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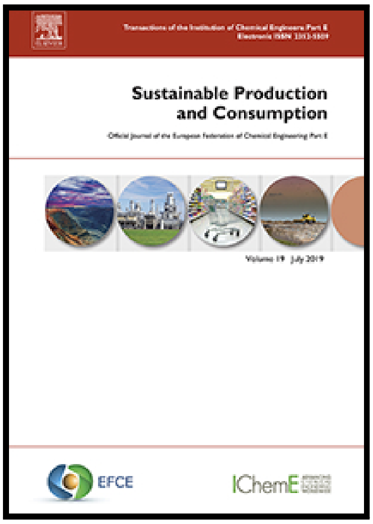

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Can TRIZ (Theory of Inventive Problem Solving) strategies improve material substitution in eco-design?

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Abstract

The material substitution (MS) is a very effective eco-design strategy for reducing the environmental impacts in a product, albeit its application can be hindered because of the other product requirements, e.g. mechanical strengths, aesthetics, etc. However, approaches that explicitly support a strategic MS in problem-solving are missing in the literature. This paper compares the reduction of the environmental impacts in 153 case studies of comparative life cycle assessment (LCA), extracted from 113 scientific articles, associated with generic MS or strategic MS according to TRIZ (Russian acronym for "Theory of Inventive Problem Solving") strategies. The association was manually performed by following a structured and step-divided procedure, where the case studies are reformulated and compared to the TRIZ strategies, by exploiting the analogy of some common ontological terms between TRIZ and design. The obtained results showed how TRIZ can be used to perform a more rational and strategic MS to meet both environmental sustainability and other product requirements, better than generic MS. The impact reduction is instead greater in all impact categories (+21% on average), whether the introduced materials are synthetic (+19% on average), natural (+13% on average), and recycled materials (+18% on average). Furthermore, the associations between the solutions that guarantee the greatest reductions in environmental impacts and the revised TRIZ strategies for MS have been determined in relation with application fields, types of products and materials. Compared to other contributions in the literature, the main novelties of this study are: the intersection between TRIZ and MS and its environmental evaluation, quantitative and enlarged to different standard categories and based on a wider and heterogeneous set of case studies. In conclusions, this study associated more quantitative environmental advantages to the provided set of revised TRIZ strategies for material substitution than generic material substitution on the basis of analogies with historical cases that inspired their formulation.

Keywords

Material substitution, eco-design, TRIZ, life cycle assessment (LCA)

1. Introduction

Material substitution (MS) has been evaluated as one of the best strategies to reduce the environmental impacts of a product by several studies based on quantitative rigorous evaluation such as LCA (e.g. Valderrama et al., 2013; Palazzo and Geyer, 2019; Kamalakkannan and Kulatunga, 2021). The environmental advantages arising from MS regard extraction, disposal, and product's manufacturing and use phase. Some examples are fuel reduction due to lighter materials (e.g., Poulikidou et al., 2015; Bribián et al., 2011), introduction of new production methods (e.g. Bovea and Vidal, 2004), robustness in packaging to improve the conservation of the contained product (e.g. Spreafico and Russo, 2021).

Most of eco-design methods suggest to apply MS in the entire mass of the product, rather than in more focused areas. However, implemented in this way, MS highlighted some limitations for environmental sustainability in many of the studies cited above. The reduction of environmental impacts could not consider the entire life cycle. For instance, some automotive components in carbon fibre are more sustainable than those in aluminium only during use, by allowing a greater reduction in vehicle mass and therefore fuel savings and not in production and disposal (e.g. Spreafico, 2021a). MS can be difficult to combine with product requirements, e.g., mechanical strength, costs, and aesthetic characteristics (Luttropp and Lagerstedt, 2006). In addition, the eco-innovation methods, which also refer to MS are often considered not very pragmatic and not very credible in properly investigating the necessary design dynamics (Hazarika and Zhang, 2019).

According to Mansor et al. (2015), when these limitations emerge, the MS can no longer be considered a traditional design problem approachable with common eco-design methods, e.g. the Ten Golden Rules by Luttropp and Lagerstedt (2006). On the contrary, it turns to be an inventive problem. For this reason, to face it, some authors (e.g., Liu et al., 2020a; Zhang and Shang, 2010; Vinodh et al., 2014) applied the TRIZ (Theory of Inventive Problem Solving) method (Altshuller, 1984). TRIZ is a heuristic method based on tools and principles, specifically developed for solving technical contradictory problems and it consists of dozens of strategies (see Section 2.1).

Although TRIZ was not developed as an eco-design method, its effectiveness in this area was demonstrated by some studies, which showed that the solutions obtained with its application are more sustainable than the others (e.g. Feniser et al., 2017; Cherifi et al., 2015; Spreafico, 2021b). At the same time these studies also proved the ability of TRIZ to not compromise other product's requirements when it is applied to improve environmental sustainability. According to their authors, this is due to the ability of TRIZ in suggesting more focused and conscious ways to implement the solutions. From their analysis, at least four main ways to combine MS and TRIZ emerged (see Section 2.2): using only TRIZ suggestions dedicated to MS, comparing MS and TRIZ suggestions, combining the two of them, applying TRIZ to solve problems deriving from MS.

However, the validity of all these attempts is questioned by some of their limitations (see Section 2.2): the tested case studies are few and not very heterogeneous, only few TRIZ suggestion were experimented, the resulting intersections were not concretely formalized in pragmatic suggestions. For this reason, the choice and application of the more suitable TRIZ strategies to be applied for MS is demanded above all to the designer's experience. The assessments about the environmental sustainability of the identified solutions are too qualitative and/or subjective, not referring to rigorous and/or standard procedures. The obtained results are not expressed through standard indicators of environmental impact. The novelty of this study lies in rigorously testing the environmental sustainability, through life cycle assessment (LCA) methodology (ISO, 2006a; ISO, 2006b), of the solutions obtained by applying MS in a manner consistent with the inventive suggestions of different TRIZ strategies.

The starting hypothesis that this study wants to verify through this test is: "*Can MS applied similarly with the suggestions provided by the TRIZ strategies achieve more sustainable solution than generic MS?"*. The point of verifying this hypothesis is to understand if the subordination of a routine design strategy such as MS to an inventive approach carried out by TRIZ pays off from an environmental point of view. Furthermore, most of the TRIZ suggestions aim to avoid MS. At the same time, the comparison of different strategies for MS can highlight what is more promising in relation to different impact categories, application fields and problems to be solved.

2. Literature Review

2.1. Overview about TRIZ method

TRIZ method suggests a standard path for solving a technical problem, based on three main phases. Initially, the starting problem is reformulated in an abstract way, using a parametric-functional language that aims to model the underlying contradiction. Then the contradiction is resolved by identifying abstract solutions. Finally, the abstract solutions are contextualized in relation to the technical domain of the starting problem.

Each phase can be supported by different specific dedicated tools, whose effectiveness was demonstrated in relation to different degrees of structuring of the solution path and individually (Nakagawa, 2011; Webb, 2002). The tools, like the general path, were extrapolated from the patent literature, with the aim of capturing and modelling the inventive reasoning of the inventors to allow its reuse. Depending on the type of tool, such reasoning may be more directed toward strategic reformulation of the problem or toward its resolution. The Minimal Technical System model provides an ontology for modelling the technical system in macro-blocks. The Element Name Value model allows to model the function performed by the technical system in a parametric way. Functional analysis, the contradiction matrix, and the physical contradiction model support the modelling of the problem in the form of a contradiction. Several types of suggestions, including 40 Inventive Principles, 76 Standard Solutions, Separation Principles, the Evolutionary Laws, provide abstract solutions to resolve the contradiction.

Since its introduction in 1956 (Althsuller and Shapiro, 1956), the TRIZ method has been greatly expanded in content, adding new tools and increasing the number of suggestions and examples. Its systematic approach has also been revised several times, both from the theoretical and ontological point of view and by defining an algorithm called ARIZ to automate it. These developments were first carried out by the same Altshuller, then by his closest collaborators and then by researchers around the world, many of whom are members of dedicated associations (e.g. International TRIZ association - MATRIZ, European TRIZ association - ETRIA).

On the validity of the TRIZ method, many foods for thought can be found in the literature. On the one hand, there are many contributions that praise the results obtained by applying it in various cases, some of which were collected in the reviews of Chechurin and Borgianni (2016) and Spreafico and Russo (2016). On the other hand, there are several studies that critically analyse its theoretical approach, questioning its scientific value in reference to design theories (e.g. Ilevbare et al., 2013; Birdi et al., 2012). From these studies it emerges substantially that the TRIZ method was not developed with the same methodological rigor as other design theories, such as Function Behaviour Structure theory (Gero, 1990) and Systematic Approach of Pahl and Beitz (Pahl and Beitz, 2013). However, despite application difficulties and an enigmatic definition about its nature, i.e. provisional method vs simply collection of triggers, the TRIZ method seems to offer clarity to problem solving and to yield innovative ideas and solutions (Ilevbare et al., 2013). In essence, TRIZ may not be considered a rigorous design method but it still leads to short-term improvements in both the creative problem-solving skills and motivations to innovate of engineers, and long-term improvements in developing ideas in the workplace (Birdi et al., 2012).

2.2. Using TRIZ for material substitution

Compared to all the suggestions provided by TRIZ, MS is marginally considered on the theoretical level and in the examples (Chechurin and Borgianni, 2016; Spreafico and Russo, 2016). In the original formulation (Altshuller, 1984), only Inventive Principle N. 40 explicitly refers to MS, suggesting to introduce composite materials. Other suggestions suggest instead to intervene on the product material without denying its substitution (e.g. Inventive Principle N. 31 "Porous materials", Inventive N. 30 “Flexible shells and thin films” and Standard Solution N. 1.2.2).

The combinations of TRIZ, eco-design and MS in the literature can be classified in three ways. In some studies (e.g. Russo and Spreafico, 2020), MS is considered an alternative option to the use of TRIZ and is proposed separately. MS is intended as a generic routine design strategy, like structural optimization. While the TRIZ strategies, re-proposed in the original form or properly reformulated, are dedicated to product innovation. Other studies consider MS in a more inventive way, providing its combination with some TRIZ suggestions. Some of them (e.g., He et al., 2006; Chen and Liu, 2001) simply formalize TRIZ suggestions specifically dedicated to MS in a more pragmatic form for eco-design. However, the obtained results are too specific in some domains, the environmental issues are little considered and the inventive nature of TRIZ is often is only marginally captured by maintaining MS too generic (e.g. Zhang and Shang, 2010). Still others use the TRIZ method to solve problems arising from MS in eco-design. Liu et al. (2020a) and Mansor et al. (2015) suggest how to use Inventive Principles to solve problems arising from the disruption of geometry after MS. At the same time, the authors also use TRIZ to design for the characteristics that a new material allows, such as new shapes, to expand the solution space. Vinodh et al. (2014) and Ang et al. (2013) expand this approach by systematically organizing the requirements in contradiction with sustainability in MS. In this case more problems are identified and solved, in addition to morphology, which also include those of the manufacturing and material behaviour during the product functioning. In addition, the increased number of considered problems also stimulated the authors to propose many more ways to use TRIZ to support MS. This same approach was also followed by Srinivasan and Kraslawski (2006), which deepened only the substitution of auxiliary materials. However, in this approach the link between MS, the technical system, the resulting problems, and the used strategies was not investigated. Consequently, the selection of the best strategies is left to the ability and experience of the problem-solver. Only Ishak et al. (2018) abstractly encode the problems and contradictions arising from MS, by providing a case-based logic scheme to suggest the most appropriate TRIZ principles to solve these problems.

Furthermore, in all these works, an objective and rigorous evaluation about the sustainability of the solutions obtained by the MS realized through the application of TRIZ is missing. In all the studies in which TRIZ is used for eco-design, which also partly deal with MS, the various limitations in the environmental assessment can be found. By isolating the contributions in which MS is considered from among all those analysed by this study, the resulting limitations are as follows:

- Presence of qualitative and approximate assessments, based on subjective considerations.
- Quantitative assessments not based on a rigorous and standard procedure.
- The results are not expressed through standard and shared indicators of environmental impact, with the sole exception of the Global Warming Potential.
- The case studies considered for testing the methods are of only a few units and make the evaluation not transversal but depending on their application domain.

