



# How can patent-based prospective life cycle assessment be used for eco-design?

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## Abstract

Over the years, eco-design methods increasingly refer to the product conceptualization phase, guaranteeing increasingly sustainable results. To move in this phase in the most strategic way, it is necessary to seek solutions related to design interventions and reliably select the most sustainable options. This study proposes a new method to actively use the prospective LCA in eco-design, for the identification and evaluation of solutions to solve an environmental problem, defined at the detail level of design features. Both the solutions and the data needed to evaluate their environmental impacts prospectively are extracted from patents through a systematic procedure, ensuring compliance with the quality and reliability requirements prescribed by the ISO 14040 and ISO 14044 standards. The more general result highlighted by the case study is the comparison between prospective LCA and eco-design, from which it emerges how the former can actively support design rather than merely evaluating existing solutions. In patents, solutions at the level of detail of design features and technical parameters can actually be found and evaluated at this level through prospective LCA. Eco-design conducted according to these solutions makes it possible to address environmental problems related to excessive consumption of resources associated with one or more phases of the life cycle of a product component. Beyond new theoretical speculations on the relationship between prospective LCA and eco-design, this study has helped to show that a patent search, also conducted according to the criteria of the ISO standards, allows this intersection to close the circle on the eco-design. In this way, it is possible to be surer of finding and selecting the design solutions that can actually solve the environmental problems of a product.

**Keywords** Prospective LCA · Eco-design · Patents

## 1 Introduction

Environmental sustainability has increasingly become a primary requirement in new product development. As a result, the approach of eco-design has changed over the years from an a posteriori to an a priori view. In other words, rather than correcting environmental problems after they arise in finished products, recent eco-design methods aim to prevent these issues during product conceptualization (He et al. 2020). Likewise, the role of eco-assessment has also changed from the need to assess the finished product's environmental performance during functioning to the need

to assess the design solutions to be developed (Thonemann et al. 2020).

The prospective LCA (Arvidsson et al. 2018) was developed to assess the sustainability of solutions that are still under development, such as concepts and emerging technologies, while ensuring the methodological rigor and data quality of the LCA according to ISO 14040 (ISO 2006a) and ISO 14044 (ISO 2006b) standards. To do this, in the prospective LCA the background inventory, composed of the measured data on the product, is replaced by the foreground inventory, containing prospective estimates, on the future operation of the product when it is developed.

However, the integrations proposed in the literature between prospective LCA and eco-design still have some limitations.

- The object of evaluation of the prospective LCA is not design interventions on the components of the product, but the future evolutions of the components, which are

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considered collectively. For instance, the prospective LCA is used to assess if a future battery (component) of a smartphone (product) will be more sustainable than the current one. Consequently, the provided suggestions are limited to the replacement of the entire component (e.g. Akizu-Gardoki et al. 2022; Foschi et al. 2020; Boix Rodríguez et al. 2023). However, there is no evaluation that takes into account future evolutions of the design features, e.g. a dimension, to clarify in which direction it is more appropriate to intervene on the current product.

- The limitations of the prospective LCA remain, such as the lack of shared criteria and tools to support (Adrianto et al. 2021). These limitations therefore undermine the objectivity of the evaluation of ideas in eco-design, negatively influencing decision-making.
- There are not even integrations between prospective LCA and technological forecasting in eco-design. Prospective LCA aims to understand the evolution of a component to predict its future environmental impacts, but does not suggest how to implement the identified solutions into the product. Technological forecasting instead does the opposite (Haleem et al. 2019).

The assumption of this study is that prospective LCA can be actively used to do eco-design, that is, to search for sustainable solutions, and not just to evaluate them. This can be possible by exploiting the technical knowledge that in prospective LCA is used to build the foreground inventory. The objective of this study is to investigate the intersections between prospective LCA and eco-design in relation to the identification of solutions and their selection.

To fulfil this purpose, a new eco-design method, in which prospective LCA is actively used in the search for solutions to environmental problems, was proposed in this study. The proposed method explains how to extrapolate from patents, in a systematic way, not all possible future evolutions of the current product, as in the patent-based prospective LCA, but solutions that can solve its environmental problems. Thus, the method quantitatively and prospectively assesses the environmental sustainability of such solutions. In addition, by taking advantage of the technical information extracted from patents, the level of detail of identified solutions and their environmental assessment is more detailed as it relates to technical parameters and design features. Then the most sustainable ones can be considered to redesign the product.

The proposed method introduces some innovations from previous contributions in the literature to fill their research gaps.

- The intersections between prospective LCA and eco-design are analysed according to the new perspective of idea generation instead of downstream of eco-design, where prospective LCA is used only to evaluate the idea

(Ricciotti et al. 2023), or upstream, where prospective LCA results are used for the future eco-design (Dong et al. 2022).

- Both the solutions and the data used for their evaluation are extrapolated from patents. Some previous contributions extrapolate solutions from patents, assessing their sustainability in a qualitative or less rigorous way than the LCA does (Liang 2023). Other contributions instead use patents to support prospective LCA, but without extracting technical knowledge from patents to support eco-design (Wrzesińska-Jędrusiak et al. 2022).
- The level of detail with which eco-design solutions are identified and evaluated, i.e. the eco-design features is higher than that of the other studies in the literature, which typically stop at the components (Akizu-Gardoki et al. 2022).

## 2 Literature background

In the literature, many authors have proposed the use of LCA to support eco-design. In all of them, there is always a clear distinction between the LCA which is always applied to evaluate environmental problems to be solved or generated solutions and some eco-design methods or tools used to generate the solutions (Rossi et al. 2016). Instead, what distinguishes them is the level of detail to which the LCA is applied in eco-design. A more detailed level allows to consider more information about the environmental problems and solutions.

However, integrations between LCA and eco-design typically do not extend beyond the level of detail concerning the components and materials of the product. Consequently, the design intervention does not go beyond the pure replacement of the component and of the material with a more sustainable alternative (Hollberg et al. 2021). Yet, few studies in the literature have shown how it is possible to combine LCA with eco-design to determine and evaluate more strategic solutions at a greater level of detail. In some studies, LCA has been performed at the level of the design options that characterize a certain component, such as orientation, size or shape (Monteiro et al. 2021). In other studies, the substitution of the material takes place even partially, combining different materials in certain ways, so as to resolve contradictions between environmental sustainability and other requirements (Spreafico 2022).

However, in all cases, a common lack is the possibility of using LCA to evaluate the conceptual solutions of eco-design. This depends on the intrinsic limitations of the LCA, which was designed and regulated according to the reference standards ISO 14040 and ISO 14044, to analyse finished products for which data can be measured.

As it was conceived, the prospective LCA can support eco-design also in the phases of conceptualization and embodiment of the solutions, through their evaluation and selection (Hetherington et al. 2014). However, this potential of the prospective LCA is still at the level of a theoretical speculation, since the contributions in the literature have not yet filled the following gaps.

