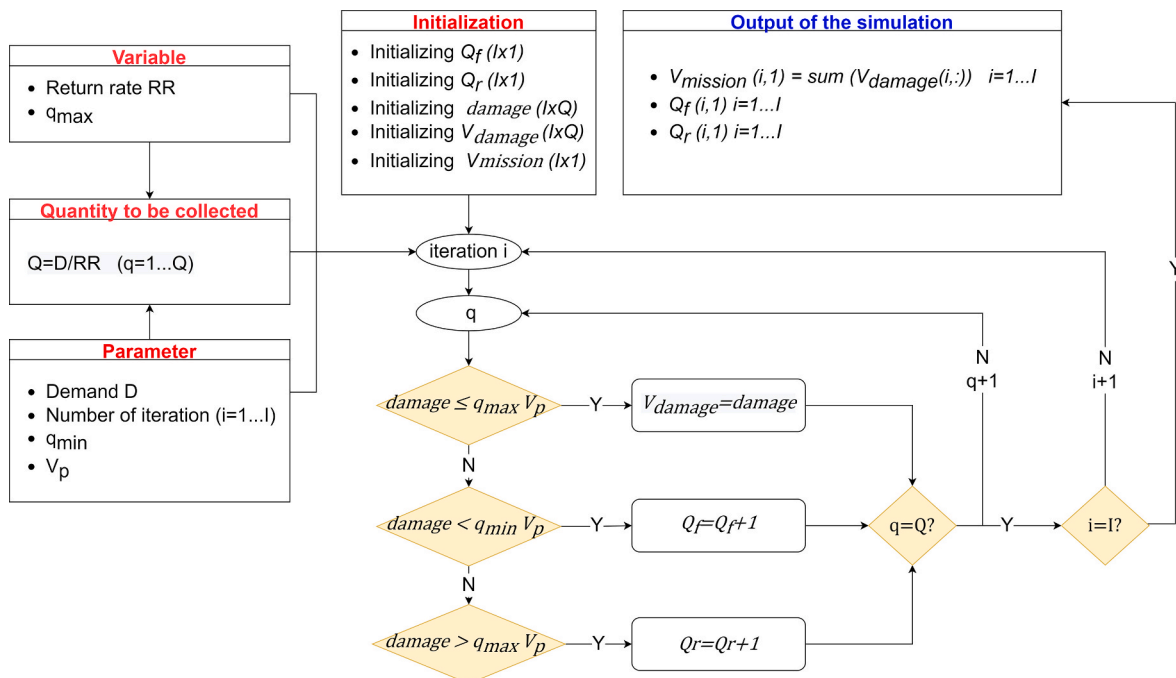


Fig. 4. Flowchart of the simulation.

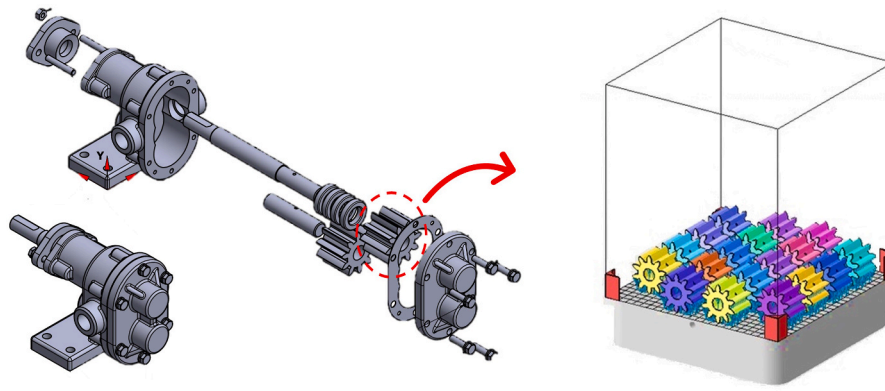


Fig. 5. Assembly of the gear pump and build utilized for producing new gears.

Table 3
Component's features.

Part ID	Material	Density [kg/cm ³]	Part volume [cm ³]	Energy density [J/mm ³]	Emission [kgCO ₂ eq/kg]
Gear	SS316L	0.008	21.301	90 (Liu et al., 2018)	97

Collecting cost ($C_{collecting}$) can be expressed as a linear function of the number of collected products through a unit collecting cost (Ovchinnikov, 2011). It reflects all the efforts required to move dismissed products to the collection centres, including transport, which has a huge impact also on $EL_{collecting}$ and $T_{collecting}$, i.e., respectively, the energy and the time spent on collection. Disassembly cost ($C_{disassembly}$) depends on several factors, most notably the level of automation of the disassembly and the quality of the returned products. To calculate the disassembly cost, the formulation proposed by Ramirez et al. (Ramírez et al., 2020) has been adopted. It expresses the cost of the disassembly when it is executed by robots, the cost of the depreciation of the disassembled components and the costs due to the recovery process (including the overhead cost).

$$C_{disassembly} = c_d \times Q + \sum_{s=1}^4 dp_s \times Q_s + \sum_{s=1}^4 oh_i \times Q_s \quad (11)$$

The factors c_d , dp_i and oh_i are respectively the unit disassembly cost, the depreciation cost of the s -th process ($s = 1$ is RMfg; $s = 2$ is reusing; $s = 3$ is recycling; $s = 4$ is disposing), and the overhead cost associated to the s -th process. The quantity Q represents the total amount of collected products, whereas the Q_s ($s = 1, \dots, 4$) is the number of products assigned to each process after inspection.

A penalty cost (penalty) has been added to consider the loss of profit due to the non-recoverable parts, i.e. parts collected but not suitable for any recovery action, except for recycling or disposal. Assuming that recycling is the only alternative to RMfg and reusing, the penalty is:

$$penalty = (p - r_{rec}) * Q_3 \quad (12)$$

where p and r_{rec} are respectively the retail profit of the recovered parts and the revenue obtained from the part to be recycled.

Table 4
Machine properties.

Machine	Price[€]	Size[mm ³]	Fibre laser [W]	Focal diameter [μ m]	Gas (argon) [l/h]
Renishaw AM250 (SLM)	100,000	248x248x300	200	70	10

Table 5
Build properties.