These limitations therefore tell us that a method has not yet been proposed and quantitatively validated in the literature to suggest how to make MS an option for eco-innovation, or to achieve environmental sustainability where it conflicts with other product requirements. Without an attempt to reformulate the MS according to the strategic principles of inventive problem-solving, it is seen only as a mere solution in routine design, more suited to optimization than to product innovation. While without a robust evaluation, even the few attempts towards the opposite direction can only be considered too specific and difficult to reproduce.

3. Methods

3.1. Revised TRIZ strategies for material substitution

The revised TRIZ strategies for MS, introduced and tested in this study, derive from a selection of the TRIZ strategies that are considered most significant at an industrial level (Cong and Tong, 2008). These strategies are part of the Evolutionary Laws and Inventive Principles. They are sufficiently heterogeneous to deal with all the main aspects of the TRIZ method: structural rearrangement, spatial and temporal focusing during the functioning, reduction of exploited resources.

In defining the revised TRIZ strategies for MS, two main aspects of the original TRIZ strategies were preserved: the ontology and the meaning of the proposed inventive suggestions. TRIZ ontology was preserved due to its ability to describe the structure and the functioning of technical system in a synthetic and precise manner, with standard definitions in the field of technical problem solving (Yan et al., 2014). This ontology was exploited to define how MS can take place. On the one hand, to discriminate which are the most strategic parts of the structure of the technical system to be considered. On the other hand, to clarify what the role of the new material should be in relation to the functioning of the product. Both these indications were considered during the selection of a new material, more environmentally sustainable and, at the same time, suitable to ensure valuable features. While the essence of the inventive suggestions proposed in the original TRIZ strategies was maintained to make the revised ones clearly addressed towards problem solving. This choice can be unusual, since these suggestions, like the TRIZ method, were not developed to support MS. For this reason, the main difficulty in revising the original TRIZ strategies was combining these inventive suggestions with MS. This was done in two ways. On the one hand, the inventive suggestions were related to the way to implement MS, e.g. providing a partial replacement only in some parts or combining the new material with the old one in an appropriate way. On the other hand, the inventive suggestions were exploited to explain how to modify and/or organize the new material on a structural level, e.g. replace a plastic panel with one made of plywood, rather than one made of plain wood.

To adequately present the revised TRIZ strategies for MS, this chapter also presents the original TRIZ strategies from which the first ones were drawn. In turn, the original TRIZ strategies were presented in a partially simplified way to facilitate their reading in Table 2 and reported in their strictly original form in Table S1 in the Appendix. Furthermore, since both the original TRIZ strategies and the revised ones refer to recurring elements of the TRIZ ontology, used to describe the structure and functioning of a device, the latter have also been reported (see Table 1).

Table 1: Definitions of the used elements from TRIZ ontology (Altshuller, 1984; Belski et al., 2016).

Ontological elements	Definitions
Technical system	The analysed device or plant
Function	The action performed by the Technical system
Object	The entity over which the Technical system performs the Function that turn into the Product
Operative zone	The area of the volume of the Object that undergoes the Function
Operative time	The effective period during which the Function is exercised on the Object
Tool	The part of the Technical system that is in direct contact with the Object during the performance of the Function. The contact can be mechanical, acoustical, thermal, chemical, electrical, magnetic, intermolecular, or biological
Other elements of the Technical system	• Supply: the part generating the energy. • Transmission: the part transmitting the energy generated by the Supply to the Tool. • Control: the part interacting with Supply, Transmission and Tool to regulate the execution of the Function on the Object
Resource	• Any substance, including waste, available in the Technical System or in the working environment. • An energy reserve, free time, unoccupied space, information. • Physical, chemical, geometric properties of the substances

In Table 2, the TRIZ strategies for MS are reported (Column 3) along with the respective original TRIZ strategies (Column 2). In all the revised strategies, the greater sustainability of the substituting material compared to the original one is intended in relation to the entire life cycle. The impacts of the substituting material can be higher than the substituted material during extraction, manufacturing and disposal, provided that their reduction during use compensates them. This is because, in some cases, the meaning of the revised strategies is to improve the phase of use of the substituting material.

Table 2: Revised TRIZ strategies for MS and original ones.

TRIZ strategies	Original definition	Revised definition for material substitution
Segmentation	Segment the Technical system or the Tool into multiple independent parts and recombine them in a more suitable way to perform the Function and meet the other requirements, e.g. easy manufacturing and disassembly (TRIZ Inventive Principle N. 1)	To perform the same Function and meeting the other requirements of a material and increasing the sustainability, segment the material within a component into multiple independent parts and recombine some of them with other parts from a more sustainable material. Alternatively, completely substitute the material with another one, after segmenting and recombining its parts to improve its sustainability
Nesting	Place one or more parts of the Technical system or the Object inside another or pass them through a cavity (TRIZ Inventive Principle N. 7)	Infill, at physical or chemical level, small portions of a more sustainable material within the original one, acting as matrix, or substitute only the less sustainable doping and additives (e.g. vegetal oil instead of metallic bactericides in active food packaging)
Macro-micro	If a design problem cannot be solved at macro-level, redesign the structure of the Tool at micro level so that the problem can be solved in this scale and in turn also at macro level. To do this, miniaturize the Tool during the interaction with the Object without changing its state of aggregation (TRIZ Evolutionary Law	Substitute the original material with another, which structure was redesigned at the micro-level to optimize the performance of the Function and reducing energy and resources consumption. Alternatively, change the level of MS, by combining the new material with the original one

	N. 7) to reduce the Operative zone and/or the Operative time. If the Tool is solid, make it thinner and sharper or segment it until powder (e.g. diamond cutting disk), while if it is fluid, reduce it in droplets or in aerosols state	at micro-level to improve their interactions in performing the Function and their compatibility
Dematerialization fluid	Replace the solid Tool with a fluid one to perform the Function at a sub-level of detail (TRIZ Evolutionary Law N. 7), since this latter can guarantee a more intimate interaction with the Object due to surface penetration, diffusion in depth, chemical reactions, and better miscibility	The original TRIZ strategy can be still considered if the fluid material is more sustainable than the solid one during the lifecycle, considering extraction, manufacturing, use (due to the improved interaction with the object) and the disposal
Transition to supersystem	Make the Technical system able to exploit all the elements available in the working environment to perform the Function: renewable energy sources, to reduce or eliminate the exploitation of fossil fuels; natural elements able to eliminate a biodegradable Object in place of traditional methods of incineration, e.g. insects and microorganisms; other Technical systems, e.g. a truck following in the wake of another to save fuel. Alternatively, when a Technical system exhausts any margin of improvement, include it in a super-system, making it one of its parts and exploiting its energy to work (TRIZ Evolutionary Law N. 4, 6, 8)	To make the Technical system able to exploit all the Resources available in the working environment to perform the Function as specified in the original definition, substitute its constituting materials with others able to interact with the Resources from the supersystem (specified in the original definition) to exploit them. In this way the energy and resources consumption can be reduced and consequently the environmental impacts arising from them
Taking out	Separate from the Technical system or from the Object a part or property interfering with the realisation of the Function. The extreme is to keep only the necessary parts or properties and eliminate everything else (TRIZ Inventive Principle N. 2)	Separate, from a material or alloy or multi-material component, the inclusions or the materials with a greater impact on the environment and substitute them with more sustainable ones. Alternatively, substitute a material with another allowing to work after taking out an impacting material from the Technical system or the working environment
Phase change	Benefit from the properties of changing the state of aggregation of a part of the Technical system, the Object, or the working environment, including the change of physical parameters, e.g. the volume and specific heat (TRIZ Inventive Principle N. 35) and the latent heat released, e.g. condensing boilers (TRIZ Inventive Principle N. 36)	Substitute a material with another able to change its state of aggregation to exploit the latent heat released and reduce the energy consumption and the arising environmental impacts

3.2. Test

This section presents how the test to evaluate the effectiveness of the revised TRIZ strategies for MS in increasing the sustainability of the obtained solutions and the followed methodology.

3.2.1. Objectives

The first step in the planning of the test involved the definition of a term of comparison to evaluate the environmental sustainability of the results obtained from the application of the revised TRIZ strategies for MS. Consistent with the starting hypothesis that this test wants to verify, the generic MS was selected as a term of comparison. The latter is the strategy most commonly proposed by the different eco-design methods (e.g. Luttropp and Lagerstedt, 2006) in which "how" and "when" is possible to discretize and focus MS is not specified. For this reason, the latter is intended within the entire volume of a component. An example is the replacement of a car hood made entirely of steel with another of the same shape and made entirely of aluminium (Sun et al., 2017).

On the other hand, since the revised TRIZ strategies for MS have a general validity and are not referred to a specific type of material or product, their application was evaluated in different case studies. In this way, an idea about the modalities of application that have obtained the greatest benefits on environmental sustainability can also be provided. For this reason, the case studies related to different products for, manufacturing technology, size, functions and requirements and original and replacement materials, have been selected.

In particular, the types of considered substituting materials were divided into three main classes:

- **Virgin synthetic materials** made from mineral and non-renewable resources, such as plastics.
- **Virgin natural materials** of vegetable or animal origin can be completely natural, such as a cork, or natural-based, when natural materials are transformed through an irreversible chemical process, as in the case of polylactic acid (PLA).
- **Recycled (/reused) material** obtained by recycling or using a virgin synthetic material (e.g. iron from scrap) or a virgin natural material.

3.2.2. Methodology

To objectively and quantitatively evaluate the revised TRIZ strategies for MS, according to the established objectives, a systematic methodology was adopted. This methodology, already defined and applied in Spreafico (2021b), was considered because of the obvious similarities of that study to this in some points:

- The Strategies to be tested, i.e. TRIZ strategies although not previously related to MS.
- The determination of the environmental sustainability associated with the solutions obtained from the application of these strategies.
- The determination of a quantitative assessment of sustainability not dependent by the single application domain and the product type.

In summary, this methodology consists in the analysis of case studies taken from the literature, where, in each case, two technical systems are compared based on their environmental sustainability. The two technical systems represent two solutions to the same problem, achieved in two different ways. The first one, used as term of comparison, is an original device, while the second is the same device that has been improved following the suggestions of the tested strategies. The comparison presented in the case study is based on Comparative LCA, a standardized methodology that has been widely accepted and tested at scientific and industrial level. In this way, some standard categories of environmental impacts of two technical systems, performing the same function according to the same functional unit, are compared. The requirements for the reliable of the evaluation concern the selection of the sources and the rigorous application of the LCA methodology according to the reference standards ISO 14040 (ISO, 2006a) and ISO 14044 (ISO, 2006b).

The greatest approximation of this methodology is the association of the case studies to the tested strategies, because the solutions in the case studies were not obtained through the strategies. The test proposed in Spreafico (2021b) already carried out a similar association from a conceptual point of view. In this study, a systematic procedure was introduced for this aim, due to the lack of supporting approach in the literature. The association is carried out by analogy in some steps. Each of them is used to classify the solutions in some reference cases about the comparison between the two Technical systems and the tested strategies. The aim is to reduce the subjectivity in the association.

Figure 1 schematizes the testing methodology through a flowchart.