- Formalizing the prospective assessment of the environmental impacts of the solutions. The many studies in the literature that have carried out the prospective LCA have used different approaches to ensure the reliability of the results. The same data to build the foreground inventory can be extrapolated from the scientific literature or obtained through simulations. In other words, there is no unified method that allows the requirements of the LCA standards to be codified according to the methods of researching foreground information (Adrianto et al. 2021). With a view to using the prospective LCA to support the eco-design decision-making phase, this lack can negatively affect the selection of the solutions to be implemented.
- Support eco-design in identifying the solutions. The prospective LCA was created with the aim of predicting the evolution of products to estimate their environmental impacts in the future. Yet, studies in the literature have never exploited this potential to suggest eco-design solutions. That is, there has never been an integration between prospective LCA and technological forecasting methods that are already used to make eco-design (e.g. Zeng et al. 2021; Manuguerra et al. 2023; Ratner et al. 2020). Consequently, these studies propose future solutions that improve sustainability in some way, but without seeking such reduction systematically and without rigorously evaluating it.
- Evaluate solutions parametrically. What has been done in certain LCA studies on some design parameters of current solutions (Monteiro et al. 2021) has not yet been proposed in the prospective LCA. In other words, there are no studies that are able to prospectively evaluate the environmental impacts of a future solution based on the future evolution of its design features. In eco-design, this could certainly be useful for which product parameters to intervene on and how.

### 3 Methods

The proposed method redefines how prospective LCA is utilized in eco-design, assigning it an active role in solution discovery. The method of Spreafico et al. (2023) was considered as a starting point to carry out the prospective LCA, as it extracts foreground inventory data from patents

in a structured way. The method proposed by Spreafico et al. (2023) serves as a starting point because it systematically extracts foreground inventory data from patents. The proposed method enriches it with the extraction of eco-design solutions from the patents. In addition, the proposed method also explains how to use the prospective LCA to select the most sustainable patented solutions, evaluating their environmental impacts in relation to their design choices.

The proposed method was built with the aim of using the outputs of the prospective LCA steps to support the typical steps of eco-design (Vallet et al. 2013):

1. Identification of the environmental problems of the current product.
2. Identification of the solutions to the environmental problems.
3. Environmental evaluation of the identified solutions for the implementation of the solutions on the current product.

The absolute novelty that the proposed method introduces is the way in which the prospective LCA is used, i.e. with an active role in the search for solutions in eco-design and not only in their evaluation. The enabling criterion is the lowering of the level of detail with which the analysis is conducted. The prospective LCA finds in the patents the possible substitutes for the product components and evaluates their impacts at the level of the components. In the proposed method, the level at which prospective LCA is applied relates to the structural characteristics of patented solutions and their environmental assessments.

This level was chosen to make the prospective LCA a pragmatic tool to support the design. For example, in evaluating the prospective impacts of a turbine (product), the prospective LCA could identify and evaluate the impacts of various patented blades (components) that may replace the current one in the future. The proposed method instead aims to use the prospective LCA to identify different shapes, which differ for example in the radius of curvature (structural characteristic), of the patented blades. Therefore, the method aims to extract from the patents, all relating to the blades, the data that characterize the radius of curvature and which will be used to calculate the impacts. For example, a more accentuated curvature requires a longer cooling time in the oven, at controlled temperatures, and therefore a greater energy expenditure.

More in detail, Table 1 compares the objectives of the prospective LCA to support eco-assessment (in the reference method of Spreafico et al. 2023) and of the prospective LCA to support eco-design (in the proposed method).

To achieve these objectives, the proposed method consists in the following steps:

**Table 1** Differences in the goals of patent-based prospective LCA (Spreafico et al. 2023) and the proposed method

Goals	Prospective LCA (patent based) for eco-assessment (Spreafico et al. 2023)	Prospective LCA (patent based) for eco-design (the proposed method)
Goal of the environmental analysis of the current product	Determining the overall environmental impacts of the current product	Determining the environmental problems of the current product, by referring them to the constituent components
Goal of the patent search	Identifying all the patented future evolutions of the components of the current product	Identifying only the more sustainable patented future evolutions of the most impactful components
Goal of the data extraction from patents	Extracting the data for the foreground inventory for making the prospective LCA of the future evolutions of the product	Extracting the data for the foreground inventory for making the prospective LCA of the identified solutions
Goal of the prospective eco-assessment	Determining the environmental impacts of future evolutions of the current product	Evaluating if the identified solutions are more sustainable than those implemented in the current product, exploring the impact of their design features
Goal of decision-making after the prospective eco-assessment	Evaluating whether to substitute the current product with its future evolution	Selecting the design features of the collected solutions to implement in the current product

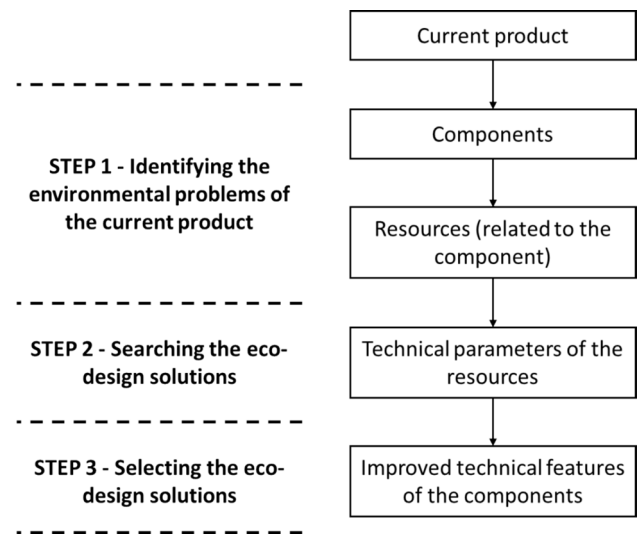
1. Identifying the environmental problems of the current product, or the reasons behind the most impactful components, through the traditional LCA.
2. Searching the eco-design solutions, within patent literature, to solve the environmental problems, through the definition of a query expressing the selected environmental problem reformulated as an eco-design strategy to be performed on a technical parameter.
3. Selecting the eco-design solutions, or the more sustainable design features of the patented solutions, to be implemented in the current product.

In practice, the proposed method exploits the patent-based prospective LCA to systematically identify the design elements to work on during eco-design. These design elements are identified in succession with an increasing degree of detail. Figure 1 schematically draws a parallel between the design elements and the steps of the method that allow their identification. The patent-based prospective LCA serves as a comparative tool to evaluate the environmental impacts of the current product against those of the identified eco-design solutions. This comparison ensures that any proposed design interventions demonstrably improve sustainability relative to the baseline performance of the current product.

In the following sections, the steps of the proposed method are explained in detail.