Part ID	N° of pieces in the build	Build height [mm]	Support volume [cm ³ /unit]	Packing density [%]	Refresh rate [%]
Gear	18	50	1.7	14	14

The recovery operations imply also spending time ($T_{recovery}$) and energy ($EL_{recovery}$), as well as robotic disassembly requires time ($T_{disassembly}$) and causes energy expenditure ($EL_{disassembly}$). Cleaning represents a further important phase during RMfg. The inspection cost can be derived by knowing the unit inspection time (t_{insp}) and cost (C_{insp}).

$$C_{inspection} = C_{insp} \times t_{ins} \times Q \quad (13)$$

Costs, time and energy expenditures associated with the collecting, disassembly and recovery are not sustained in the case of new productions.

Energy consumption, followed by material usage, has been proven to have a major role in determining the environmental sustainability of AM processes (Faludi et al., 2017). The environmental impact due to the material and energy consumption of the AM process has been calculated as follows:

$$EL_{material} = E_{mat} \bullet m_{mission} \quad (14)$$

$$EL_{energy} = E_{mission} \bullet CES_{country} = \sum_{i=1}^{N_b} E_{b,i} \bullet CES_{country} \quad (15)$$

where E_{mat} is the embodied energy of the material; $E_{b,i}$ indicates the expected energy consumption of the i -th build during the mission (eqs. (4) and (5)), while $CES_{country}$ is the carbon emission signature of the country where the production takes place (Jeswiet and Kara, 2008). Both $EL_{material}$ and EL_{energy} contribute to the environmental impact of RMfg and manufacturing of new products.

4.4. Montecarlo simulation

Simulation is the last step of the proposed methodology. It is necessary for implementing a what-if logic to evaluate the sustainability

Table 6
AM process parameters.

Hatch spacing [mm]	Layer thickness [mm]	Scanning speed [mm/s]	Time to scan unit area [s/mm ²]	Coating time per layer [s/layer]
0.1	0.02	1100	0.013	10

Table 7
Specific build times.

Warm up time [h]	Cool down time [h]	Job assembly time [h]	Machine setup time [h]	Removal time [h]
1	4	1	1	3

Table 8
Unit costs.

Pre-processing labour cost [€/h]	Machine labour cost [€/h]	Inert gas cost [€/m ³]	Energy cost [€/kWh]
20	20	7	0.20

of the competing production strategies in different scenarios. In this study, the number of returned products and their damage degree have been adopted as uncertain process variables for the RMfg strategy and their variation changes the scenario. The Montecarlo method has been adopted to simulate the systems' behaviour. It simulates thousands of possible scenarios of the RMfg strategy to assess its sustainability against the sustainability of the new production strategy, which has been set as the reference scenario according to Eq. (6). Fig. 4 illustrates the logic of the simulation.

The aim is to simulate a typical RMfg mission (collection, inspection, disassembly, remediation).

In each iteration, the manufacturer collects Q items. The amount of collected products depends on the market demand and the RR, which has been set as a random variable. The collected products are distinguished based on their damage level, also set as a random variable. The damage has been considered as the lack of material due to fatigue, erosion or any other deterioration process. Thus, the damage can range between zero (no damage) and the product's volume. Only the products whose damage is between a minimum value ($q_{min}V_p$) and a maximum value ($q_{max}V_p$) will be repaired. Products characterised by damage higher than $q_{max}V_p$ will be recycled. Instead, products having a damage level under $q_{min}V_p$ will be considered reusable without any repair process. The output of each iteration is the total volume of material to add for restoration and the total number of products to be recycled and reused. Based on this information, MC, MEI and MT are calculated for the RMfg strategy. Here, RR and q_{max} , which range between 0 and 1, have been chosen as the system's variables that determine the set of solutions (the domain) for the values assumed by the SI. Whereas, the market demand (D), the lower threshold (q_{min}) and the part volume (V_p) have been assumed as parameters for the simulation. It is worth noting that RR does not depend on the decision maker, but it is influenced by sales, the life expectancy of products and the return behaviour of the customers (Liang et al., 2014). The threshold q_{max} is set by the decision-maker. The output of the simulation is the expected amount of material volume required to complete the RMfg mission. The total repair cost (C_{repair}) can be derived by assuming a unit repair cost (C_{repair}):

Table 9
Build report.

Capacity utilization [%]	Completion time [days]	Build rate [cm ³ /h]	Total cost [€/build]	Specific build cost [€/cm ³]	SEC [MJ/kg]
13.55	3.21	5.72	578.59	1.42	142

Table 10
Data about unit recovery costs, retail price and revenue obtained from the recycling of one gear.

Part ID	p [€/unit]	r_{rec} [€/unit]	OH_1 [€/unit]	OH_2 [€/unit]	OH_3 [€/unit]	DP_1 [€/unit]	DP_2 [€/unit]	DP_3 [€/unit]
Gear	10.78	0.084	0.103	0.041	0.041	0.259	0.173	0.207

Table 11
Unit collection, disassembly, inspection and reparation costs.

$c_{collect}$ [€/unit]	c_d [€/unit]	c_{insp} [€/h]	t_{insp} [h]	c_{repair} [€/cm ³]
2	10	10	0.5	3

$$C_{repair} = c_{repair} \times V_{mission} \tag{16}$$

The unit repair cost includes the variable costs associated to the utilized resources (materials, energy, machines, etc.).

5. Results and practical insights

5.1. Case study and input data

The methodology has been tested considering the gear of a gear pump (Hartono et al., 2023). Fig. 5 shows the whole assembly of the gear pump and the single-gear components into the printing build for the case of a new production strategy.

Although the use case is very specific, it is useful to assess the effectiveness of the methodology and to show the implementation course. The application describes how to collect the variables of interest to build the PDM and calculate the sustainability performance of the competing production strategies. Moreover, findings give interesting indications about the advantages of adopting AM technologies to repair damaged products rather than produce new ones. Adopting a case study to show the way of implementing the methodology, as well as to better explain its usability and effectiveness, is a very common approach (Hao et al., 2023) and it was used in this study.

This application aims to evaluate the SI for both strategies and to identify the areas of convenience by measuring their performance in terms of economic and environmental impact as well as manufacturing responsiveness towards the market demand. Two main assumptions have been made to conduct the analysis.

1. Some mutual upstream processes, such as the transport of raw material, and downstream processes (finishing, assembly and testing) have been neglected in this phase. These processes are common to the two production strategies, so they can be neglected for comparison.
2. Uncertainty about the arrival time of the cores (used products), as well as the environmental impacts and costs deriving from cores transportation have been neglected for the RMfg strategy; this second assumption is conservative for the new production strategy.