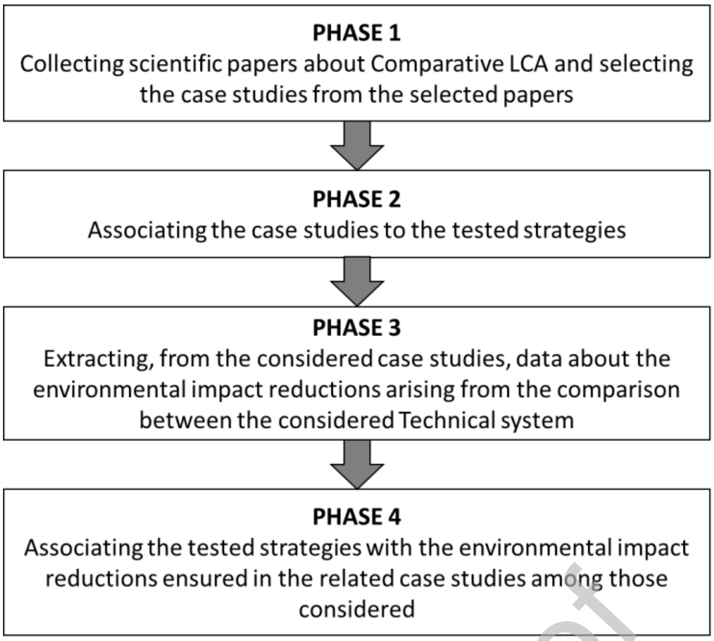


Figure 1: Flowchart of the testing methodology.

Provided that all the necessary requirements are carefully met, the use of this methodology has undoubted advantages compared to a LCA performed from scratch. The number of considered case studies can be considerably increased, easily exceeding one hundred, and with them the heterogeneity of the considered application domains. The time required for the analysis is reduced since the careful selection of the case studies and their analysis, although onerous, are still advantageous compared to an ad hoc analysis of the overall number of exploited case studies. The obtained the results are reliable, since they were obtained by closely applying LCA methodology in their containing case studies and they were rigorously peer-reviewed. Because of these advantages and the similarities of this study with Spreafico (2021b), the same testing methodology was applied. While some precautions in the various steps, which depend on the different tested strategies were considered. In the following, the different phases of the testing methodology are presented with reference to the test performed in this study.

PHASE 1 - Collecting the case studies from the literature

Only articles published in indexed international peer-review journals since 2010 were considered to guarantee reliable and updated results. These documents were retrieved from Scopus and Google Scholar databases through the following query (referred to Scopus syntax) “compar* AND (LCA OR (life W/ cycle W/ assessment))”. Among the many obtained documents, the relevant ones were selected according to an onerous manual analysis, deliberately using a very generic query due to the difficulty of defining the search perimeter in a more precise way. Codifying the content of the tested strategy and the concept of MS with keywords is very difficult and risks being detrimental to the collection of documents. In fact, the considered case studies rarely use terminology compatible with TRIZ ontology. In referring to “material substitution”, the name of the specific substituting material is preferred to the generic term "material". While the types of materials, identified in the case studies, turned out to be many and difficult to hypothesize a priori.

The selected documents contain the following elements:

1. A comparative LCA study between two solutions, carried out in accordance with ISO 14040 (ISO, 2006a) and ISO 14044 (ISO, 2006b), based on the same functional unit, operative scenario, initial conditions, calculation procedures. The same impacts categories to express the results were also considered.
2. The difference between the two solutions deals with the MS, carried out in a generic manner, i.e. diffuse throughout the reference volume, or in accordance with one of the revised TRIZ strategies for MS.

In addition, in order to not distort the results of this investigation, the case studies were selected if the provided environmental evaluations do not include an ad-hoc pejorative term, used only to enhance the performance of the other. This evaluation was performed on the basis of a contest analysis in the literature. The final pool of considered case studies, after the selection following these criteria, counts 153 case studies, extracted from 113 articles.

PHASE 2 - Classifying the case studies according to the tested strategies

The classification of the case studies according to revised TRIZ strategies for MS was carried out through a systematic step-divided procedure. This latter follows in part that in Spreafico (2021b) and with the same intention: reducing subjectivity in the classification due to the lack of pre-established rules allowing its automation. For this reason, both approaches refer to the more general systematic approach with which the TRIZ method allows the association between a specific known solution and a specific problem. First, the specific problem and the specific solution are respectively reformulated into an abstract problem and an abstract solution sharing share the same ontology. Hence the abstract solution is associated with the abstract problem on the basis of the correspondence between the ontological terms. The scientific nature of the TRIZ method and of the approaches deriving from it has not been demonstrated in the literature. However, the comments on its practical effectiveness and methodological rigor in the reformulation of the problem are flattering (e.g. Ilevbare et al., 2013).

The steps of the procedure adopted in this study are the following:

1. In each case study, for each compared material (i.e. the original one in the first Technical system and replaced one in the second Technical system), the Function performed on an Object, exploiting a certain physical effect, is determined. Function and Object refer to TRIZ ontology.
2. The revised TRIZ strategies were reformulated into more specific sub-strategies (reported in Table 3), where the provided suggestions are formalized according to the TRIZ ontological elements used in step 1. In this way, the sub-strategies explain different modalities to substitute the material.
3. The codified modalities of MS within the case studies are then associated with the sub-strategies, i.e. the codified specific parts of the revised TRIZ strategies for MS. The criterion underlying the association is the analogy between the elements of the TRIZ ontology in the two of them.

The association between the case studies and the revised TRIZ strategies for MS, articulated through Steps 1-3, was carried out entirely by hand by the author. At this stage, the author drew on much of his preparation. The basis is a good knowledge of the TRIZ method, gained through almost ten years of experience in academic research and applied in multiple consultancy activities with companies from different sectors. The necessary knowledge on LCA, eco-design and materials has instead been learned by the author in the last four years, in a similar way to the learning of the TRIZ method.

As an example of an association between the case study and TRIZ strategy for MS, consider the one obtained for the article by Özdemir and Onder (2020). In it, the environmental impacts arising from the entire life cycle of two panels to be used in the floor of a railway wagon are compared through the comparative LCA methodology. One panel is made of steel and the other of honeycomb aluminium, which is considered an innovative solution by the same authors. The second resulted more sustainable than the first due to the smaller mass. In their reformulation (STEP 1), steel has been defined as the original material, while honeycomb aluminium as the substituting material. While the common Function of the two is the mechanical resistance towards the Object, that is the load transported in the wagon. At the same time, the sub-strategies were determined from the TRIZ strategies for MS (STEP 2). In particular, the sub-strategy "The substituting material was optimized at micro-level to perform the Function (at macro-level) better than original material" was determined from the TRIZ strategy for MS "Macro-micro" (see Table 2). Finally, in STEP 3, this sub-strategy was associated with the considered case study since the micro-structure (i.e. honeycomb) of the substituting material (i.e. aluminium) allows to perform the Function with a smaller quantity of material than the of the original material which is a steel with a full structure. Consequently, the same case study was automatically associated to “Macro-micro” strategy for MS.

Table 3 reports all the used sub-strategies (Column 2), derived from the revised TRIZ strategy for MS (Column 1) and examples of associated case studies properly synthesized and formalized according to TRIZ ontology (see Column 3).

Table 3: Revised TRIZ strategies for MS, sub-strategies and examples of associated case studies.

Revised TRIZ strategies for material substitution	Sub-strategies	Examples of associated case studies
Segmentation	• The Function performed by the original material is simultaneously performed by both the original material and the oubstituting material. • Alternatively, the original material is split and arranged with substituting material, or substituting material is	To improve the insulation, a “wood” (original material) wall is substituted by another where layers of “wood” are altered to layers of “light straw clay” (substituting material) (Ben-Alon et al., 2021). A panel of “aluminium” is substituted by one made of “oriented strand wood board” (Segovia et al., 2019)

	split in multiples parts which are then arranged in different ways	
Nesting	• The Function performed by original material is simultaneously performed by both original material and substituting material. • At the same time, substituting material is nested within original material	In buildings, “Concrete” (original material) is filled with “rocks” (substituting material), recovered from the territory, to reduce the quantity of the first one and ensure the structural characteristics of the second one (Liu et al., 2013)
Macro-micro	• Original material and substituting material interact at micro-level to perform the Function together at macro-level on the Object • Alternatively, the substituting material was optimized at micro-level to perform the Function (at macro-level) better than original material	Railway passenger panel made by “steel” (original material) is substituted by one made by “honeycomb aluminium” (substituting material) to guarantee the same structural resistance (Function) by decreasing at the same time the weight of the panel (Özdemir and Onder, 2020)
Dematerialization fluid	• The original material is solid, and the substituting material is gaseous or liquid. • Substituting material performs the Function at a lower level of detail than original material	“Oil” (original material) in fryers is substituted by “hot air” (substituting material) to avoid environmental problems arising from the disposal (Carvalho et al., 2018)
Transition to supersystem	Substituting material is supported by a Resource and/or a Field, present in the external environment, in performing the Function	“Petroleum” (original material) is substituted by “Bioethanol” (substituting material) produced through “bio algae” (Resource) activated by “sunlight” (Resource) (Hossain et al., 2019)
Taking out	• The interfering parts are removed from original material and substituted with substituting material. • Alternatively, original material is entirely substituted by substituting material, which can work even after removing interfering materials from the working environment	“Polyurethane” (original material) insulation panel substituted with “polystyrene” (substituting material) with a meatus where the vacuum is made by eliminating “air” (interfering part) (Dylewski and Adamczyk, 2014)
Phase change	Substituting material can change its state of aggregation and/or exploiting thermal dilatation or contraction better than original material in performing the Function	Substituting “molten salt” (original material) with phase “change materials made by 54 wt.% KNO_3 46 wt.% $NaNO_3$ eutectic mixture” (Substituting material) in thermal energy storage systems for solar power plants (Oró et al., 2012)

Table 4 reports the Number of case studies associated with each tested strategy and the types of substituting materials after the followed procedure of classification.

Table 4: Number of case studies associated with each tested strategy and the types of substituting materials.

	Generic substitution	**Segmentation**	**Nesting**	**Macro-micro**	**Dematerialization fluid**	**Transition to Supersystem**	**Taking out**	**Phase change**
Virgin synthetic materials	11	8	5	6	8	9	5	7
Virgin natural materials	8	12	15	7	5	5	10	< 5
Recycled materials	15	5	10	5	6	< 5	5	< 5

PHASE 3 - Extracting data from the case studies

In this phase, the environmental impacts resulting from the life cycle of each considered option from the case studies were extracted. The selected impact categories are the most common in the literature and include both global and local effects affecting both environment and humans. The selected impact categories are:

- Global warming potential (GWP), limited to the production of CO_2 eq.
- Acidification potential (AP), limited to the production of SO_2 eq.
- Eutrophication potential (EP), calculated as the arithmetic mean of terrestrial, fresh water and marine eutrophication.
- Particulate matter formation (PMF), considering the production of PM2.5 or PM10 or their arithmetic mean if both are available.
- Resources depletion (RD), obtained from the arithmetic mean of mineral, fossil, and non-renewable resource depletion indicators.
- Water consumption (WC), expressed in m^3.
- Average impact, calculated as the arithmetic mean of all the considered indicators.

PHASE 4 - Quantifying the eco-sustainability of the tested strategies

The percentage reduction in each environmental impact category (j) associated with each tested strategy (x) was calculated as the arithmetic mean of the percentage reductions, in the same impact category, in all the (N) case studies associated to that strategy (during PHASE 2), as already made in Spreafico (2021b). In the calculation, both the generic MS and the revised TRIZ strategies for MS are considered.

$$\% \, I_j \; reduction \;_{Strategy\; x} = \frac{\sum_{i=1}^{N} \% I_{j,i} reduction}{N} \tag{1}$$

Where the percentage reduction of the given environmental impact category (j) in a case study (k) was calculated as the difference of the environmental impact, of the same category, of option 2 (regarding the substituted material) and that of option 1 (regarding the original material), divided by the environmental impact of option 2.

$$\% \, I_{j,k} \; reduction = \frac{I_{j,k}(option\; 2) - I_{j,k}(option\; 1)}{I_{j,k}(option\; 2)} \tag{2}$$

4. Results and discussion

4.1. Results

In the presentation of the results, provided in this section, the revised TRIZ strategies for MS were compared on the basis of percentage reductions in the selected environmental impact categories. At this stage, the reader is invited to consider the presented results also in relation to the number of considered documents (see Table 5). Furthermore, to maintain the significance of the provided results, only those based on at least five case studies were presented, this threshold was arbitrarily chosen. All the results are reported in Table S2 in the appendix.

The most general result of this study is the comparison between the Percentage reductions of the Average impact in the case studies associated with generic MS and the revised TRIZ strategies for MS. Table 5 describes this comparison through some statistical parameters relating to the two populations.