### 3.1 STEP 1: identifying the environmental problems of the current product

In this method, an environmental problem is defined as excessive resource consumption associated with a component of the product, at a certain stage of its life cycle (Marconi and Favi 2020). In accordance with ISO 14040



**Fig. 1** Comparison between the steps of the proposed method and the eco-design elements they allow to determine

and ISO 14044 standards, the functional unit defines the reference for comparing environmental impacts. In the proposed method, the functional unit is linked to different levels of analysis to ensure methodological consistency. Specifically, the current product represents the reference system for the functional unit. The environmental impacts are first assessed at the product level and then disaggregated to the level of components, elements, and technical parameters. This hierarchical approach ensures that impacts identified at the component and parameter levels are always evaluated relative to the functional unit. In this way, the contribution of each technical parameter to the overall environmental performance is normalized based

on its role within the product system defined by the functional unit.

In line with the definition of the environmental problem provided by Marconi and Favi (2020), the proposed method, to determine the environmental problems of the current product, suggests performing the traditional LCA at a level of detail such as to identify the environmental impacts deriving from the consumption of resources linked to a component during its life cycle. In particular, these consumptions of resources refer to the energy and auxiliary materials used to produce, maintain or manage the end of life of the component or that consumed by the component itself during operation.

The LCA objectifies the selection of environmental problems; however, the choice cannot ignore the different categories of impact which can be more or less significant for the type of product. Furthermore, the proposed method does not consider the environmental problems deriving from the impact of unsustainable materials that make up the component. In fact, we believe that the resolution of these problems can be easily tackled with the many current methods of eco-design and that many sustainable materials can be found even without resorting to patent analysis.

## 3.2 STEP 2: searching the eco-design solutions

In this step, the proposed method suggests how to build an effective query to search for patented solutions to the selected environmental problem. Also in this case, as in the prospective LCA method of Spreafico et al. (2023), the patent search logic is the functional one. However, the difference lies in the content of the query and in the number of patents to search. In Spreafico et al. (2023), there is a query that describes each sub-function exercised by each component of the current product. In the proposed method, there is only one query which describes each eco-design intervention to be carried out to solve the selected environmental problem. The formulation of the query has been divided into three sub-steps described in the following sub-sections.

### 3.2.1 STEP 2.1: reformulation of the environmental problem

In line with what is specified by the design and problem-solving methods, the initial problem must be appropriately reformulated to be able to face it, and in particular to be able to seek knowledge to support its resolution (Wanzenböck et al. 2020).

In the proposed method, the reformulation of the problem is essential to transform the environmental problem obtained in STEP 1 into an eco-design problem. To this purpose, this sub-step proposes to associate the environmental impact of the component, defined as in STEP 1, to a design feature of

the component, on which it is possible to intervene through eco-design, and the indication of how to intervene. This association is performed through the following sub-steps.

**3.2.1.1 STEP 2.1.1: technical parameter identification** The technical parameter of the element, according to the TRIZ (Russian acronym for “Theory of Inventive Problem-Solving”) (Altshuller 1984) is a feature that can be worked on during the design activity to improve the element. In the context of eco-design, this coincides with the need to reduce the consumption of resources to reduce environmental impacts. For example, the too high environmental impact of the energy consumption (element) of the engine (component) of a chainsaw (current product) depends on the electric current (technical parameter).

The identification of the technical parameters of the element is possible in several ways. A starting point is the collection of generic technical parameters that the TRIZ method provides in the contradiction matrix. Many studies, mainly related to the TRIZ method, have enriched this list and propose automatic methods, also based on artificial intelligence, to identify new and more precise ones from patent analysis (e.g. Li et al. 2022; Ding et al. 2023). For example, ChatGPT can be easily used in this regard, by querying it directly in natural language (Spreafico and Sutrisno 2023).

**3.2.1.2 STEP 2.1.2: eco-design strategy identification** This step consists in identifying the type of design intervention to be carried out on the technical parameter, or how the technical parameter must be modified to reduce the environmental impacts of the considered element. For example, the electric current (technical parameter) of the chainsaw engine should be reduced (eco-design strategy) to decrease the impact of the chainsaw engine and therefore of the latter.

To support this phase, the proposed method suggests the use of the element name value (ENV) model, another tool of the TRIZ method. The ENV model was conceived with the aim of enriching the definition of the function performed by a device. The function is described as the transformation of an object that undergoes the action of the device. In the ENV model, the characteristics of the object before and after the transformation are described through numerical or qualitative values. In this way, it is possible to reformulate the function in relation to the changes of the characteristics. For example, the chainsaw cuts (function) the intact branch (object), obtaining a severed branch (transformed object). Hypothetically, if the length (characteristic) of the intact branch is 50 cm and that of the severed branch is 30 cm, the “cut” function can be reformulated, more technically, as reducing the length of the branch by 20 cm. Furthermore, in the ENV model it is also possible to report the ideal value of the characteristic which should be obtained if the function were performed in an ideal way. In this way, by comparing

the real and the ideal value, it is possible to evaluate the device's ability to perform the function. For example, if the ideal length of the cut branch were 20 cm instead of 30 cm, we could consider the chainsaw unsatisfactory.

The assumption that this study introduces is the association of the considered environmental problem with the discrepancy between the real and the ideal value of the technical parameter of the considered element. While the eco-design strategy will be a way of intervening on the technical parameter of the element so that its real value approaches the real one, until the values coincide.

### 3.2.2 STEP 2.2: query formulation

The goal of the patent search is to identify solutions that implement the identified strategy. To increase the effectiveness of the query, as in Spreafico et al. (2023), the latter must be formulated in a functional way. However, unlike that study, to guarantee the precision of the result in the search for eco-design solutions, the search query must include: the strategy, expressed as a verb (e.g. reduce), the technical parameter, the element, the component and the current product.

Finally, to increase the effectiveness of the search in relation to the recall, the query must be reformulated, enriching it with all the synonyms of the terms present and also with any misspellings that are deliberately inserted in the patents by the attorneys to prevent their diffusion. In this regard, there are many approaches and tools to support (Russo et al. 2022).

### 3.3 STEP 3: selecting the eco-design solutions

From the patents obtained, by launching the query in the database, the design features and data are then extracted which allow for an assessment of their environmental impacts. To draw a parallel between design features and their environmental impacts, at this level of detail, two types of data must be extracted from patents:

- Data for the foreground inventory of the design features, e.g. mass or energy consumed by a solution implementing the design feature. The procedure is subject to the same criteria introduced by the method of Spreafico et al. (2023) to ensure the quality of the environmental analysis according to the requirements of the ISO 14040, ISO 14044 standards and the pedigree matrix for the LCA. Therefore, it is necessary to filter the patents obtained according to their relevance and their legal status, i.e. if they have successfully passed the exam. Among the criteria for data extraction, there is the need to verify if the data are supported by experimental evidence, conducted

according to standard procedures, and positively evaluated during the examination.