The component's properties are listed in Table 3.

The mission costs, environmental impact and completion time associated with the production of new gears have been calculated by adopting the mixed production cost allocation model for AM (MiPro-CAMAM) (Fera et al., 2017). It allocates the total cost of a build to each geometry inside the build. It considers the cost of preparing geometry data (BUILDJOB) and the job (PREP), the machine set-up cost (SETUP), the actual building cost (the printing phase) (BUILD) and the removal cost (the activities required to remove the printed products from the machine chamber/plate) (REMOVAL). The parameters used in this paper to model the printing process for the new production strategy are reported in the following Table 4, 5, 6, 7 and 8.

For both strategies, the machine's hourly cost was calculated by considering 7000 operating hours per year, which represent 80% of the

Table 12
Resource and electricity consumption of two cleaning technology.

Cleaning Technology	Resource	Amount
High-temperature decomposition	Electricity	0.4 kWh
	Diesel	5.6 kg
Liquid blasting cleaning	Electricity	0.67–0.88 kWh
	Water	0.4 kg
	Abrasive	15–19.8 g

solar available time. This assumption is justified by the fact that AM is almost fully automated. The unit build time (Eq. 17), associated with the BUILD phase is derived by summing the unit warm-up time (w.up), the unit cool-down time (c.down), the unit scanning time (scan.) and the unit coating time (coat.). Moreover, it is adjusted by considering the Overall Equipment Efficiency (OEE), which considers the inefficiency due to unavailability, low performance and low quality during production (Basak et al., 2022). Table 9 shows KPIs related to the build for a new production.

$$Unit\ build\ time = \frac{w.up + c.down + scan. + coat.}{OEE} \quad (17)$$

Concerning the RMfg strategy, the data for disassembly operations (precedence and disassembly times), part retail price (p), revenue from recycled parts (r_{rec}), overhead (OH) and depreciation (DP) recovery costs have been obtained from Ramirez et al. (Ramírez et al., 2020) for the case of a robotic disassembly. Data are listed in Table 10. The unit collection, disassembly and inspection costs are listed in Table 11.

Once the product is disassembled, the cleaning phase is carried out. Two cleaning steps involving high-temperature decomposition and liquid blasting are necessary. For such activities, the data used have been retrieved from Peng et al. (2017) and they are reported in Table 12.

After cleaning, the gear is inspected to determine the damage, which is represented by the loss of material due to cracks, blowholes, corrosion and surface defects.

As for the MiProCAMAM, the RMfg process has been modelled in a mixed Excel®-Matlab® environment considering the same input parameters as new productions (AM machine, production rate and SEC). A Montecarlo simulation has been run considering a market demand of 100 units by varying both the RR and the q_{max} from 10% to 90%. The number of iterations has been set to 10⁵, the lower threshold q_{min} has been set to 2%, meaning that parts with damages under 2% of the gear volume are reused without being repaired. The same weight (0.33) has been set for w_c, w_e, w_t, meaning that the three considered sustainability dimensions have the same importance for the decision-maker.

5.2. Results

Fig. 6 shows the distribution of costs over the manufacturing stages and the impacts of machine, energy, material and gas costs on the

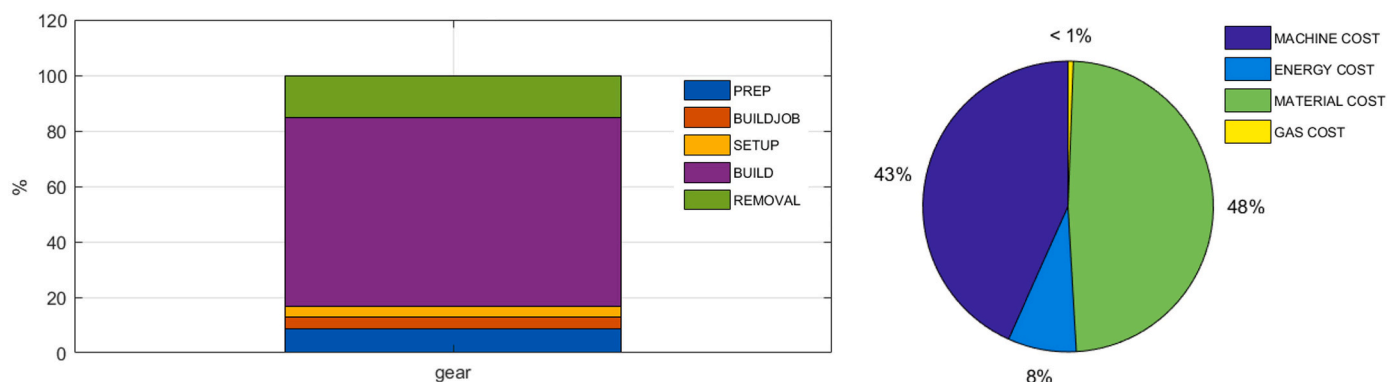


Fig. 6. Distribution of costs over the printing process and impacts of machine, energy, material and gas on the composition of the total build cost.

Table 13
Sustainability performance of producing newly printed gears.

Sustainability dimension	Mission performance
Economic impact [€]	1823.10
Environmental impact [kgCO ₂ eq]	1892.20
Order response time [days]	17.46

composition of the total build cost in case of new productions. In this application, the active building stage accounts for more than 60% of the total cost deriving from the completion of one build. The material represents the main cost, followed by machine and energy costs. These findings have been obtained by setting OEE to 90%.

The comparison between the two manufacturing strategies is carried out for a defined production mission, meaning a fixed product demand. For the production of 100 new gears through the predesigned build, the economic and environmental impacts and the order response time of the mission are reported in Table 13. The CES has been set to 118 kgCO₂eq/MJ, according to the Italian power grid.

The performance of the new production strategy represents the reference scenario for calculating the SI index.