Table 5: Statistical comparison between the percentage reductions of the Average impact associated with the generic MS and the revised TRIZ strategies for MS.

	Generic material substitution	**Material substitution with revised TRIZ strategies**
Average in the related case studies	21%	42%
Standard deviation	18%	27%
First quartile	7%	21%
Third quartile	27%	60%
Number of case studies	33	120

Figure 2 reports the box plot of the percentage reductions of the Average impact associated with the generic MS and the revised TRIZ strategies for MS in the considered case studies.

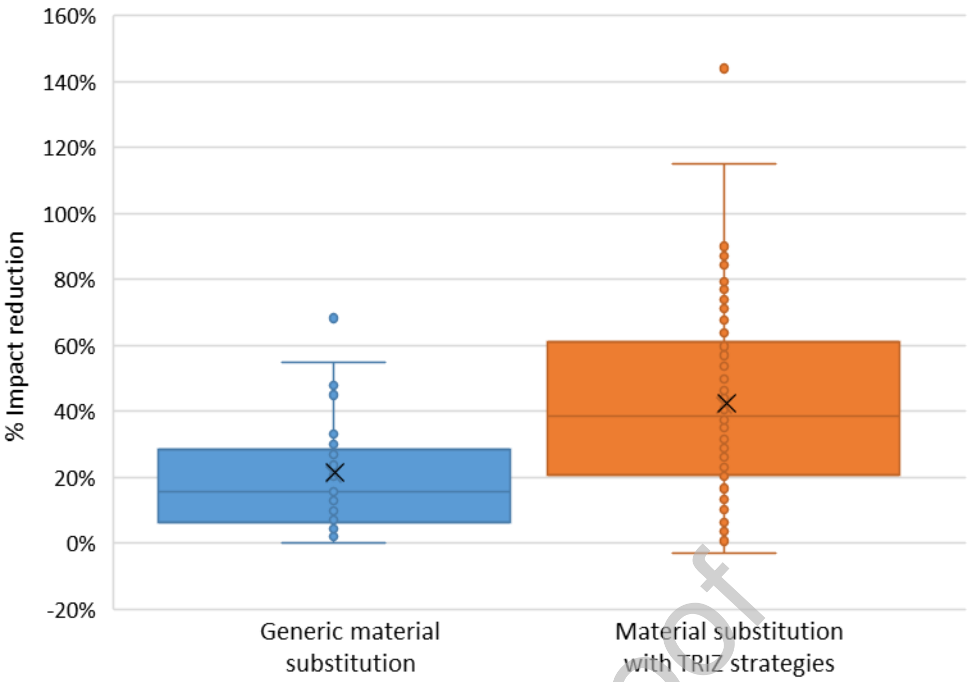


Figure 2: Box plot of the percentage reduction of the Average impact associated with the generic MS and the revised TRIZ strategies for MS in the considered case studies.

The results reported in Table 5 and Figure 2 are useful to confirm the starting hypothesis, i.e. “Can MS applied similarly with the suggestions provided by the TRIZ strategies achieve more sustainable solution than generic MS?”. In fact, it can be seen from them that MS associated with the revised TRIZ strategies is better than the generic one in reducing the Average impact. This is evident when considering the difference between the averages of the reductions in the Average impact in the two sets (i.e. + 21%). The quartile data also go in this direction, while the lower standard deviation in generic MS may be due to the smaller number of case studies associated with this option (i.e. 33) compared to the others (i.e. 120).

In order to highlight the contribution of the type of substituting material and the different strategies, Figure 3 depicts the comparison of the percentage reductions of the Average impact obtained for each of them. In this graph, these values are classified according to the type of substituting material (i.e. virgin synthetic material, virgin natural material and recycled material), and the strategy used for MS (i.e. generic substitution or the revised TRIZ strategies for MS).

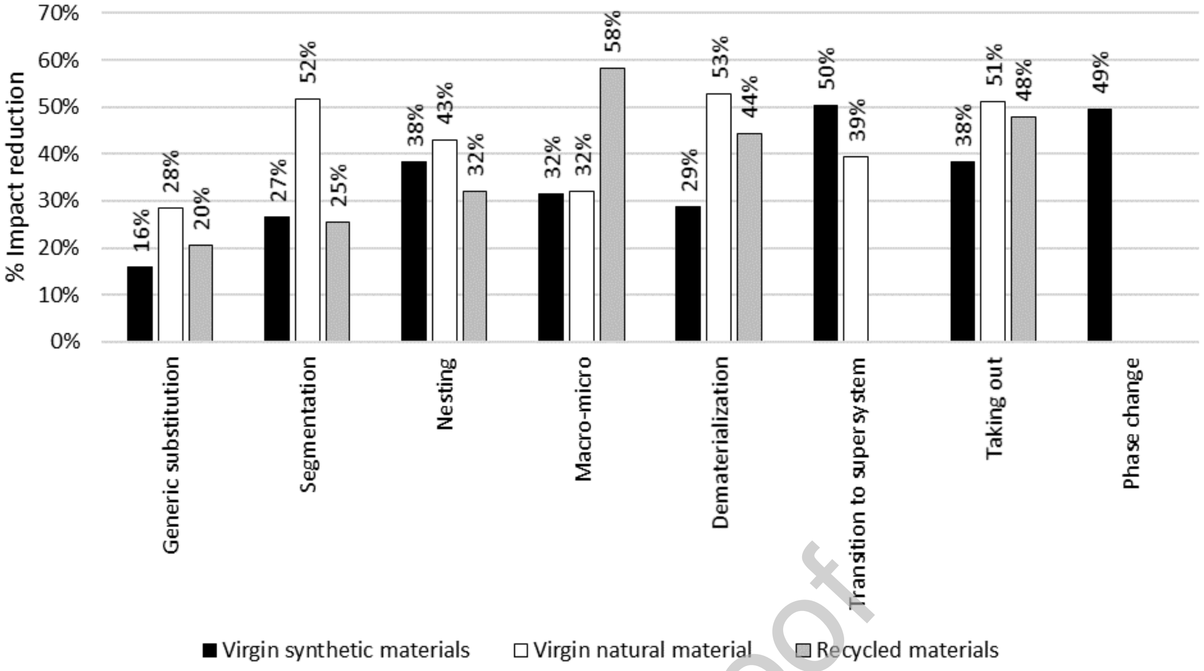
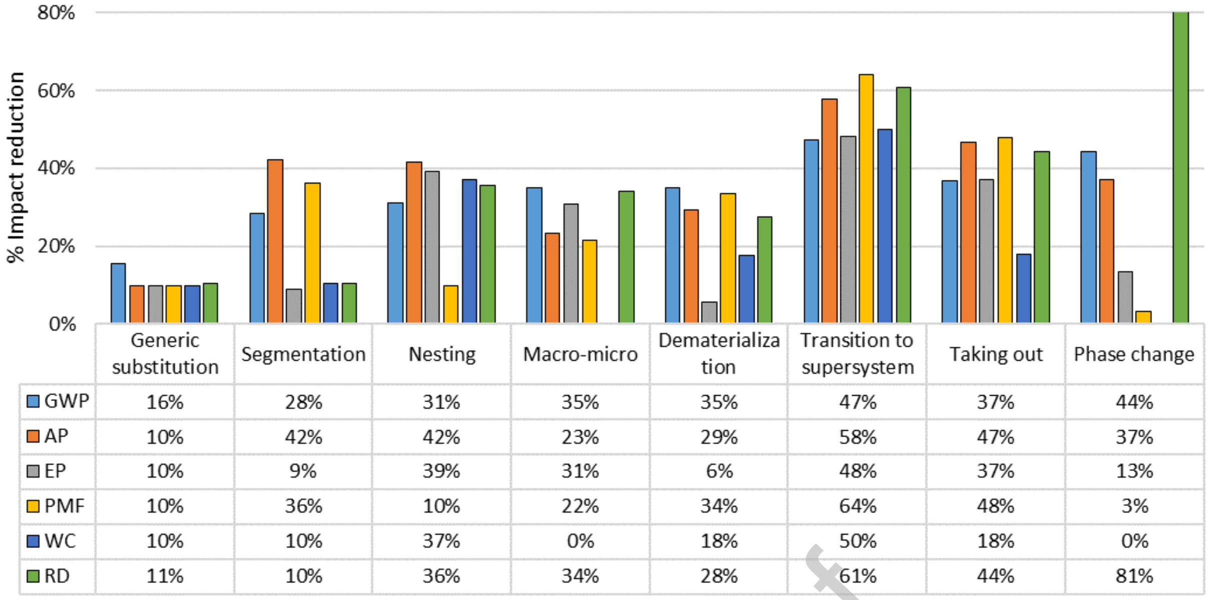


Figure 3: Percentage reductions of the Average impact associated with the generic MS and the revised TRIZ strategies for MS, based on the introduction of virgin synthetic materials, natural materials, and recycled materials.

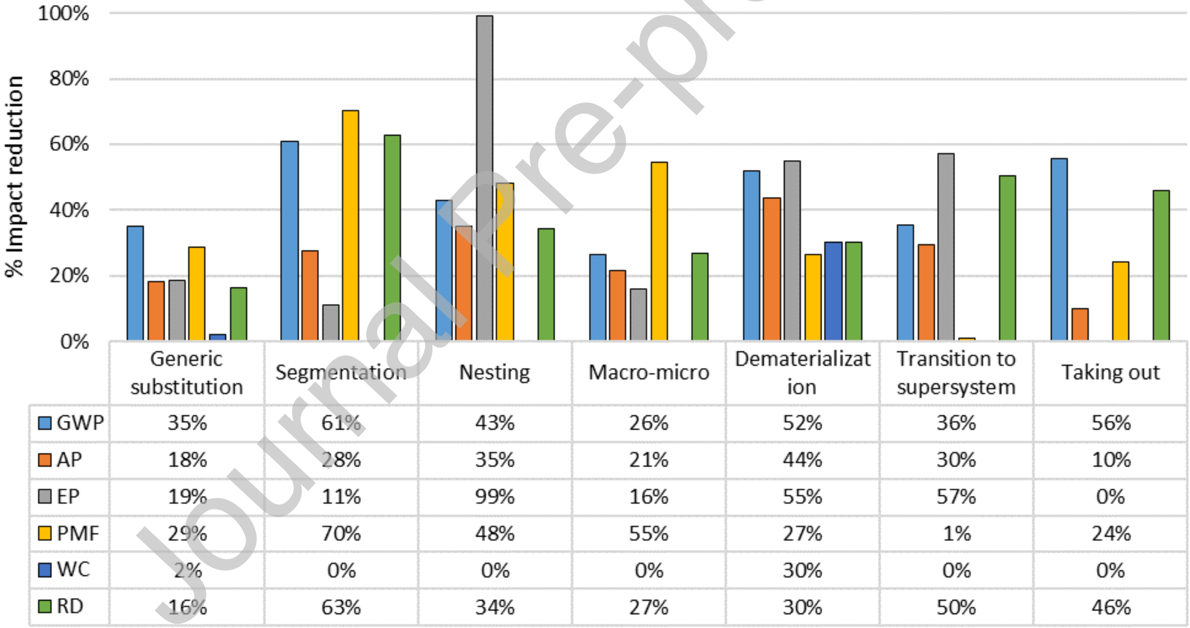
Regarding the type of substituting material (see Figure 3), the greatest percentage reduction in the Average impact was associated with virgin natural materials, with an arithmetic average of this indicator equal to 43% in all the tested strategies. The value of the indicator is lower in recycled materials (38%) and in virgin synthetic materials (35%). As far as the strategies are concerned, all the revised TRIZ strategies obtained percentage reductions in the Average impact greater than those associated with the simple substitution, for all types of substituting materials. The most advantageous strategy for environmental sustainability was Phase Change, with an average reduction in Average Impact of 49%, although considering its limited number of case studies, followed by Taking Out (46%) and Transition to Supersystem (45%). Finally, the combination of the types of materials and the tested strategies shows the greatest environmental benefits, in terms of percentage reduction in Average impact. They were obtained with the application of the Macro-micro strategy with recycled materials (58%), followed by Segmentation with virgin natural materials (52%).