- Data describing the design features, to be able to tie the environmental impacts to them with precision. These data must be quantitative and are not used in the foreground inventory for the construction of the prospective LCA, but must in any case be kept to characterize the results obtained.

From the comparison between the levels of data aggregation for the inventory and the data describing the design features, two options are possible. If the levels of aggregation coincide, the parallel is already drawn. For example, a patent demonstrates that the proposed solution allows to save the electricity consumed by a certain percentage, comparing it with an identical solution in all respects, except for the implementation of the design features. Conversely, an allocation of data according to the design feature is necessary. For example, the implementation of a design feature in a solution, together with others, allows the reduction of energy consumption. In this case, it is necessary to find criteria for allocating the share of energy savings guaranteed only by the design feature considered.

Finally, from the comparison between the environmental impacts that have been determined for the various design features, the more sustainable ones are proposed as eco-design solutions.

### 3.4 Uncertainty management in patent-based prospective LCA

Managing uncertainty is a critical aspect of patent-based prospective Life Cycle Assessment (LCA), due to the inherent characteristics of data sources and the dynamic nature of emerging technologies. In this context, uncertainty originates from several key factors. First, patents often describe innovations that are in pre-prototype stages, relying on experimental data that may be incomplete, estimated, or based on hypothetical conditions. Additionally, the continuous evolution of technology introduces variability regarding future developments, performance, and scalability of the proposed solutions. Another layer of uncertainty stems from the long-term feasibility of some eco-design solutions identified through patents, as these may not be immediately applicable or may require significant technological advancements to become viable.

To address these uncertainties, a combination of qualitative and quantitative strategies is employed. Qualitatively, data reliability is assessed using the pedigree matrix method, which evaluates the quality of data based on factors such as data origin, temporal relevance, geographical correlation, and technological representativeness. This approach ensures methodological rigor and consistency with ISO 14040 and

ISO 14044 standards. On the quantitative side, sensitivity analyses are conducted to determine how variations in key design parameters influence environmental impact outcomes. This helps to identify critical variables and assess the robustness of LCA results under different scenarios.

The management of uncertainty also has significant implications for eco-design. While some of the identified solutions may not be feasible for immediate implementation, they offer strategic insights that can guide sustainable product development in the long term. By systematically addressing uncertainty, the proposed approach not only enhances the reliability of LCA results, but also supports the selection of eco-design strategies that remain effective despite technological and market fluctuations.

## 4 Case study

To show how the proposed method can be applied and to discuss the strengths and weaknesses of its results, especially in comparison with traditional prospective LCA, the same case study of Spreafico et al. (2023) has been considered.

The case study refers to a process for the production of titanium powders, based on the Electrode Induction Gas Atomization (EIGA) reactor. In this process, the titanium ores, i.e. ilmenite, are processed through the Kroll process, the vacuum arc remelting (VAR), the rolling machine, the EIGA reactor and the sieving machine and finally packed. Through the various steps, the ores are respectively

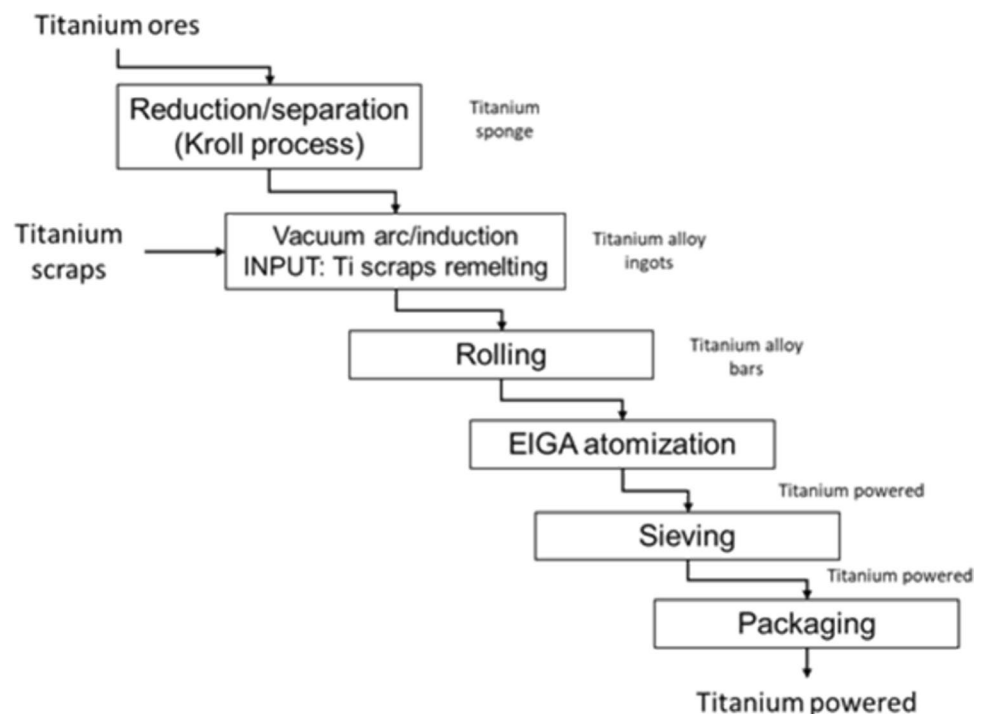
transformed into sponge, ingots, bars, powders, sieved powders and packed powders (see Fig. 2).

To conduct the traditional and the prospective LCA of the collected solutions, the reference standards ISO 14040 and ISO 14044 have been considered. All the assumptions, previously made in Spreafico et al. (2023), have been considered also in this study: the functional unit deals with the production of 1 tonne of titanium powder, and the system boundaries consider all the described steps. The same life cycle inventory (LCI) was considered and the results calculated according to the same calculation methods. The LCA results are expressed using the same impact categories: global warming potential (GWP), stratospheric ozone depletion (SOD), ionizing radiation (IR), ozone formation—human health (OFH), fine particulate matter formation (PMF), ozone formation—terrestrial ecosystems (OFT), terrestrial acidification (TA), freshwater eutrophication (FEu), marine eutrophication (MEu), terrestrial ecotoxicity (TEc), freshwater ecotoxicity (FEc), marine ecotoxicity (MEc), human carcinogenic toxicity (HCT), human non-carcinogenic toxicity (HNCT), land use (LU), mineral resource scarcity (MRS), fossil resource scarcity (FRS) and water consumption (WC).

### 4.1 STEP 1: identifying the environmental problems of the current product

In the first step, the traditional LCA was conducted on the considered process at the level of its constituent components, with the aim of determining the environmental

**Fig. 2** EIGA titanium powder production process



problems related to the excessive consumption of resources related to the same components. Therefore, the environmental impacts of the most impactful component have been stratified according to the consumption of resources associated with it. Figure 3 shows the percentage distribution of environmental impacts among the various components (left) and the percentage distribution of environmental impacts among the consumption of resources related to the most impacting component (right).