Fig. 7 illustrates the experimental surface related to the mean values assumed by the SI over the simulation by changing the RR and q_{max}. Fig. 8 represents the areas of convenience for both production strategies. The curves represent the zero-level contour lines of the 3d plot for the mean (red curve), minimum (green curve) and maximum (blue curve) values assumed by SI during the simulation. Remembering that the RMfg strategy is preferred to the production of new products when SI is positive, the areas above the curves are the locus of points (RR, q_{max}) for which RMfg is more sustainable than new productions according to the current set of process variables and weights. The convenience region for the RMfg strategy is at low RR and high q_{max}. The region under the curves is the locus of points for which printing new items is the most sustainable strategy. The region between the green and blue curves is uncertain.

Fig. 9 shows the box plots of the three sustainability metrics (CSI, ESI, RSI) and highlights the median, first and third quartiles and the outlier values of each one.

RMfg is always the less cost-effective solution for this type of product, while it is always the less impacting strategy on the environment. The results for RSI are very balanced because the index fluctuates around zero.

Further analyses can be conducted by changing the weights of the metrics according to the company policies. Fig. 10 illustrates how the zero-level contour for the mean SI changes when the weight (w_e) of the environmental impact increases, while the weights of the other 2 dimensions are the same. It can be noted that the area of convenience for RMfg increases as the importance of the environmental impact increases.

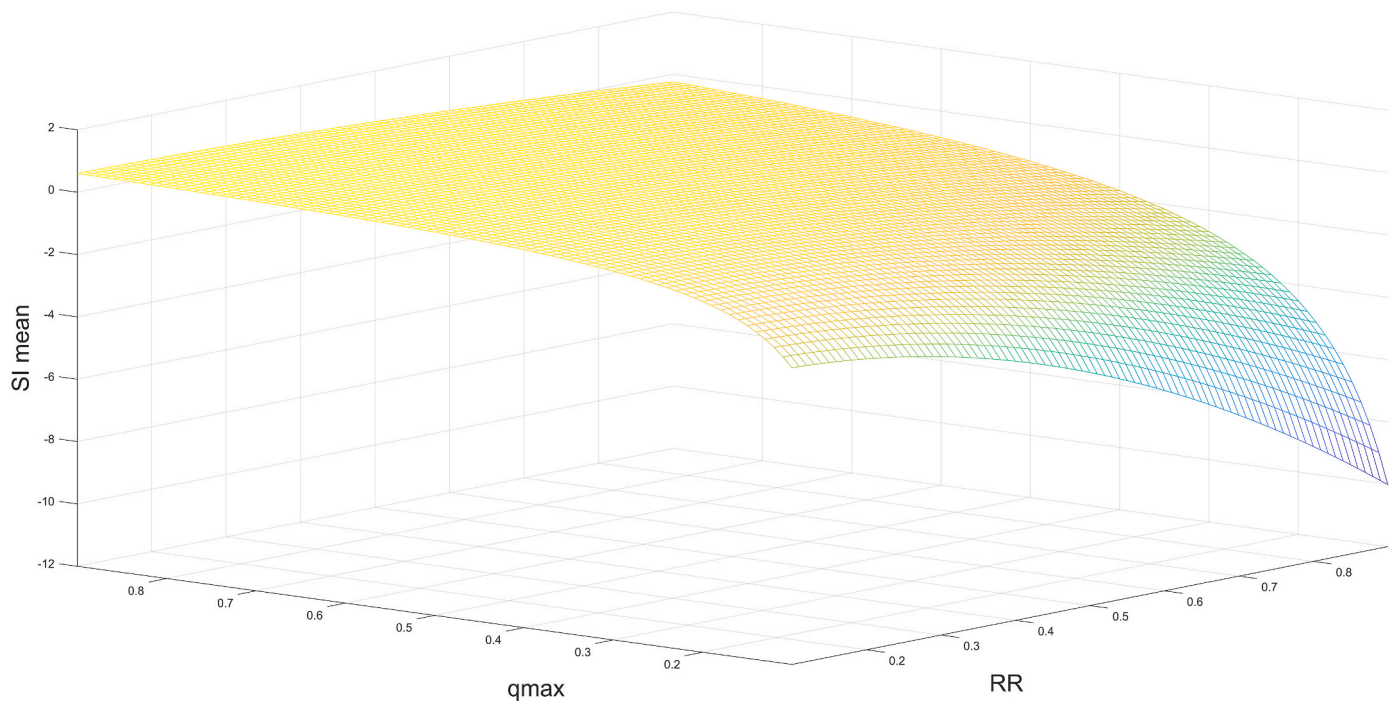


Fig. 7. Average SI over the simulation to vary of RR and qmax.

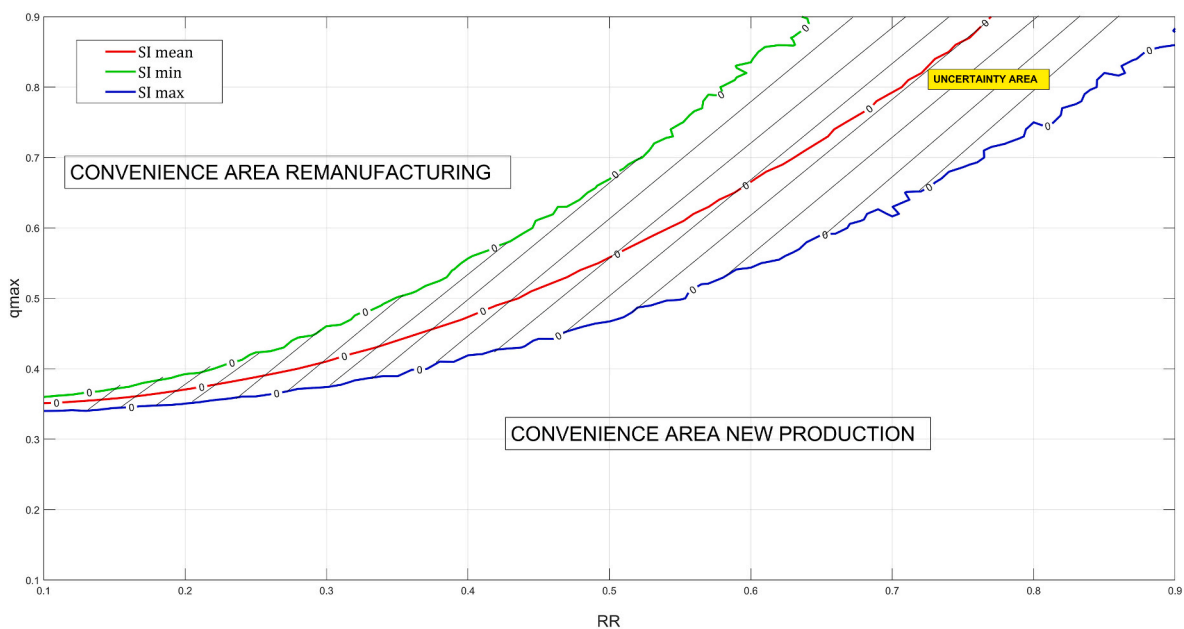


Fig. 8. Areas of convenience for the two analysed production strategies.