The analysis of the values obtained for the single impact categories can be strategic to comprehend the causes behind the confirmation of the starting hypothesis. For these reasons, Figure 4 represents a comparison of the percentage reductions of each considered impact category for each tested strategy when the substituting material is a virgin synthetic material. While Figure 5 and Figure 6 depict the same comparison when the substituting material is respectively a virgin natural material and a recycled material.



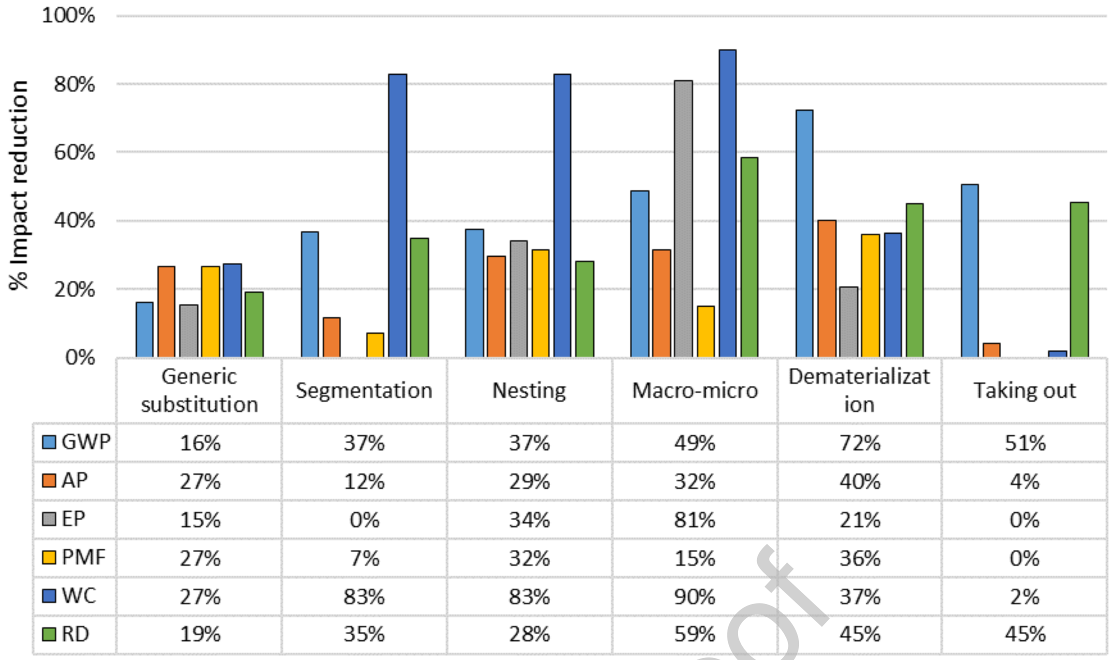
	Generic substitution	Segmentation	Nesting	Macro-micro	Dematerialization	Transition to supersystem	Taking out	Phase change
GWP	16%	28%	31%	35%	35%	47%	37%	44%
AP	10%	42%	42%	23%	29%	58%	47%	37%
EP	10%	9%	39%	31%	6%	48%	37%	13%
PMF	10%	36%	10%	22%	34%	64%	48%	3%
WC	10%	10%	37%	0%	18%	50%	18%	0%
RD	11%	10%	36%	34%	28%	61%	44%	81%

Figure 4: Percentage reductions of each impact category associated to the tested strategies for MS, based on the introduction of virgin synthetic materials.



	Generic substitution	Segmentation	Nesting	Macro-micro	Dematerialization	Transition to supersystem	Taking out
GWP	35%	61%	43%	26%	52%	36%	56%
AP	18%	28%	35%	21%	44%	30%	10%
EP	19%	11%	99%	16%	55%	57%	0%
PMF	29%	70%	48%	55%	27%	1%	24%
WC	2%	0%	0%	0%	30%	0%	0%
RD	16%	63%	34%	27%	30%	50%	46%

Figure 5: Percentage reductions of each impact category associated to the tested strategies for MS, based on the introduction of virgin natural materials.



	Generic substitution	Segmentation	Nesting	Macro-micro	Dematerialization	Taking out
■ GWP	16%	37%	37%	49%	72%	51%
■ AP	27%	12%	29%	32%	40%	4%
■ EP	15%	0%	34%	81%	21%	0%
■ PMF	27%	7%	32%	15%	36%	0%
■ WC	27%	83%	83%	90%	37%	2%
■ RD	19%	35%	28%	59%	45%	45%

Figure 6: Percentage reductions of each impact category associated to the tested strategies for MS, based on the introduction of recycled materials.

The detail about the virgin synthetic materials (see Figure 4) is useful to explains the particularly high value of the percentage reduction of the Average impact of the Transition to supersystem strategy. This is is due to the very high values of the percentage reductions of all the impact categories, ranging from 47% to 64%. The result of the phase change strategy depends above all on the high percentage reduction in RD, since the other impact categories obtained much more modest results. The Taking out strategy obtained a more homogeneous distribution among the various impact categories, which are almost all close to 40%. From the detail on virgin natural materials (see Figure 5), some significant peaks in some impact categories and in some strategies can be observed, as well as a rather jagged overall trend. The reductions of EP in Nesting, Dematerialization and Transition to supersystem strategies are particularly high. The same consideration is valid for PMF in Segmentation and Macro-micro strategies, GWP in Segmentation and Taking out strategies and RD in Segmentation and Transition to supersystem strategies. Finally, the impact categories that obtained the greatest percentage reductions in the case of the introduction of recycled materials (see Figure 6) were WC in the case of Segmentation, Nesting and Macro-micro strategies and GWP for Dematerialization, Taking out and Macro-micro strategies.

Even considering the individual strategies, both by observing Figures 3-6, and by analysing the case studies associated with them, different results can be read. The largest percentage reductions in Average impact (> 60%) in seven of eight cases studies associated with Segmentation were achieved through the introduction of natural materials, although with a difference between natural-based and completely natural materials. The analysis of the product types and their application fields showed that Segmentation strategy achieved the greatest reductions in Average impact when applied to large products and in a coarser manner. Some examples are the realization of sandwich insulation panels for buildings (e.g. La Rosa et al., 2014; Ben-Alon et al., 2021) or real walls for buildings with load-bearing and dividing function (e.g. Zea Escamilla et al., 2018). By reducing the size of the products and the scale of application of Segmentation, the reductions in impacts decrease. Some examples are the insulators for transportation means (e.g., Özdemir and Onder, 2020) and packaging (e.g., Zhang et al., 2015; Vigil et al., 2020), where the impact reduction is greater when the size is very small. Furthermore, except for the general preference of natural materials over others, this aspect, in the analysed case studies, is not associated with the type of used material. To evaluate the difference at a numerical level, all the case studies were divided into two groups according to the dimensional scale in relation to which the Segmentation strategy was performed, i.e. the characteristic dimension of the obtained plot. Overall, 16 case studies refer to Segmentation on a centimetre plot, while 9 on a millimetre plot. The reduction in the Average impact was respectively 48% in the first class and 22% in the second. Furthermore, the first class is better than the second in all impact categories, with maximum deviations in PMF (+ 33%) and in RD (+ 32%).

In the case of the Nesting strategy, the difference between the used materials, at the level of Average impact reduction, is clearly less marked than in the case of the Segmentation strategy. Even in the case of natural materials, which were nevertheless found to be the most sustainable choice, the percentage reductions of the same indicator are quite similar between completely natural materials (e.g. Liu et al., 2013) (44% in 10 case studies) and natural-based materials (e.g. Hengen et al., 2014) (40% in 5 case studies). Again, as with Segmentation strategy, the scale factor played a key role. In fact, to the introduction of centimetre scale parts (e.g. Liu et al., 2013) (8 case studies) greater percentage reductions in Average impact than the introduction of sub-millimetre scale parts (e.g. Vigil et al., 2020) (18 case studies) were associated. Their values were found to be 52% and 30%, respectively. All impact categories were in favour of the centimetre scale, but the largest differences were found for EP (+38%) and GWP (+33%).

The clear difference in the percentage reductions in the Average indicators that were found in Macro-micro strategy with recycled materials and with the other types of materials is mainly due to the introduction of recycled nanomaterials (e.g. Gao et al., 2013). Regarding the Dematerialization strategy, the rather clear gap of virgin natural materials and recycled materials over virgin synthetic materials depended first on the introduction of gaseous mediums, used to transmit heat (e.g. Carvalho et al., 2018) or as catalysts (e.g. Choe et al., 2013). In the case studies associated with the Transition to supersystem strategy, a clear distinction was found the introduction of virgin synthetic materials and virgin natural materials. In particular, an advantage derives from the substitution of small parts or fibres of synthetic material, while maintaining the matrix, such as plastics in textiles (e.g. Schiavoni et al., 2016). Finally, in almost all of the collected case studies about Phase change strategy, the exploited materials are synthetic (e.g. Peng et al., 2016; Zhang et al., 2020).

Other results were instead obtained to comprehend if the revised TRIZ strategies are more sustainable than the original TRIZ strategies. To answer this question, the obtained results can be compared with those of Spreafico (2021b) in which the original TRIZ strategies were tested following the same procedure as in this study, albeit on different case studies. Figure 7 presents the comparison between the percentage reductions of the Average indicator of each tested strategy in the two studies. As regards the results of this study, the average values of the percentage reductions of the Average indicators of the three types of considered materials have been reported.

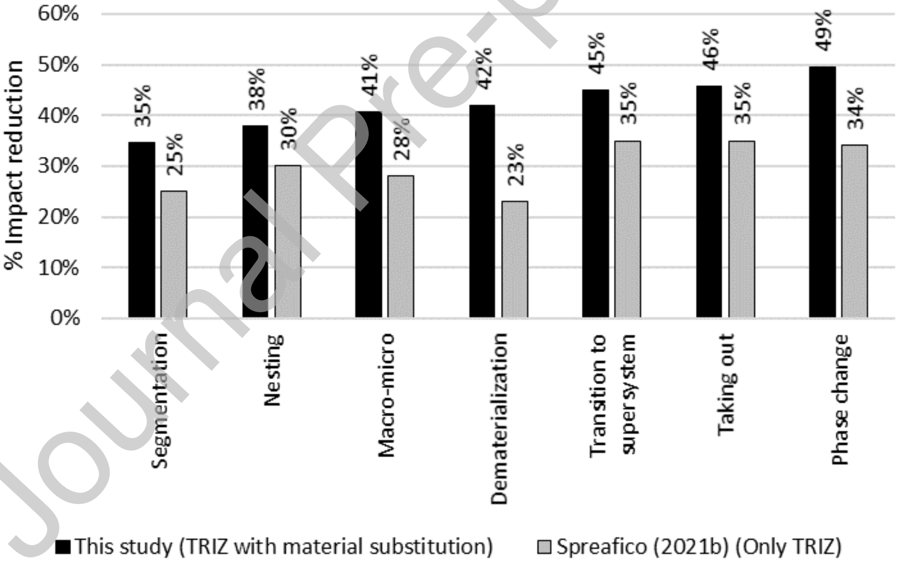


Figure 7: Comparison of the percentage reductions of the Average impact associated to the revised TRIZ strategies for MS, in turn expressed as the arithmetic mean of the values of the three types of considered materials, and those associated to the original TRIZ strategies (from Spreafico, 2021b).

As can be seen from the comparison shown in Figure 7, each revised TRIZ strategy for MS allowed to reduce the impacts more than its equivalent original TRIZ strategy. The average increase in the percentage reduction in the Average impact of all the strategies was 12%, while the strategies that achieved the greatest increases in percentage reductions are Dematerialization (+19%) and Phase change (+15%). This result clearly argues in favour of the contamination of TRIZ with MS, showing that the advantage is twofold, as well as for MS (see Figure 3) also for TRIZ.