From the analysis of Fig. 2, the predominant roles of EIGA reactor can be seen among the components of the considered process. In fact, EIGA reactor is responsible for almost all impacts in almost all categories except in FEc, MEc and MRS where the raw material is by far the main culprit, while in the TEc the contribution of the VAR is also noted.

From the detailed analysis of the environmental impacts of the consumption of resources relating to the EIGA reactor, it emerged instead that the consumption of argon has a predominant contribution to the generation of environmental impacts in all categories, followed at a distance by that of electric energy, while that of the water has almost an irrelevant contribution.

This result leads to quantitative confirmations, about this environmental problem, on the observations already provided about the excessive consumption of argon in this phase by some studies in the literature (Dunkley 2019). However, the consumption of argon in relation to the mass of the produced powders is a parameter on which it is difficult to intervene, as it is fixed by the chemical reactions during atomization and by the amount of processed material (Guo et al. 2020). However, margins of intervention are possible on electric energy consumption, thanks to the optimization of induction (Spitans et al. 2020).

### 4.2 STEP 2: searching the eco-design solutions

To search for eco-design solutions, the environmental problem, i.e. the too high consumption of argon in the EIGA reactor during operation, was reformulated, characterizing it according to technical parameters to which unacceptable values are associated. Then, the eco-design strategies relating to the methods of intervention on the technical parameters aimed at reducing the consumption of argon were determined. The identified technical parameters are: “flow, density, pressure, temperature, speed”. The technical parameter values that describe them can be classified as too high or not suitable. Therefore, eco-design strategies are “reduce, improve, optimize”.

In line with the proposed method, the query was formulated according to the following criteria:

- The technical parameters and the design strategies were inserted in the query, linking them according to the functional logic. To refer the object complements (i.e. technical parameters) to the verbs (i.e. eco-design strategies), each verb–object pair was searched in the same sentence. In turn, the technical parameters were referred to argon (i.e. the resource), by means of specification complement.
- To increase the recall of the search, the synonyms of both technical parameters and design strategies were inserted into the query.
- To increase the precision of the search, also the names of the component and the analysed process, or their functional descriptions through verbs and object complements, were added in the query.
- To search for innovative contributions proposing new solutions, avoiding patents describing such concepts in the background of invention part, the query was launched in the title, abstract and claims fields.

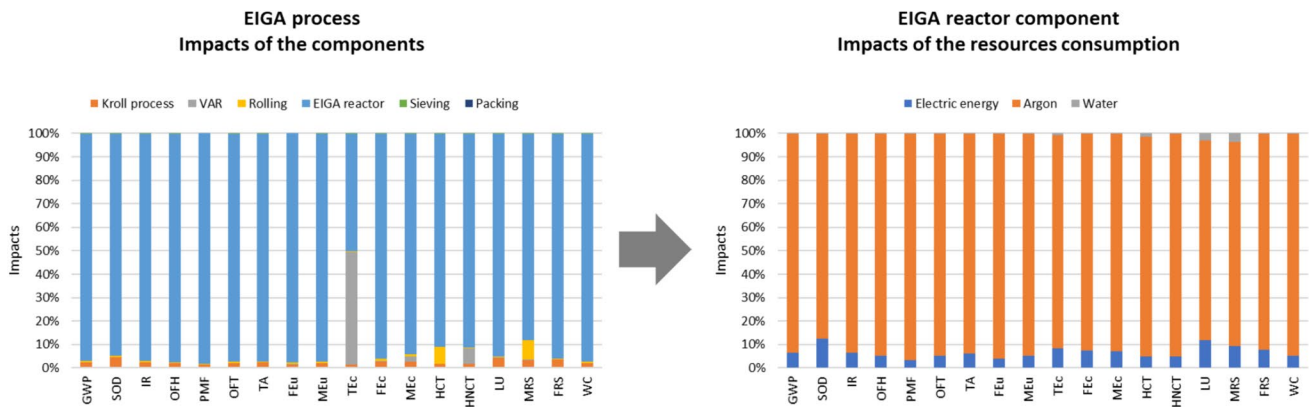


Fig. 3 Environmental impacts comparison of the different components and consumptions of resources related to the most impacting component

The query used (with reference to the Orbit DB syntax, in which it was launched) is the following: “REDUC + OR DECR + OR AMELIOR + OR OPTIM + OR CONTROL + OR LOW + OR IMPROV + OR HIGH + ) S ((FLOW + OR MASS + ) OR DENSITY OR PRESS + OR TEMPER + OR SPEED + ) S (ARGON + OR GAS + ) AND (ATOMIZ + S (TI + OR METAL + ))/TI/AB/CLMS”.

The patents obtained by Orbit DB with this query are 12,342. This number, although very large, is in any case lower than those involved in the patent-based prospective LCA following the method of Spreafico et al. (2023). In that case, several queries for each component/sub-function would have to be used. For instance, to search for patents related to the “atomize” function of the EIGA reactor, the query could have been partially included in the one used, e.g. “(ATOMIZ + S (TI + OR METAL + ))/TI/AB/CLMS”, which would have returned over 71,000 patents in the same database. Therefore, provided that the patents obtained are adequately filtered, according to the criteria established in Step 3, the patents to be analysed amount to a few thousand. This number is decidedly more affordable for a semi-automatic analysis of the content, necessary to extract and analyse the information, with a sufficient degree of detail, to support an eco-design activity.

### 4.3 STEP 3: selecting the eco-design solutions

The patents obtained were selected according to the criteria prescribed in STEP 3 to guarantee the quality of the extracted data, and therefore of the foreground inventory for the prospective environmental assessment of the solutions. First, the patents were automatically filtered, keeping only those that passed the evaluation exam, i.e. (4287 patents). Another automatic filter was set to the priority date, retaining only patents, which have been applied for in the last 5 years. The final set of 2253 patents were manually analysed in their content to evaluate the relevance.

From these patents, various solutions were extracted, which allow to reduce the consumption of argon in the EIGA reactor. All these solutions work on the reduction of various technical parameters of the flow of argon which is introduced into the chamber, both in relation to its speed and to its pressure. The common goal, declared in the patents, is to optimize the flow of argon according to the flow of melted titanium entering in the atomization chamber.

From the analysis and classification of the solutions identified, three design features emerged which characterize them and which all concern the sub-component of the crucible. The task of the latter is to collect the molten titanium downstream of the smelting chamber and guide its entry into the atomization chamber. The control over the mixing between the flow of molten titanium and the flow of argon

allows to make the physical mechanism of atomization more efficient, thus requiring a lower flow of argon.

By analysing in detail, the structure of the crucible in the various solutions, three design features emerged:

- Design feature 1: exit angle of the crucible (Patent n. CN108941590).
- Design feature 2: radius of curvature of the crucible (Patent n. WO2021/139334).
- Design feature 3: section of the crucible outlet nozzle (Patent n. CN113210616).