The next analysis is carried out considering two different production technologies, one for the production of the new items and one for RMfg. Fig. 11 shows the outcomes deriving from the comparison between the production of new gears through SLM and the RMfg of worn items through the laser cladding process, whose important process parameters are reported in Table 14 (Peng et al., 2019). Laser cladding, a direct energy deposition technology, is one of the most used techniques for reconstructing and repairing damaged products (Rahito Wahab and Azman, 2019). It is particularly suitable to remanufacture fractured blades of impellers and turbine wheels (Peng et al., 2017).

Fig. 11 demonstrates that using laser cladding technologies, instead of SLM machine, favours the RMfg strategy; this happens because the

laser cladding is more environmentally effective than SLM (ESI increases) and also more responsive (RSI increases), as shown in Fig. 12. Also, the costs of RMfg become comparable with those of new products introducing laser cladding.

All results are valid under the two starting assumptions. Specifically, the second assumption is conservative for the new production strategy. Including transportation costs would make the new production strategy more cost effective than RMfg. However, the RMfg strategy has a strong margin in terms of environmental impact and production responsiveness in the laser cladding scenario: about 40% more eco-friendly and about 80% more responsive.

Further managerial insights can be derived by adopting this

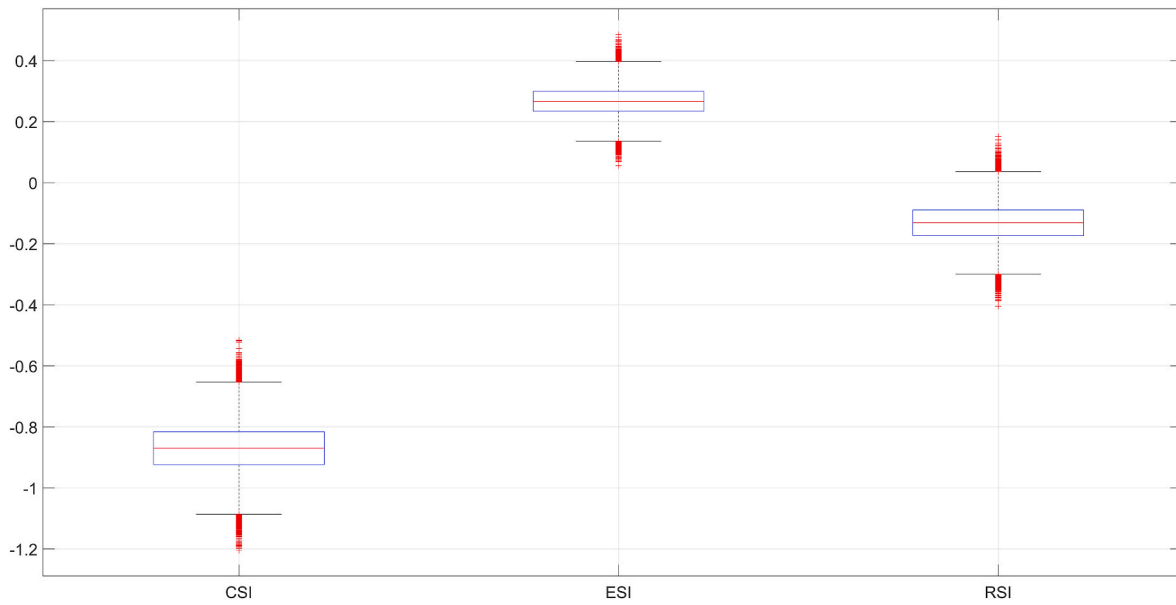


Fig. 9. Box plots of the CSI, ESI and RSI.

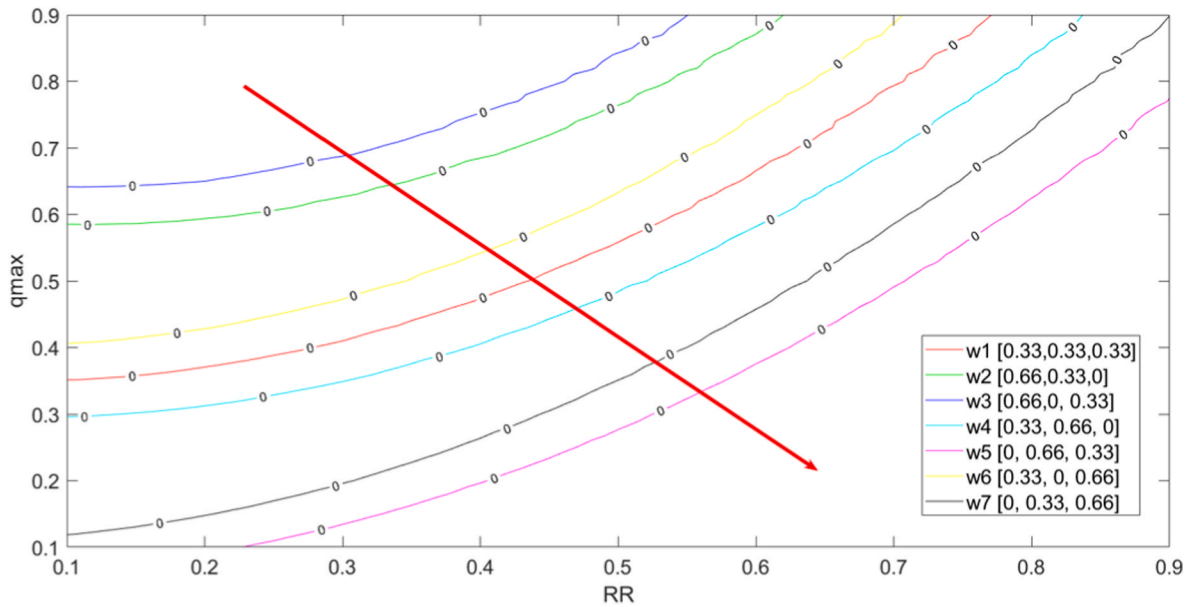


Fig. 10. Modification of the areas of convenience by varying the importance of the environmental impact over the rest of the sustainability metrics.

approach. A sensitivity analysis has been conducted to evaluate how the decisions of managers could change according to the variation of crucial parameters. Looking at the MC^{RMfg} , Fig. 13a shows the percentage weights of all cost items when RR and q_{max} are set to 50%; whereas, Fig. 13b highlights the time spent in each phase. The repair, the penalty and the inspection costs turn out to be the most impacting cost items on average. This result has been obtained by adopting the unit costs reported in Tables 10 and 11. The repair cost depends on the total volume of material to be added during the mission. Thus, it increases with the decrease of q_{max} .