4.2. Discussion of the results

In general, the confirmation of the starting hypothesis provided by this study (see Figures 2-6), in consideration of its limitations, mainly depends on several aspects. The rationalization of MS in the component has been more sustainable than the complete replacement since most of the revised TRIZ strategies for MS point in this direction. This consideration is confirmed, limited only to the reduction of GWP, by the study of Kawajiri et al. (2020), which compare MS in variable percentages with respect to the mass of different automotive components. The same conclusion is also confirmed at the economic level by Hugo et al. (2020). This study compared the costs of MS for different types of products and developed a model to determine the most cost-effective rate, also considering other product requirements, such as mechanical strength. However, such works merely identify which portion of a material could be replaced but do not provide details on how to implement the replacement and combine the substituting material with the original one.

Multi-material parts or components were more sustainable than mono-material ones through the application of most of the revised TRIZ strategies for MS. This consideration contrasts with a widespread negative perception of multi-materials parts, which has also been formalized among the best practices for the eco-design of some works (e.g. Foschi et al., 2020; Sanyé-Mengual et al., 2014; Muñoz et al., 2006). However, in all these studies, the criticism of multi-material parts is directed primarily at disposal, which is more impactful than in mono-material parts, without considering the entire life cycle, as in this study.

In addition, the revised TRIZ strategies for MS leaded to more sustainable results than the same TRIZ strategies in the original version (see Figure 7), although in consideration or the limitations of this comparison. In fact, in the present study, only case studies where MS is beneficial for environmental sustainability were considered. While in Spreafico (2021b) some non-advantageous case studies were also considered, albeit limited in number and with rather limited disadvantages. For this reason, the margin obtained from this comparison could be reduced if even in Spreafico (2021b) only case studies advantageous for sustainability had been considered. Even in this case, according to an estimate, the result obtained in the comparison would not be reversed.

More in detail, a crucial aspect in the reduction of impacts and common to various strategies was found to be the size factor of application of MS. Regarding the Segmentation strategy, the evidence about the dimensional scale confirms on a more general level some specific evidence that the study by Cabrera et al. (2021). In that case, the obtained conclusions were about eco-design of micro and nanolayer films based on polyolefins involving recycled materials. The same authors illustrated the complications arising at the realization level, when, using a recycled material and guaranteeing the same properties in terms of stress and deformation, the scale of a multilayer film is reduced. The result is a finer control of the reaction parameters and an increase in the expended energy as a function of the amount of realized material. In the case of Nesting strategy, this result should be look very carefully in relation with the addressed problem and the boundary conditions. For instance, Kuswandi (2017), with a study on the sustainability of the constituent materials of active food packaging, confirmed that as the size of the nested bactericide particles decreases, the manufacturing complications increase. This is true, even for the greenest materials, with a consequent increase in environmental impacts. Nevertheless, nanometric particles are essential to inhibit the action of a large number of bacteria inside the packaging to extend food conservation. Contrary to the Segmentation and Nesting strategy, in the Macro-micro strategy the greatest benefits have been identified with the introduction of recycled nanomaterials, i.e. reducing the dimensional scale.

Another aspect concerns the use of bio-based materials. In the case of the Macro-micro strategy, the reductions in both the Average impact and almost all the impact categories were well above the average results for the Macro-micro strategy. In this case, the microstructural optimization between the fibres of bio-based materials and the matrices of natural or synthetic materials allowed to significantly reduce the environmental impacts. At the same time, the structural and mechanical characteristics of alternative or natural synthetic products, not optimized at structural level, are preserved. This result brings a useful quantitative evidence to confirm the qualitative considerations about the greater environmental sustainability of natural-based composites compared to other composite materials (e.g., Balea et al., 2014; Onuaguluchi and Banthia, 2016; Dunne et al., 2016). Although in those contributions, the perspective of analysis is much narrower than in this study, focusing only on some specific fields of application such as construction cement or automotive materials. While in the Transition to supersystem strategy, all the case studies dealing with natural materials (e.g. Hossain et al., 2019; Mondello et al., 2017) propose the use of living species, including bacteria and algae, activated by solar energy. In this way a specific chemical action related to obtaining products from waste, e.g biogas production from manure digestion, can be obtained by replacing much more impacting reagents and technologies.

More heterogeneous and detailed considerations emerged only for some strategies. In the Dematerialization strategy, natural gases proved to be more sustainable than synthetic ones with the same calorific value, flow rate and other chemical-physical characteristics. In the specific case of heat transfer, an obvious advantage was instead to recycle inside the plant or outside, hot fumes or gases to transmit heat (e.g. Kwofie and Ngadi, 2017). In the Transition to supersystem strategy, the environmental advantages arising from virgin synthetic materials deals with the use of a less impactful material within canonical technologies for the exploitation of renewable energies (e.g. Elkhayat et al., 2020). Another possibility concerns the introduction of materials that, being able to interact with fields (e.g. magnets), also allow the dematerialization of the system, eliminating the parts that work by contact (e.g. Schreiber et al., 2019). In the latter case, the reduction of the environmental impacts of the material is due to its more sustainable life cycle and the technological improvement that leads to the elimination of some parts and the reduction of energy consumption. In Taking out strategy, the increased sustainability of virgin natural materials, compared to the others and the oxygen removal from their inside or from the working environment have dual benefits. On the one hand, the aim is to reduce the impact of the material and, on the other, to reduce the impact of gas management. In this case, synthetic materials are the only choice contemplated in the relevant case studies. Finally, in Phase change strategy, the environmental advantages in the exploitation of the latent heat during the phase transition confirms and extends the conclusions drawn by Thambidurai et al. (2015). Although these latter are based on experimental data and are limited only to the buildings sector and the GWP impact category.

Table 6 summarizes the key considerations presented in Sections 4 and 5 regarding the ways to implement the revised TRIZ strategies for MS that achieved the greatest environmental benefits in this study.

Table 6: Summary of the modalities of applications of the revised TRIZ strategies for MS associated to the solutions in the analysed case studies that leaded to the better results for sustainability.

Revised TRIZ Strategies for material substitution	**More sustainable substituting materials**	**Better modalities of applications and/or application fields for improving sustainability**	**Impact categories with the highest percentage reductions**
Segmentation	Virgin natural-based materials	Segmentation within products of a larger scale (centimetre) is preferable to those of a smaller scale (millimetre)	AP, PMF
Nesting	A clear preference did not emerge	Nesting of larger-scale particles (centimetre) is preferable to nesting of smaller-scale particles (millimetre)	EP (Virgin natural-based materials), WC (Recycled materials)
Macro-micro	Recycled materials	Introducing bio-based composites and recycled nanomaterials	WC, EP
Dematerialization	Virgin natural-based materials and Recycled materials	Using gaseous medium and fumes to transmit heat	GWP, PMF (Virgin natural-based materials), WC (Recycled materials)
Transition to supersystem	Virgin synthetic materials and natural-based materials	Virgin synthetic materials: Technologies for the exploitation of renewable energies and magnetic materials to dematerialize transmissions by contact. Natural-based materials: introducing living species, e.g. bacteria and algae, which exploit solar energy	PMF, RD (Virgin synthetic materials), EP (Virgin natural-based materials)
Taking out	Virgin natural-based materials and Recycled materials	Replacement of synthetic fibres in composite materials and fabrics with natural-based materials, maintaining the matrix. Oxygen removal in energy processes	GWP (Virgin natural-based materials)
Phase change	Virgin synthetic materials	Exploiting the latent heat of the material during phase transition	RD

5. Conclusions

This study proposed a set of revised TRIZ strategies for MS and showed that the solutions in the case studies that can be associated with them are more sustainable than those where a generic MS was considered. To obtain them, the suggestions provided by a heterogeneous and representative set of TRIZ strategies were specifically adapted for MS. The test was conducted following a rigorous and systematic procedure, based on LCA of 153 case studies, extracted from 113 articles. The use of this methodology to assess TRIZ in guiding MS is another novelty of this study. In addition, the number of case studies considered in this evaluation is considerably higher than in previous studies and the domains of application and the types of considered materials are many and more heterogeneous. The results were expressed as a function of standard categories of environmental impact (i.e. global warming potential, acidification potential, eutrophication potential, particulate matter formation, non-renewable resource depletion and water depletion) and compared with each other. The association of the case studies with the revised TRIZ strategies for MS is also part of the followed rigorous procedure and was carried out manually.

The main limitations of this study, in consideration of which the obtained results must be read, are the following. The limited number of case studies related to certain stratifications. Although the considered case studies are many, certain considerations presented are based on a much smaller number of case studies, which in some classes do not exceed ten units. The methodology with which the case studies were associated with the strategies has been widely structured and objectified but is still based on a manual interpretation, subjective and based on a good knowledge of the TRIZ method. The classification of the case studies was carried out only by the author of this study. Despite the process of selecting the sources, the considered case studies are academic and the data extrapolated from them presuppose a trust in the authors and reviewers of the containing articles.

In light of these limitations, the comparison of the results confirmed the starting hypothesis, i.e. “Can MS applied similarly with the suggestions provided by the TRIZ strategies achieve more sustainable solution than generic MS?”. These advantages were found in all the considered impact categories and substituting materials. In addition, by analysing in detail all the obtained results and comparing them with other studies in the literature, the application modalities of the different revised TRIZ strategies associated with the most promising case studies were collected. In most cases, the rationalization of MS proven to be more sustainable than the complete substitution. Similarly, the solutions based on multi-material components or products were also found to be more sustainable than those with mono-material parts. The judgment on both these considerations contrasts with some studies in the literature, albeit mainly because of the different way in which environmental sustainability is assessed. In addition, applying TRIZ strategies with MS resulted in more sustainable solutions than applying the same strategies without MS. This is an unusual result since TRIZ is generally applied alternatively to MS.

A few interesting points emerged among the application modes and application areas that yielded the greatest environmental benefits for each tested strategy. The inclusion and combination of different materials have been more sustainable when the characteristic dimensions are on the order of centimetres, rather than going below a millimetre. The introduction of natural-based composites was more strategic than that of traditional composite materials, suggested by one of the original TRIZ principles. In heat transmission, gaseous mediums are more sustainable than solid ones. Finally, another option is to prefer materials that can interact better with the resources present in the environment such as electromagnetic fields and living animal and plant organisms.

The change of perspective about generic MS and the common use of TRIZ was useful to lead to interesting results in the field of eco-design. This conclusion was corroborated by the variety of the many analysed case studies and by the rigorous method of analysis. The adaptation of this latter from a previous study also allowed to compare the results of the two studies, drawing one of the main conclusions.

Furthermore, this study also allowed us to highlight at least two counterintuitive and non-obvious insights about the use of TRIZ compared to conventional design and eco-design approaches on a more general level. The minimization in the use of certain resources, and the related environmental benefit, may be a consequence of the application of TRIZ rather than an explicitly researched goal. For this reason, the control over the specific resources to be minimized can be more blurred than in the other eco-design methods. The comparison between TRIZ and the types of materials, their characteristics and the applications limitations, to effectively guarantee environmental sustainability proved to be fundamental to highlight a certain neglect of the TRIZ suggestions towards the dimensional scale. In fact, the method proposes abstract solutions having a general validity that often transcends the level of detail, including its criticalities. It is then the designer's task to know how to concretely decline them at a structural level to obtain specific solutions.

The obtained results can be useful to the scientific community in different ways. The researcher of eco-design can find in this study a comparison on the environmental sustainability of the solutions resulting from the application of classic or innovative (i.e. TRIZ-based) MS. The TRIZ community could look forward to the novel perspective of providing an inventive role to MS. At the same time, the discussion on the methodological rigor of the tested revised strategies could also be encouraged. For the designer, this study could be useful to demonstrate the effectiveness of approaching eco-design through TRIZ even in the case of MS.

In order to overcome the limitations of this study, possible further developments regard: the involvement of other experts in the classification of the case studies; the search for other criteria to favour greater objectification in the classification; the use of less academic case studies, deriving from real industrial projects to eventually identify new ways to revise the TRIZ strategies for MS. The already identified strategies, as well as those potentially new, could serve as a basis for the development of an eco-design framework. Finally, further investigations could be dedicated to the other sustainability problems that TRIZ could address, in addition to the MS, and that this paper were only marginally highlighted: reduction of energy consumption, reduction of auxiliary materials, improved product disassembly, exploitation of waste resources to favour the transition towards circular economy.