Figure 4 provides a graphical representation of the identified design features in relation to the structure of the EIGA reactor.

To evaluate the different design features, to determine the most environmentally sustainable, all the data for the construction of the foreground inventory to carry out the prospective LCA were extracted from their patents. Figure 5 shows the percentage comparison between the minimum and maximum prospective reductions of the total environmental impacts of the EIGA process, guaranteed by the patented solutions that refer to the various design features.

Analysing Fig. 5, it can be noted first of all that all three considered design features allow reducing the environmental impacts of the EIGA process in all the categories. While their results are fairly consistent, design feature 1 came out on top in all categories, followed by design feature 2 and design feature 3.

This result is very interesting as it adds the new criterion of the environmental sustainability in all those studies evaluating the effects of different crucibles on the atomization performances. In fact, all of them considered only certain aspects. One is the percentage of impurities in the produced powders, due to the rubbing with the walls of the crucible (Qaddah et al. 2022). Another aspect deals with the diameter and the speed of solidification of the powders, in relation to the speed of fall of the molten titanium flow imposed by the shape of the crucible (Wu et al. 2022). In particular, environmental sustainability can be a crucial parameter in the choice of those processes, also described by these studies, where the performances and the features of the produced powders are comparable when the structure of the crucible changes.

## 5 Discussion

The presented case study, albeit limited to the specificity of the application field, demonstrated the ability of the proposed method to extend the use of prospective LCA in the identification and evaluation of solutions to the level of the detail sought, i.e. that of design features. The practical repercussions of using the prospective LCA in this way are

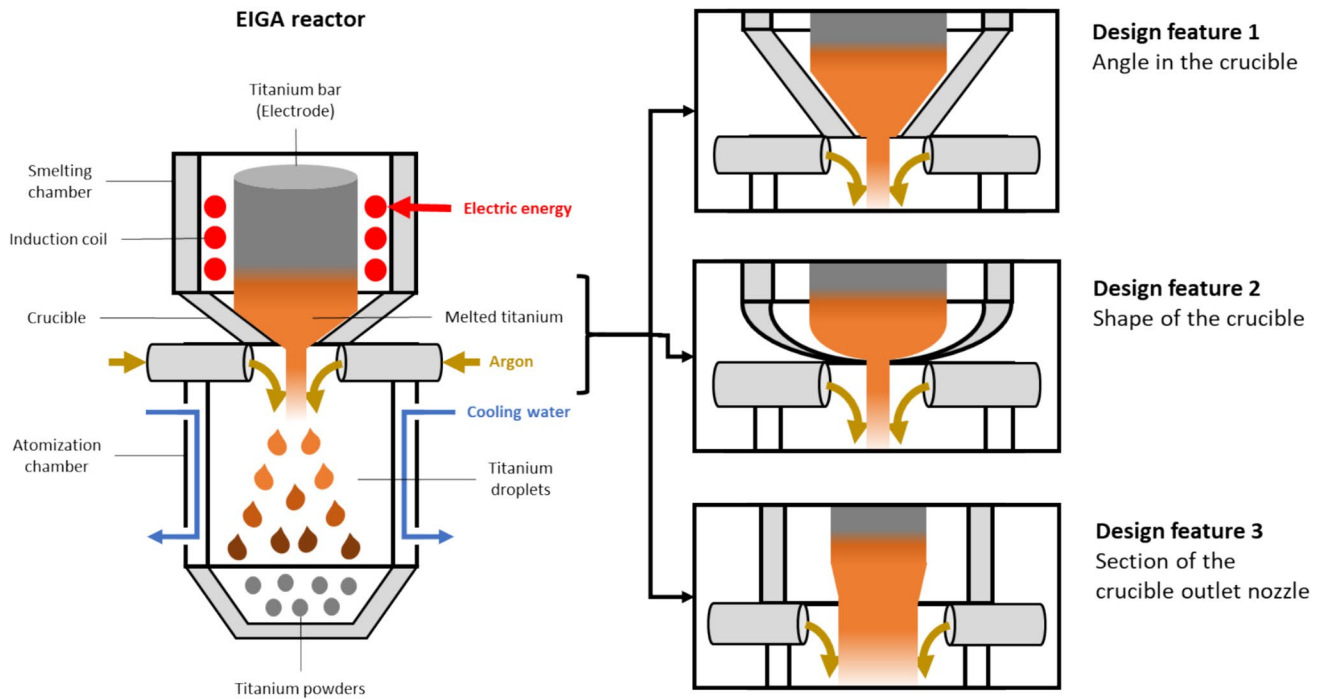


Fig. 4 The identified design features

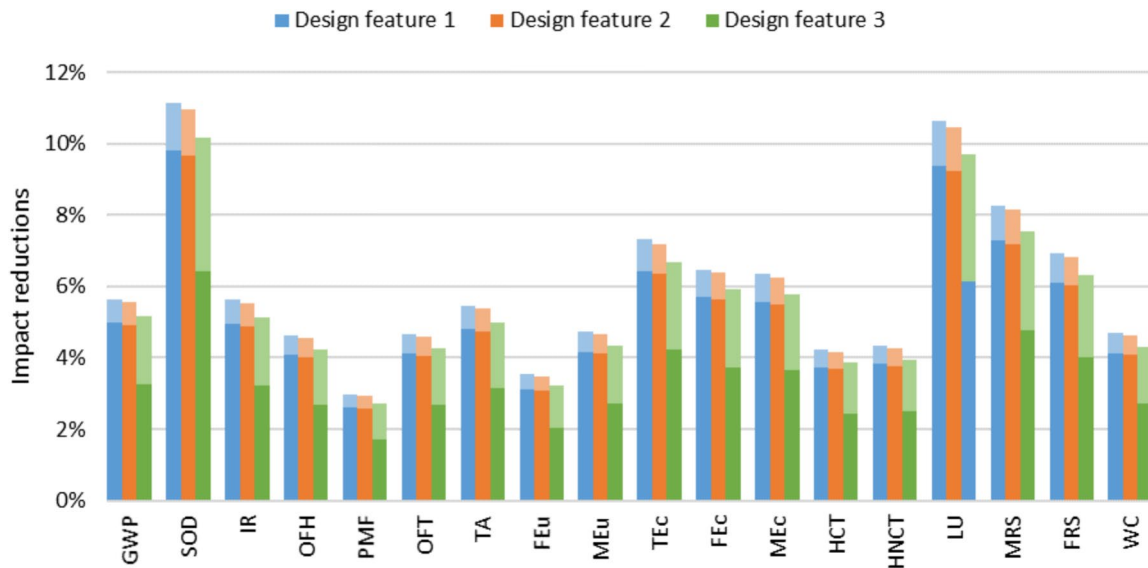


Fig. 5 Minimum and maximum impact reductions of the three models of the improvement 2

different, both on eco-assessment and on eco-design. The method of use is much more strategic for the design, given that one works at the level of design parameters and not of ready-made structural solutions. The novelty with respect to the parametric LCA is found in the type of solutions considered, i.e. the new ones extracted from the patents and not the known ones which have necessarily already been

implemented (Kamalakkannan and Kulatunga 2021). The novelty with respect to eco-design lies instead in the use of a systematic approach to functional design which passes from the reformulation of the function into a technical parameter, as in the TRIZ method. However, a formal integration between TRIZ and eco-design based on patent search is missing in the literature (Chechurin and Borgianni 2016).