The penalty cost is linearly dependent on the number of products to be recycled which, in turn, decreases with the increase of q_{max} . Therefore, the decision about q_{max} implies a trade-off between repair cost and penalty cost (Fig. 14). The analysis allows determining the value of q_{max} which minimises the sum of the repair and penalty costs (red point in Figure). The repair cost is sensitive to the value assumed by the unit

repair cost (Fig. 15). In fact, as the unit repair cost decreases, the minimum is reached for higher values of q_{max} , i. e. increasing the number of products to be remanufactured.

Decision makers could also be interested in evaluating how the MT^{RMfg} varies by changing some parameters. According to Fig. 13b, inspection and repair are the two most time-consuming phases (according to the adopted data). The decision-maker could be interested in determining the scenarios where repair and inspection times are similar. Fig. 16 shows the trend of the ratio between the inspection time and the repair time by varying the unit inspection time (repair time is fixed).

When the unit inspection time increases, the ratio between inspection time and repair time tends to one by increasing values of q_{max} .

Findings show that the most suitable q_{max} changes with the variation of the process parameters, such as unit costs and times.

It is worth noting that the analysis has been carried out by considering the values of RR and the threshold q_{max} in the range 0–1. While

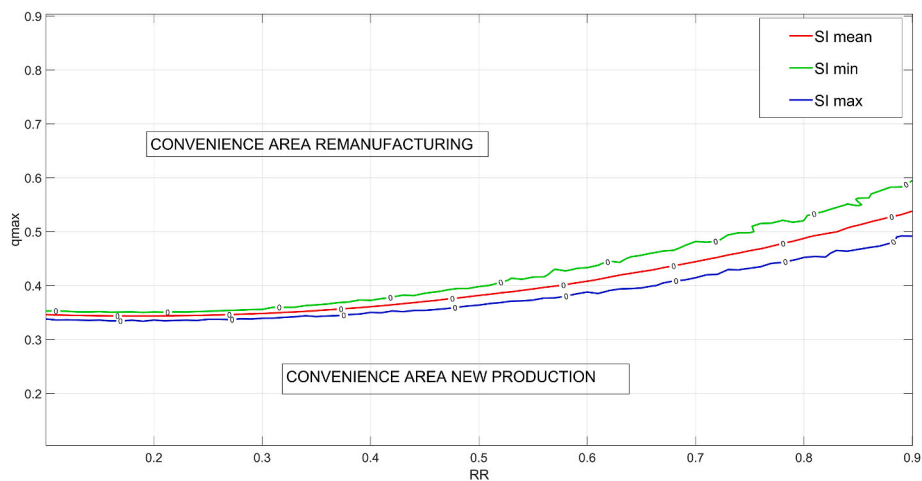


Fig. 11. Areas of convenience in the case of Laser Cladding.

Table 14
Parameters used for the LC process.

Technology	Machine price [€]	Laser Power [W]	Scanning speed [mm/s]	Powder feed rate [cm ³ /h]	SEC [MJ/kg]
Laser cladding	~ 95000	800	9	75	362

extreme values are realistic for the RR, the same cannot be said for the q_{max} (it should not be realistic that a worn gear lose so much volume during operations). However, the purpose of this application is to demonstrate the methodology’s usefulness, showcase its practicality, and highlight its implications for managers. Additionally, it serves as an opportunity to evaluate the sustainability of the analysed production scenarios and the technologies involved.

5.3. Discussion

This section presents the evidence that arose from the application of the proposed model, describing what can be learned from this study and

expanding knowledge on sustainability of productions strategies from a theoretical and practical point of view. The model proposed in this paper and the results of its application contribute to the literature in different ways. Starting from the model, it introduced a methodology to compare different production strategies based on sustainability aspects. In particular, the methodology consists of 4 steps, related to: (i) the identification of the production strategies to compare; (ii) the identification of the sustainability objectives by the company and the related KPIs; (iii) the definition of the mathematical models representing the behaviour of the production strategies; (iv) the simulation of the production scenarios through a proper sustainability assessment method. The strength of the model is given by its generality, which allows to adapt it to any production strategy. While past models usually aimed to evaluate different production technologies (Seuring and Müller, 2008; Vinodh et al., 2014; Xia et al., 2017), this model has the potential to combine them with different strategies to assess. This is a strong advance, which allows to evaluate the overall performance of the production system and not only those of the production technologies. Thus, the model presented in this paper allows us to give a positive answer to RQ1, having demonstrated that it can be applied to compare different production strategies based on sustainability pillars.