Appendix

Table S1: Definition of the used TRIZ Evolutionary Laws and Inventive Principles, from Salamatov and Souchkov (1999) and Altshuller (1984).

Evolutionary Laws (EL)	**EL N. 4 - Increasing the degree of Ideality of the system and resources exploitation.** All systems evolve towards the increase of degree of Ideality or by increasing benefits and reducing costs and harms. This is possible by using a greater number of resources available within its structure or in the working environment
	EL N. 6 - Transition to a super-system. During evolution, systems merge and form bi and poly-systems. When a system exhausts the possibilities of further significant improvement, it is included in a super-system as one of its parts and a new development of the system becomes possible
	EL N. 7 - Transition of a system structure from macro to microlevel. The development of working organs proceeds, at first, on a macro and then on a micro level. The scale of a system changes by transition from supersystem to a system, from the system to its subsystem and substance that is the last goal. The change of the degree of the system is provided by increasing the degree of fragmentation (dispersibility) of a substance
	EL N. 8 - Increasing the S-Field involvement. Non-S-field systems evolve to S-field systems. Within the class of S-field systems, the fields evolve from mechanical fields to electro-magnetic fields. The dispersion of substances in the S-field increases. The number of links in the S-fields increases, and the responsiveness of the whole system tends to increase
Inventive principles (IP)	**IP N. 1 – Segmentation.** Divide an object into independent parts. Make an object easy to disassemble. Increase the degree of fragmentation or segmentation
	IP N.2 - Taking out. Separate an interfering part or property from an object, or single out the only necessary part (or property) of an object
	IP N. 7 – Nesting. Place one object inside another. Place each object, in turn, inside the other. Make a part pass through a cavity in the other
	IP N. 36 - Phase transitions. Take advantage from phenomena occurring during phase transitions (e.g. volume changes, loss or absorption of heat, etc.)

Table S2: Sources with the associated TRIZ strategies, materials, and LCA data (where GWP = global warming potential, AP = acidification potential, PMF = particulate matter formation, EP = eutrophication potential, WC = water consumption, RD = resources depletion, Pt = average index).

Articles	**Considered system/process**	**System 1**	**System 2**	**Introduced material**	**TRIZ strategy**	**GWP**	**AP**	**PMF**	**EP**	**WC**	**RD**	**Pt**
Adghim et al. (2020)	Dairy waste processing	Conventional	Anaerobic digestion	Synthetic	Taking out	-25%	-49%		-18%			-31%
Agarski et al. (2017)	Catalyst synthesis process	Catalyst fluid	Ultrasonic aerosol	Synthetic	Dematerialization, Transition to supersystem	-86%	-80%	-83%	-50%		-70%	-74%
Azzouz et al. (2017)	Wall insulation	Wall	Recycled fabric infilling	Recycled	Nesting	-32%					-9%	-21%
Bailis et al. (2013)	Pyrolysis	None	Cogeneration	Recycled	Dematerialization	-325%	-10%		-10%			-115%

Bailis et al. (2013)	Kiln for steel production	Hot tail kiln	Hot gas recirculation	Synthetic	Dematerialization	-30%	-5%	-15%				-17%
Ben-Alon et al. (2019)	Wall	Concrete masonry wall	Natural cob	Natural	Nesting	-75%					-18%	-47%
Ben-Alon et al. (2021)	Wall insulation	Wood wall	Wood wall with light straw clay and cob	Natural	Nesting, Segmentation	-92%					-71%	-82%
Bertolini et al. (2016)	Milk packaging	PET	Multilayer cartoons/plastic	Natural	Segmentation	-37%	-24%		-6%			-22%
Boland et al. (2014)	Car grill shutter	PP+30% glass fibre	PP+30% cellulose fibre	Natural	Generic substitution	-19%					9%	-5%
Bonamente and Aquino (2019)	Ground heat pump	Traditional	Phase change	Synthetic	Phase change	-17%	-15%					-16%
Çankaya and Pekey (2019)	Cement	Cement	Cement substitution	Synthetic	Generic substitution	-1%					-11%	-6%
Cánovas et al. (2013)	Heat pump residential heating	Heat pump single state	Heat pump brine/water	Synthetic	Phase change	-71%						-71%
Cánovas et al. (2013)	Heat pump residential heating	Heat pump single state	Heat pump air/water	Synthetic	Phase change	-59%						-59%
Carvalho et al. (2018)	Fryer	Stovetop deep frying	Hot-air frying	Natural	Dematerialization	-92%						-92%
Cecchel et al. (2018)	Crossbeam	Steel	Al	Synthetic	Generic substitution	0%						0%
Chen et al. (2016)	PET production	New PET	Bio-based recycled PET	Natural, Recycled	Generic substitution	-19%					-22%	-21%
Choe et al. (2013)	Water treatment ion exchange	Perchlorate selective filter	Gaseous catalysts	Natural	Dematerialization	-30%	-70%		-93%		-30%	-56%
Colangelo et al. (2020)	Wall	Wall	Recycled material infilling	Recycled	Nesting	6%	-20%				-38%	-17%
Colangelo et al. (2020)	Wall	Wall	Bio-polymer infilling	Natural	Nesting	5%	-15%				-30%	-13%
Colazo et al. (2015)	Solid waste anaerobic digestion	Wet	Dry	Natural	Dematerialization	-18%	-20%	-17%	-17%	-30%		-20%
Cossutta et al. (2020)	Super capacitors	Carbon activated	Graphene	Synthetic	Macro-micro	-36%					-14%	-25%
D'Amico et al. (2021)	Buildings	Concrete	Cross laminate timber	Natural	Segmentation	-2%						-2%
de Guinoa et al. (2017)	Insulation	Baseline	Aeroplane insulation	Synthetic	Macro-micro	-12%						-12%
Debreuil et al. (2010)	Front end frame	Steel	Mg	Synthetic	Generic substitution	-45%						-45%
Debreuil et al. (2010)	Front end frame	Steel	Al	Synthetic	Generic substitution	-26%						-26%
dos Santos Pegoretti et al. (2014)	Car acoustic components	DL-PU	DL cotton	Natural	Nesting	-35%						-35%
dos Santos Pegoretti et al. (2014)	Car acoustic components	DL-PU	Recycled ABA-cotton	Recycled	Generic substitution	-1%	-40%	-40%				-27%
Duflou et al. (2014)	Composite	Glass fibre	Bio-composite fibre	Natural	Nesting	-50%						-50%
Dylewski and Adamczyk (2014)	Insulation panel	PU	Expanded polystyrene vacuum panel	Synthetic	Taking out	-78%	-77%	-85%	-77%		-68%	-77%
Dylewski and Adamczyk (2014)	Insulation panel	PU	Granule plaster	Natural	Nesting	-36%	-60%					-48%
Elkhayat et al. (2020)	Glazing system	None	Photovoltaic glazing system	Synthetic	Transition to supersystem						-87%	-87%
Elkhayat et al. (2020)	Glazing system	None	Electrochemical glazing system	Synthetic	Transition to supersystem						-25%	-25%

Feng et al. (2014)	Flue gas desulphurization	Coal firing	Combined cycle	Recycled	Dematerialization	-3%	-70%	-38%	-35%	-80%	-45%	-45%
Gao et al. (2013)	Insulation material	Insulation	Nano insulation with silica and recycled ethanol	Recycled	Macro-micro						-144%	-144%
Gao et al. (2013)	Insulation material	Insulation	Nano insulation silica	Synthetic	Macro-micro						-64%	-64%
García-Alcaraz et al. (2020)	Disinfection wood wine barrel	Water vapour + SO2	Ozone	Natural	Dematerialization	-47%	-48%					-48%
García-Gusano et al. (2015)	Cement	Cement	Cement substitution	Synthetic	Generic substitution	-10%	-10%	-10%	-10%	-10%	-10%	-10%
Goulet et al. (2017)	Metered dose	Mechanic/pneumatic Inhaler	Electric nebulizer (macro-micro)	Synthetic	Dematerialization, Transition to supersystem	-50%						-50%
Guerra et al. (2014)	Sugarcane production	Vapour cycle	Regenerative vapour cycle	Recycled	Generic substitution	-6%	-6%	-6%		-6%		-6%
Hafner and Schäfer (2017)	Wall	Concrete	Timber	Natural	Segmentation	-37%						-37%
Hengen et al. (2014)	Acid mine drainage treatment	Active	Passive	Natural	Nesting	-70%		-42%			-44%	-52%
Hossain et al. (2018)	Wood waste	Cement	Wood waste-based cement	Recycled	Nesting	-70%					-2%	-36%
Hossain et al. (2019)	Bioethanol production	Traditional	Using algae activated by sun	Natural	Transition to supersystem	-50%						-50%
Hossain et al. (2016)	Aggregate production	New	Recycled glass	Recycled	Nesting	-61%	-46%				-54%	-54%
Hossain et al. (2017)	Cement	New	Recycled	Recycled	Generic substitution	-12%					-15%	-14%
Karami et al. (2015)	Vacuum panel	Normal	Tested	Natural	Taking out	-20%					-10%	-15%
Kelly at al. (2015)	Car components	Steel	Carbon fibre	Synthetic	Segmentation	-30%						-30%
Kelly at al. (2015)	Car components	Steel	Mg	Synthetic	Generic substitution	-26%						-26%
Kelly at al. (2015)	Car components	Steel	Aluminium	Synthetic	Generic substitution	-25%						-25%
Kelly at al. (2015)	Car components	Steel	AHSS	Synthetic	Generic substitution	-10%						-10%
Khalil (2018)	Carbon fibre recycling	Thermolysis (pyrolysis with contact heat transfer)	Solvolysis (using supercritical water)	Synthetic	Dematerialization	2%	4%	4%	1%			3%
Klemes (2012)	Wastewater reuse	Landfill	Reuse wastewater	Recycled	Generic substitution					-30%		-30%
Knoeri et al. (2013)	Concrete	Concrete	Recycled concrete	Recycled	Nesting	-18%	-22%		-22%		-20%	-21%
Kurda et al. (2020)	Concrete	None	Recycled concrete	Recycled	Generic substitution	-5%						-5%
Kwofie and Ngadi (2017)	Rice parboiled system	Traditional	Heat recirculation	Recycled	Dematerialization	-83%	-92%	-69%				-81%
La Rosa et al. (2014)	Sandwich material	Epoxy glass fibre	Natural (hemp) material sandwich	Natural	Segmentation, Nesting	-82%	-85%		-99%		-83%	-87%
La Rosa et al. (2021)	Composite resin	Novel composite	Composite with recycled resin	Recycled	Macro-micro	-89%	-65%		-81%	-90%		-81%
Landi et al. (2020)	Asphalt production	Traditional	Waste tire fibre reinforced	Recycled	Nesting	-25%	-31%	-31%				-29%
Landi et al. (2020)	Asphalt production	Traditional	Cellulose reinforced	Natural	Nesting	-10%	-10%	-11%				-10%