Furthermore, the proposed method has shown a way to verify the hypotheses on the potential and future developments of the prospective LCA, which several studies in the literature have done regarding its integration within eco-design (Hetherington et al. 2014; Adrianto et al. 2021). The limit of these studies did not lie so much in the use of the prospective LCA within eco-design, but more in its methods of use in this perspective. The fields of application were extremely narrow and the solutions identified were extremely detailed, as well as extracted from a too small documentary pool (Barjoveanu et al. 2022).

In the proposed method, the patent search preparatory to the prospective LCA is conducted on a much smaller number of patents than when the prospective LCA is used in eco-assessment. Consequently, the patent analysis is less onerous. This is possible above all thanks to the refinement of the query, which is functional but more precise, also containing the technical parameters and the name of the component. This link can be considered the missing piece that in many cases reduces the effectiveness of eco-design and the relevance of the proposed solutions when it is applied downstream of the LCA (Marconi and Favi 2020).

The analysis of the limitations of the proposed method is also important to better understand how prospective LCA is applied within eco-design and not downstream as usually happens. Therefore, the discussion was set up in this regard. The formulation of the initial problem depends a lot on how the current product is analysed through traditional LCA. As prospective LCA is applied in eco-design, an erroneous analysis in this sense can lead to identifying eco-design elements on which to work (e.g. technical parameters, design features) that are not pertinent. The eco-design results will not be helpful in solving the initial environmental problem.

In reformulating the problem, identifying technical parameters to be improved plays a fundamental role since it can greatly condition the search for solutions in patents. While in prospective LCA for eco-assessment, this problem does not arise since patents sought are those that perform a known function of current products. Knowledge about technical problems faced is fundamental—something that tools such as artificial intelligence can support but not completely replace. In any case, an expert must be consulted to evaluate suggested technical parameters.

Some solutions to limitations could come from developing artificial intelligence systems for information analysis and from new methodological approaches. To overcome overly onerous manual selection and classification of patents according to technical parameters, an ontology of design features could be introduced. A criterion for cataloguing them, as well as an initial list of standard design features, could be useful to speed up analysis by filtering results more automatically (Li et al. 2022).

Additionally, it is crucial to consider how disruptive technologies can be intercepted within this framework. The advent of such technologies presents both challenges and opportunities for eco-design practices. By identifying emerging innovations through systematic patent analysis, designers can proactively integrate these technologies into their processes. This involves not only recognizing new materials or manufacturing techniques but also understanding their potential environmental impacts through prospective LCA assessments. Engaging stakeholders across disciplines can facilitate knowledge sharing and foster innovation while ensuring that these technologies are effectively adapted for sustainable design purposes. Moreover, implementing feedback loops within this process allows for continuous improvement as new information about disruptive technologies becomes available. By remaining agile and responsive to technological advancements, designers can navigate complexities while striving for greater sustainability in product development.

The future developments related to prospective LCA concerning automatic extraction of data from patents remain pertinent even when using it for eco-assessment (Spreafico et al. 2024). Although analysing a smaller number of sources may alleviate some challenges associated with data overload, it does not eliminate them entirely.

## 6 Conclusions

This study proposed a new method for integrating prospective LCA into eco-design in an active way. The method, through a systematic step-divided procedure, allows to identify the solutions to a product's environmental problems, from patents. The solutions are then selected through prospective impact analysis, extracting data from the same patents to build the foreground inventory. The level of detail of the solutions is that of design features, which allow to redesign the product structure, without merely replacing materials or structure as in many eco-design methods.

Net of the limitations of the case study, i.e. the specificity of the application field, the number of considered patents and the number of analysed solutions, the following strengths of the proposed method and the following observations about the intersections between prospective LCA and eco-design emerged.

- In general, prospective LCA can be used directly in the creative part of eco-design, providing the technical knowledge to support idea generation. This was made through the use of a systematic patent analysis procedure to support prospective LCA, to ensure recall and precision to research of the solutions and reliability to their environmental assessment.

- The level of detail with which the identified solutions are defined, i.e. in relation to design features, is crucial. This makes it possible to redesign the product more strategically, i.e. by rationalizing resources, to solve its environmental problems.
- However, the identification of the most strategic design features in patents is dependent to the proper identification of environmental problems and their reformulation, from which the research query is defined. Due to this, fewer patents must be analysed when prospective LCA is used for eco-design than when it is used for environmental assessments of future product developments, by saving time and costs.

To corroborate these conclusions, and to better characterize the intersection between prospective LCA and eco-design, the proposed method will be applied in other case studies. While, a future development of broader respire concerns the implementation of the proposed method in tools that can automate or objectify its most critical parts.

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**Data availability** The datasets generated and/or analyzed during the current study are available from the corresponding author upon reasonable request.