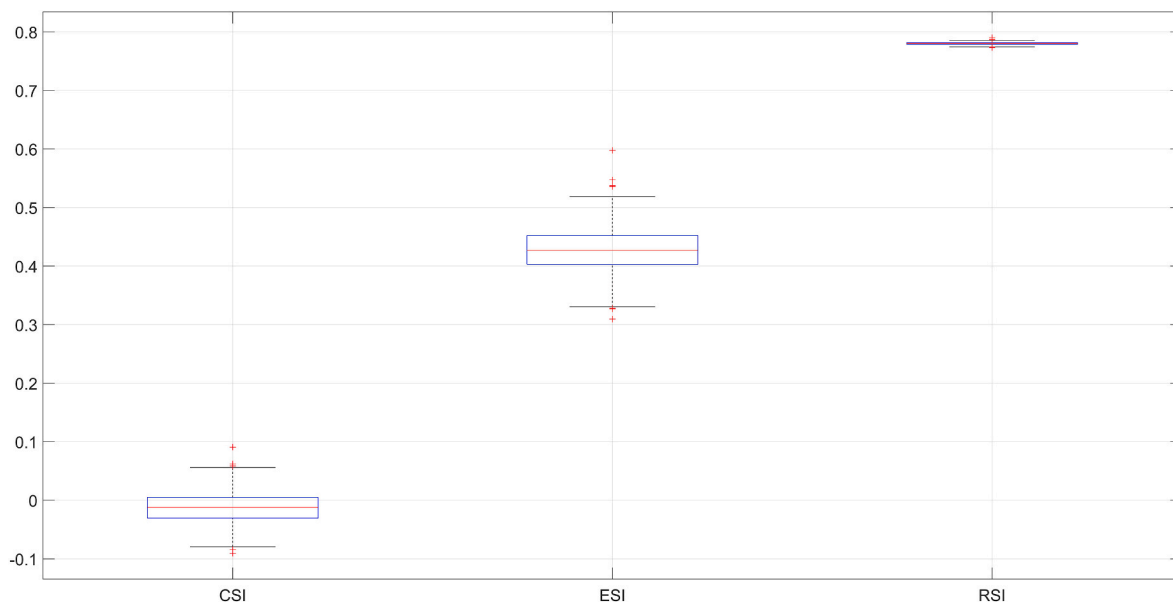


Fig. 12. Box plots of the CSI, ESI and RSI in the case of LC as repair technology.

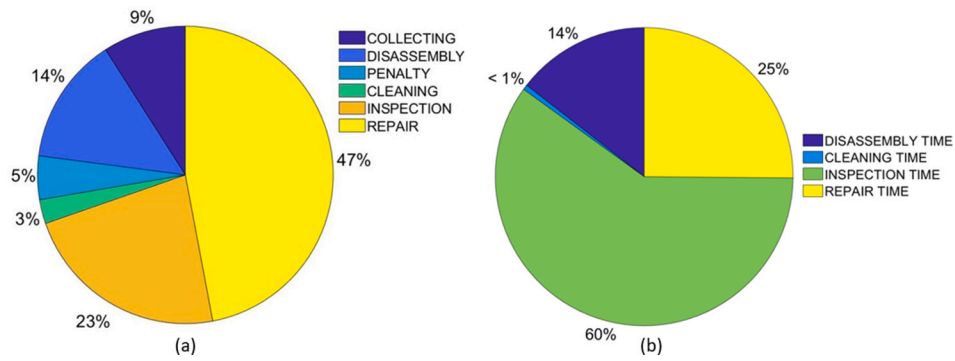


Fig. 13. (a) Percentages of cost items in RMfg operations; (b) Percentage of completion times in RMfg operations.

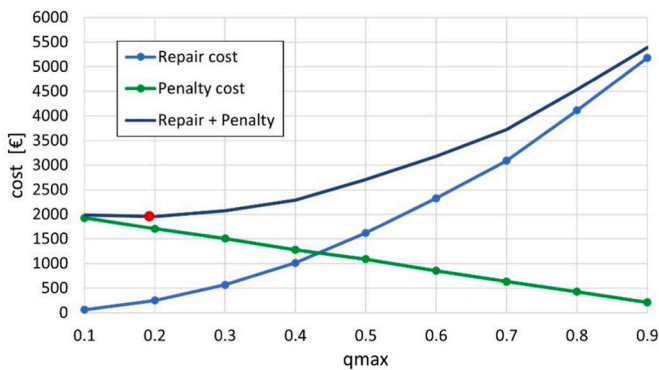


Fig. 14. Trade-off between repair cost and penalty cost in RMfg operations.

Concerning RQ2, the application of this methodology helps to expand the knowledge about the impact of RMfg on sustainability and generally to confirm that AM can be used not only for producing new objects, but also for repairing used ones, as previously demonstrated (Liu et al., 2018a; Kandukuri et al., 2021). The results of this study allow to conclude that the production of new items is to prefer to RMfg when the return rate is high, and the q_{max} is low. This is in line with expectations because a high RR means that many of the remanufactured products will not be sold because the offer is higher than the market demand, which is influenced by the low perceived quality of remanufactured products (Jakowczyk et al., 2017). The other big issue of RMfg is linked to the quality of the returned products, which often leads RMfg companies to waste them and thus lose money because of their low quality (Guide, 2000). The findings of this study support this theory, confirming the problem in buying products without an appropriate preliminary control on their quality. Early findings from this work also underline that the product quality should be considered as a crucial driver for promoting sustainable production strategies. Considering the single pillars of sustainability, researchers depict RMfg as a source of

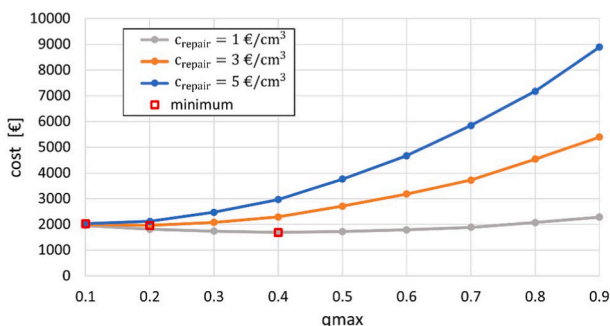


Fig. 15. Repair cost plus penalty cost by varying c_{repair} in RMfg operations.

economic savings for companies and consumers (Nasr, 2019). A different result is registered in this study, where the results showed that the cost of the RMfg strategy is higher than the new production strategy. This result could be justified considering the type of product considered in this study.

In fact, for the small gear analysed in this study, the impact of the collection, disassembly, cleaning and inspection costs is very important; this makes the RMfg alternative the worst in terms of economic efficiency. It is interesting to note that the same result is found when changing the production technology. Moving from an SLM machine to a laser cladding, results show that it is possible to reduce the economic gap between the production strategies, but RMfg keeps being the worst one. On the other hand, findings from the case study represented in Figs. 9 and 12 allow to conclude that RMfg has a better behaviour than the new production from the environmental point of view. The reason is that the use of new materials is very limited in comparison to the new production strategy. This corroborate past literature, which addresses RMfg as an environmental-friendly strategy (Eionet, 2021; Sarkar and Bhuniya, 2022). Considering the social pillar of sustainability, the results highlight that the two strategies have very similar times of response to the market. This is a milestone in the field of RMfg because, as showed in Table 1, this paper is the only one that also considered a social pillar in RMfg.