## Declarations

**Conflict of interests** The authors declare no competing interests.

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## References

- Adrianto LR, van der Hulst MK, Tokaya JP, Arvidsson R, Blanco CF, Caldeira C, Hauck M (2021) How can LCA include prospective elements to assess emerging technologies and system transitions? The 76th LCA Discussion Forum on Life Cycle Assessment, 19 November 2020. *The Int J Life Cycle Assessment* 26:1541–1544
- Akizu-Gardoki O, de Ulibarri B, Iturrondobeitia M, Minguez R, Lizundia E (2022) Ecodesign coupled with Life Cycle Assessment to reduce the environmental impacts of an industrial enzymatic cleaner. *Sustain Product Consum* 29:718–729
- Altshuller GS (1984) Creativity as an exact science: the theory of the solution of inventive problems. Gordon and Breach
- Arvidsson R, Tillman AM, Sandén BA, Janssen M, Nordlöf A, Kushnir D, Molander S (2018) Environmental assessment of emerging technologies: recommendations for prospective LCA. *J Ind Ecol* 22(6):1286–1294
- Barjoveanu G., Teodosiu C., Mihai M., Morosanu I., Fighir D., Vasiliu A. M., & Bucatariu F. (2022) Life cycle assessment for eco-design in product development. In *Assessing Progress Towards Sustainability* (pp. 247–271). Elsevier.
- Boix Rodríguez N, Rossi M, Cappelletti F, Favi C (2023) Engineering eco-design of heat exchangers in domestic heating systems using life cycle assessment methodology. *Int J Interact Design Manufact (IJIDeM)* 18(8):5749–5771
- Chechurin L, Borgianni Y (2016) Understanding TRIZ through the review of top cited publications. *Comput Ind* 82:119–134
- Ding Z., Srinivasan A., MacNeil, S., & Chan J. (2023) Fluid Transformers and Creative Analogies: Exploring Large Language Models' Capacity for Augmenting Cross-Domain Analogical Creativity. In *Proceedings of the 15th Conference on Creativity and Cognition* (pp. 489–505).
- Dong Y, Zhao Y, Wang H, Liu P, He Y, Lin G (2022) Integration of life cycle assessment and life cycle costing for the eco-design of rubber products. *Sci Rep* 12(1):595
- Dunkley JJ (2019) Metal powder atomisation methods for modern manufacturing. *Johnson Matthey Technol Rev* 63(3):226–232
- Foschi E, Zanni S, Bonoli A (2020) Combining eco-design and LCA as decision-making process to prevent plastics in packaging application. *Sustainability* 12(22):9738
- Gero JS (1990) Design prototypes: a knowledge representation schema for design. *AI Mag* 11(4):26–26
- Guo RP, Xu L, Zong BYP, Yang R (2017) Characterization of prealloyed Ti–6Al–4V powders from EIGA and PREP process and mechanical properties of HIPed powder compacts. *Acta Metallurgica Sinica (English Letters)* 30(8):735–744
- Haleem A, Mannan B, Luthra S, Kumar S, Khurana S (2019) Technology forecasting (TF) and technology assessment (TA) methodologies: a conceptual review. *Benchmarking: an Int J* 26(1):48–72
- He B, Li F, Cao X, Li T (2020) Product sustainable design: a review from the environmental, economic, and social aspects. *J Comput Inf Sci Eng* 20(4):040801
- Hetherington AC, Borrion AL, Griffiths OG, McManus MC (2014) Use of LCA as a development tool within early research: challenges and issues across different sectors. *The Int J Life Cycle Assessment* 19:130–143
- Hollberg A, Kiss B, Röck M, Soust-Verdaguer B, Wiberg AH, Lasvaux S, Habert G (2021) Review of visualising LCA results in the design process of buildings. *Building Environ* 190:107530
- ISO (2006a). 14040:2006 Environmental Management - LCA - Principles and Framework.
- ISO (2006b). 14044:2006 -Environmental Management - LCA - Requirements and Guidelines.
- Kamalakkannan S, Kulatunga AK (2021) Optimization of eco-design decisions using a parametric life cycle assessment. *Sustain Product Consum* 27:1297–1316
- Li SP, Yu KM, Yeung YC, Keung KL (2022) Patent review and novel design of vehicle classification system with TRIZ. *World Patent Inf* 71:102155
- Liang JS (2023) A knowledge with ontology representation for product life cycle to support eco-design activities. *J Eng, Design Technol* 21(4):991–1026
- Manuguerra L, Cappelletti F, Manes F, Germani M (2023) A predictive eco-design method and tool for electric vehicles of Industry 4.0. *Procedia Comput Sci* 217:248–257

- Marconi M, Favi C (2020) Eco-design teaching initiative within a manufacturing company based on LCA analysis of company product portfolio. *J Clean Prod* 242:118424
- Monteiro H, Freire F, Soares N (2021) Life cycle assessment of a south European house addressing building design options for orientation, window sizing and building shape. *J Building Eng* 39:102276
- Qaddah B, Chapelle P, Bellot JP, Jourdan J, Rimbart N, Deborde A, Franceschini A (2022) Swirling supersonic gas flow in an EIGA atomizer for metal powder production: numerical investigation and experimental validation. *J Mater Processing Technol* 311:117814
- Ratner S, Gomonov K, Revinova S, Lazanyuk I (2020) Eco-design of energy production systems: the problem of renewable energy capacity recycling. *Appl Sci* 10(12):4339
- Ricciotti L, Occhicone A, Ferone C, Cioffi R, Roviello G (2023) Eco-design of geopolymer-based materials recycling porcelain stoneware wastes: A life cycle assessment study. *Environ, Development Sustain* 26(2):4055–4074
- Rossi M, Germani M, Zamagni A (2016) Review of ecodesign methods and tools. Barriers and strategies for an effective implementation in industrial companies. *J Clean Prod* 129:361–373
- Russo D, Spreafico C, Avogadri S, Precorvi A (2022) Investigating the impacts of misspellings in patent search by combining natural language tools and rule-based approaches. *Knowledge* 2(3):487–507
- Spitans S, Franz H, Baake E (2020) Numerical modeling and optimization of electrode induction melting for inert gas atomization (EIGA). *Metall and Mater Trans B* 51(5):1918–1927
- Spreafico C (2022) Can TRIZ (Theory of Inventive Problem Solving) strategies improve material substitution in eco-design? *Sustain Prod Consum* 30:889–915
- Spreafico C, Spreafico M (2021) Using text mining to retrieve information about circular economy. *Comput Ind* 132:103525
- Spreafico C, Sutrisno A (2023) Artificial Intelligence Assisted Social Failure Mode and Effect Analysis (FMEA) for Sustainable Product Design. *Sustainability* 15(11):8678
- Spreafico C, Landi D, Russo D (2023) A new method of patent analysis to support prospective life cycle assessment of eco-design solutions. *Sustain Product Consumption* 38:241–251
- Spreafico C., Thonemann N., Pizzol M., Arvidsson R., Steubing B., Cucurachi S., & Spreafico M. (2024) Using patents to support prospective life cycle assessment: opportunities and limitations. *The International Journal of Life Cycle Assessment* 1–20.
- Thonemann N, Schulte A, Maga D (2020) How to conduct prospective life cycle assessment for emerging technologies? A systematic review and methodological guidance. *Sustainability* 12(3):1192
- Vallet F, Eynard B, Millet D, Mahut SG, Tyl B, Bertoluci G (2013) Using eco-design tools: An overview of experts' practices. *Des Stud* 34(3):345–377
- Wanzenböck I, Wesseling JH, Frenken K, Hekkert MP, Weber KM (2020) A framework for mission-oriented innovation policy: Alternative pathways through the problem–solution space. *Sci Public Policy* 47(4):474–489
- Wrzesińska-Jędrusiak E, Muradin M, Herkowiak M, Łaska-Zieja B, Myczko A (2022) Environmental performance of the innovative, patented mixing system in an agricultural biogas plant based on LCA approach. *J Clean Prod* 349:131420
- Wu J, Xia M, Guo S, Wang J, Ge C (2022) Effect of Electrode Induction Melting Gas Atomization Process on Fine Powder Yields: Diameter of Free-Fall Gas Atomizer. *J Mater Eng Perform* 32(8):3390–3400
- Zeng T, Durif F, Robinot E (2021) Can eco-design packaging reduce consumer food waste? An experimental study. *Technol Forecast Soc Chang* 162:120342