Finally, considering the overall SI index, outcomes from the literature state that the total sustainability of the RMfg processes needs to be improved, especially from the economic point of view (Liu et al. (2018a)). Our results confirm those findings and show that while the environmental and social positive contribution can be demonstrated, the economic convenience of RMfg needs to be improved.

In addition, this application demonstrated that, a change in the production technology, also affects the final sustainability scores. As stated, passing from an SLM to a laser cladding machine for the RMfg strategy improves the RMfg costs, reducing the gap with the new

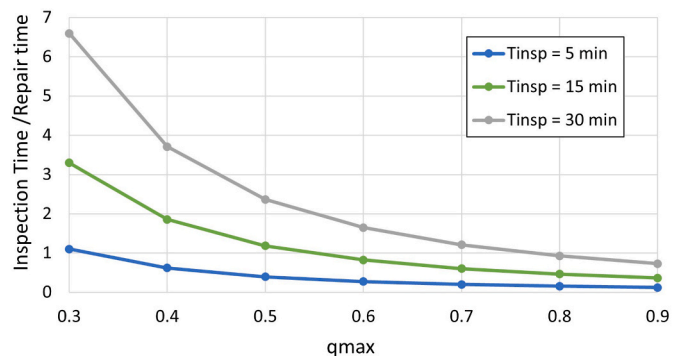


Fig. 16. Trends of the ratio between Inspection time and repair time by varying t_{insp} .

production strategy. In fact, although laser cladding is more energy intensive than SLM, it has a higher production rate, which allows to drastically reduce the active repairing time (the phase of material addition). Similar conclusions have been formulated by Peng et al. (2017), who have discussed the convenience of laser cladding machines in terms of environmental performances, mainly due to a greater efficiency in the use of materials, less absorption of electricity and a reduced response time due to its reduced repairing time.

The model also demonstrated to be feasible to be used to simulate different companies' visions and needs, translated in the model as different weights of the three sustainability pillars or the change of important parameters, such as the return rate and q_{max} . The sensitivity and scenario-based analyses conducted in the application demonstrated that it is possible to evaluate how the costs change according to these parameters. Therefore, while SI can be used to determine the areas of convenience of the alternative production strategies, sensitivity and scenario-based analyses are useful to validate the methodology and to find the most suitable values of the decision-making variables to vary the most interesting managerial parameters. In this specific application, parameters have been changed to evaluate how the costs change accordingly. The results demonstrated that the repair and penalty costs are sensitive to quality changes. In particular, the repair cost is minimized for q_{max} values around 0.4, i.e. when the maximum missing material is 40% of the original volume.

6. Conclusions

Sustainability assessment poses a significant challenge for modern companies. While existing literature has mainly focused on studying the impact of production technologies on sustainability pillars, evaluating the sustainability of various production strategies remains an open issue due to the complexity of modelling entire production processes. To address this issue, this study presents a methodology for the comparison of different production strategies based on sustainability aspects. The novelty of this paper and its main contribution are in the methodology that, differently from the current literature, aims to act as a decision support system for managers that need to evaluate the economic, environmental and social benefits for the choice of the best production strategy based on their specific needs. The methodology comprises four phases, each requiring specific input parameters and producing outputs that often serve as inputs for subsequent phases. The three pillars of sustainability are considered through the economic convenience, environmental impact and order response time of each strategy. These dimensions are combined into a single index, called SI, which defines the areas of convenience of the production strategies according to predefined variables, chosen according to the company's objectives and opportunely simulated to mimic various production scenarios. Moreover, the possibility of conducting sensitivity analyses may provide significant managerial insights for decision makers. The impact of changing production scenario on the sustainability pillars can be easily evaluated and the information related to some specific indices (CSI, ESI, RSI) could be retrieved by the model.

The methodology has been applied for two different production strategies: RMfg, which promotes the CE principles, and new productions, both operated through AM technologies. The return rate and the quality of worn parts were adopted as scenario variables to determine the evolution of the SI, while the single pillars (economic, environmental and response time) were evaluated through LCA methodologies. The results demonstrated the model's applicability sensitivity to changes, since altering the SI weights or changing the AM technology led to different outcomes compared to the initial experiment. The application also demonstrated that, for small items such as the gear considered, RMfg might not represent a good solution due to the high impact of the costs of collecting, disassembling and cleaning the products. This insight is a significant contribution to the current literature, which addresses RMfg always as a more cost-effective strategy than new

productions. However, these results also depend on the specific AM technology considered. In fact, in the second application, in which laser cladding was used as AM technology, the economic index of RMfg improved.

Nevertheless, the methodology has some drawbacks, which also represent the main limitations of this paper. Some process variables, such as resource consumption and build time, were treated as deterministic factors, though they may be subject to variability in real-world scenarios. Furthermore, the RMfg strategy also has other open issues, not considered in this paper: for example, the arrival time, intended as the time in which the products to remanufacture are available, is an uncertain variable, but it was not modelled in this paper. Moreover, the impact deriving from the transportation of products from the point of use (point of collection) to the factory was neglected, influencing the final scores.

To mitigate these drawbacks, one approach is to model the process variables used for the simulations based on statistical processes, to obtain more precise data for mathematical models. The same approach could be used to model the uncertain variables related to the RMfg strategy, such as the arrival time, the type of product, the market and, in general, all the boundary conditions of the production system. Another way to address uncertainties is to simulate the variability of these uncertain factors, generating multiple scenarios to better prepare managers for different cases. Future research in this field will implement these approaches, by modelling the deterministic variables considered in this paper by means of statistical analyses and stochastic or fuzzy models. Additionally, other multi-criteria decision-making methods will be explored, incorporating multiple attributes for each sustainability dimension. Finally, alternative simulation methods will be tested, moving beyond the Montecarlo method utilized in this paper.

CRedit authorship contribution statement

Pasquale Manco: Conceptualization, Methodology, Software, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing. **Mario Caterino:** Conceptualization, Methodology, Formal analysis, Writing – original draft, Writing – review & editing, Visualization. **Marta Rinaldi:** Data curation, Writing – review & editing, Supervision. **Roberto Macchiaroli:** Writing – review & editing, Supervision, Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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