Leal et al. (2020)	Street slope repair	Rock fill cementation	Electro-osmosys	Synthetic	Transition to supersystem	-90%						-90%
Leal et al. (2020)	Street slope repair	Rock fill	Fibre reinforced soil	Natural	Nesting	-75%						-75%
Liu et al. (2013)	Dam	Concrete	Concrete filled with rocks	Natural	Nesting	-63%		-50%			-53%	-55%
Liu et al. (2019)	Toilet flushing	Traditional	Seawater	Natural	Generic substitution	-10%	-16%	-21%				-16%
Liu et al. (2020b)	Cotton yarns	New	Recycled yarns (50%) and new (50%)	Recycled	Segmentation, Nesting	-60%	-3%	-6%		-83%	-11%	-33%
Long et al. (2018)	Concrete	Concrete	Infilling with graphene with recycled fine aggregates	Recycled	Macro-micro	-7%					-2%	-4%
Lorite et al. (2017)	Active food packaging	PET	PLA nanocomposites active packaging	Natural	Macro-micro, Nesting	1%		-90%			0%	-30%
Lu et al. (2017)	Electronic waste	None	Recycle	Recycled	Segmentation	-17%	-33%					-25%
Manfredi and Vignali (2015)	Packaging	Hot filling	Aseptic	Synthetic	Taking out	-21%	-19%	-11%	-8%	-18%	-29%	-18%
Masoni and Scalbi (2015)	Transistor cooling	Conventional fluid	Single stage nanofluid	Synthetic	Macro-micro	-79%	-37%	-40%	-48%			-51%
Masoni and Scalbi (2015)	Transistor cooling	Nanofluid single stage	Double stage nanofluid	Synthetic	Phase change, Macro-micro	-24%	-3%	-3%	-13%			-11%
Modaresi et al. (2014)	Car components	Steel	Aluminium	Synthetic	Generic substitution	-8%						-8%
Mondello et al. (2017)	Waste elimination	Composting with UREA	Composting with insects	Natural	Transition to supersystem	-28%	-56%		-55%		-50%	-47%
Mondello et al. (2017)	Waste elimination	Composting with urea	Anaerobic digestion with urea	Synthetic	Taking out	-33%	-42%		-45%		-36%	-39%
Monfared et al. (2014)	Refrigerator	Traditional	Magnetic	Synthetic	Transition to supersystem	-22%						-22%
Montazeri and Eckelman (2018)	Wood coating	Conventional	UV-curing bio-based	Natural	Transition to supersystem	-40%					-51%	-46%
Munoz et al. (2021)	Wall insulation	Wall	Eco-material (Biomass) infilling	Natural	Nesting	-5%					-4%	-5%
Nabavi-Pelesaraei et al. (2017)	Urban waste (paper, plastic, glass, metal)	Landfill	Recycle	Recycled	Generic substitution	-50%	-60%		-40%			-50%
Nanaki and Koroneos (2012)	Car fuel	Diesel	Biodiesel	Natural	Generic substitution	-60%	-21%	-63%				-48%
Ning et al. (2013)	Solid waste incinerators	Mechanical grate	Fluidized bed	Synthetic	Segmentation, Dematerialization	-8%	-67%			-11%	41%	-11%
Oh et al. (2019)	Lightweight ship	Conventional (glass fibre and resin)	Lightweight (reducing resin)	Synthetic	Taking out	-26%						-26%
Opher and Friedler (2016)	Wastewater	None	Reuse wastewater	Recycled	Generic substitution	-24%	-24%	-23%	-24%	-24%	-23%	-24%
Orò et al. (2012)	Energy storage for solar power plants	Molten salts (liquid)	Phase change materials	Synthetic	Phase change							-58%
Özdemir and Onder (2020)	Railway passenger panel	Baseline	Sandwich aluminium honeycomb	Recycled	Segmentation, Macro-micro	-65%	-68%	-68%			-38%	-60%

Özdemir and Onder (2020)	Railway passenger panel	Baseline	Sandwich polyester resin/polymer foam	Synthetic	Segmentation	-63%	-65%	-65%			-14%	-52%
Özdemir and Onder (2020)	Railway passenger panel	Baseline	Sandwich phenolic resin/polymer foam	Synthetic	Segmentation	-34%	-35%	-35%			-25%	-32%
Özdemir and Onder (2020)	Railway passenger panel	Baseline	Sandwich glass fibre/polymer foam	Synthetic	Segmentation	-34%	-35%	-35%			-13%	-29%
Özdemir and Onder (2020)	Railway passenger panel	Baseline	Aluminium/Polymer foam	Recycled	Segmentation	-6%	8%	8%			-40%	-8%
Özdemir and Onder (2020)	Railway passenger panel	Baseline	Aluminium/ Aluminium honeycomb	Recycled	Segmentation, Macro-micro	-35%	38%	38%			-50%	-2%
Ozoemena et al. (2018)	Wind turbine transmission	Direct driving gearbox	Driven permanent magnet	Synthetic	Transition to supersystem	-13%	-36%		-47%			-32%
Paccanelli et al. (2015)	Nitrogen management in manure digestion	No treatment	Bacteria	Natural	Transition to supersystem	-28%	-3%	-1%	-60%			-23%
Palazzo and Geyer (2019)	Car components	Steel	Aluminium	Synthetic	Generic substitution	-16%						-16%
Pardo and Zufia (2012)	Food conservation	Autoclave non-thermal pressurization with gas	Modified atmosphere packaging	Synthetic	Nesting	-23%	-45%		-48%	-64%	-23%	-41%
Pardo and Zufia (2012)	Food conservation	Thermal pasteurization with water/steam injection	Autoclave non-thermal pressurization with gas	Synthetic	Dematerialization	-29%	11%		68%	-24%	-29%	-1%
Peng et al. (2016)	Remanufacturing cleaning technologies	High temperature air	Supercritical with liquid CO_2	Synthetic	Phase change	-82%	-93%				-90%	-88%
Pereira et al. (2015)	N-butanol production	Catalytic	Fermentation removing oxygen	Natural	Taking out	-12%	-10%	-24%			-10%	-14%
Poinssot et al. (2014)	Nuclear plant	Open fuel cycle	Closed fuel cycle	Recycled	Generic substitution	-3%	-15%		-2%			-7%
Pradhan et al. (2019)	Buildings	Concrete	Natural-coarse aggregate concrete	Natural	Nesting	-6%	-6%				-7%	-6%
Principi and Fioretti (2014)	Office lighting	Incandescence	LED	Synthetic	Dematerialization	-41%					-41%	-41%
Pusavec et al. (2010)	Cutting fluid	Conventional	Jet	Synthetic	Macro-micro	-25%	-30%				-25%	-27%
Quintana et al. (2018)	Plasterboard	Composite	Bio-based epoxy composite	Natural	Macro-micro, Nesting	-50%						-50%
Razza et al. (2015)	Foamed packaging	None	Bio-based Biodegradable	Natural	Generic substitution	-60%	8%		30%		-50%	-18%
Remy et al. (2014)	Wastewater treatment	Filtration membrane	Dual membrane filtration	Synthetic	Segmentation	-36%					-39%	-38%
Rew et al. (2018)	Snow removal airlift	Normal asphalt with Mechanical snow removal	Conductive asphalt (with graphite and electric energy)	Synthetic	Nesting, Transition to supersystem	-28%						-28%
Rios et al. (2019)	Building material (steel frame)	Wood (single use)	Steel (with reuse)	Recycled	Generic substitution	-36%				-89%	-40%	-55%
Rodriguez et al. (2020)	Coffee jar	None	Bio-composite reinforcement (Banana fibre max)	Natural	Macro-micro	-35%					-40%	-38%
Rodriguez et al. (2020)	Coffee jar	None	Bio-composite	Natural	Macro-micro	-30%					-35%	-33%

			reinforcement (with Banana fibre medium)									
Rodriguez et al. (2020)	Coffee jar	None	Bio-composite reinforcement (Banana fibre low)	Natural	Macro-micro	-25%					-30%	-28%
Rodriguez et al. (2020)	Coffee jar	None	Polylactic acid composite	Natural	Macro-micro	-20%					-30%	-25%
Satola et al. (2020)	Vacuum insulation wall	Standard	Recycled material	Recycled	Taking out	-5%	-4%			-2%	-4%	-4%
Schakel et al. (2014)	Co-firing plants with carbon capture and storage	Supercritical pulverized coal	Integrated gasification combined cycle	Recycled	Dematerialization	-6%						-6%
Schiavoni et al. (2016)	Vacuum insulation	Polyurethane	Sheep wool	Natural	Taking out	-77%					-82%	-80%
Schiavoni et al. (2016)	Vacuum insulation	Polyurethane	Recycled textile	Recycled	Taking out	-76%					-82%	-79%
Schiavoni et al. (2016)	Vacuum insulation	Polyurethane	Hemp	Natural	Taking out	-90%					-65%	-78%
Schiavoni et al. (2016)	Vacuum insulation	Polyurethane	Recycled Polyethylene	Recycled	Taking out	-52%					-78%	-65%
Schiavoni et al. (2016)	Vacuum insulation	Polyurethane	Cellulose	Natural	Taking out	-45%					-78%	-62%
Schiavoni et al. (2016)	Vacuum insulation	Polyurethane	Kenaf fibre	Natural	Taking out	-65%					-58%	-62%
Schiavoni et al. (2016)	Vacuum insulation	Polyurethane	Stone wool	Natural	Taking out	-77%					-46%	-62%
Schiavoni et al. (2016)	Vacuum insulation	Polyurethane	Stone wool	Natural	Taking out	-78%					-36%	-57%
Schiavoni et al. (2016)	Vacuum insulation	Polyurethane	Kenaf	Natural	Taking out	-55%					-41%	-48%
Schiavoni et al. (2016)	Vacuum insulation	Polyurethane	Vermiculite	Recycled	Taking out	-48%					-47%	-48%
Schiavoni et al. (2016)	Vacuum insulation	Polyurethane	Recycled polyethylene terephthalate	Recycled	Taking out	-72%					-16%	-44%
Schiavoni et al. (2016)	Vacuum insulation	Polyurethane	Expanded perlite	Natural	Taking out	-39%					-32%	-36%
Schreiber et al. (2019)	Wind turbine transmission	Direct driving gearbox	Driven permanent magnet	Synthetic	Transition to supersystem	-42%		-45%		-50%		-46%
Segovia et al. (2019)	Panel	Aluminium	Medium density fibreboard	Natural	Segmentation	-68%		-74%			-56%	-66%
Segovia et al. (2019)	Panel	Aluminium	Oriented strand board	Natural	Segmentation	-91%		-80%			-82%	-84%
Segovia et al. (2019)	Panel	Aluminium	Plywood	Natural	Segmentation	-74%		-57%			-67%	-66%
Shen et al. (2010)	PET bottles	None	Recycled polyethylene terephthalate	Recycled	Generic substitution	-25%	-40%	-60%	-8%			-33%
Simion et al. (2013)	Building	Natural inert	Waste (rubble)	Recycled	Nesting	-84%	-70%	-81%	-70%		-80%	-77%
Sinka et al. (2018)	Concrete	Concrete	Magnesium bar nesting	Synthetic	Nesting	-80%	-70%		-60%			-70%
Spreafico and Russo (2020)	Wall insulation	Wall	Wall insulation with expanded polystyrene	Synthetic	Segmentation	-10%						-10%
Strazza et al. (2010)	Power system boat	Methanol	Bio-methanol combined	Natural	Segmentation	-80%	2%		63%		-79%	-23%
Tadele et al. (2020)	Automotive components	Talc-polypropylene composite	Biochar polypropylene composite	Natural	Macro-micro	-25%	-21%	-19%	-16%		-26%	-21%
Teixeira et al. (2015)	Cement	Cement	Cement with ashes	Recycled	Nesting	-25%	-25%	-24%			-12%	-22%
Toniolo et al. (2013)	Plastic bottle	New	Recycled	Recycled	Generic substitution	-11%	-2%	-4%	-3%	-3%	-4%	-5%
Vigil et al. (2020)	Food packaging	Reference	Active polypropylene (with zinc oxide)	Synthetic	Segmentation, Nesting	-11%	-10%	-10%	-9%	-10%	-12%	-10%

Vigil et al. (2020)	Food packaging	Active polypropylene	Active polylactic acid	Natural	Generic substitution	-2%	-2%	-2%	-2%	-2%	-2%	-2%
Villanueva-Rey et al. (2014)	Viticulture	Conventional	Biologic (with compostable fertilizer)	Natural	Generic substitution	-61%	-60%		-84%			-68%
Wang et al. (2013)	Plastic moulding reinforcement	Glass fibre	Natural fibre	Natural	Composite	-80%	-45%	-85%	-14%	-90%	-92%	-68%
Wang et al. (2019)	Biomass gasification	Standard	Reuse waste water	Recycled	Generic substitution	-7%						-7%
Wu et al. (2020)	Biogas production from manure digestion	Gas pumping	Algae activated by sun	Natural	Transition to supersystem	-31%						-31%
Xia et al. (2020)	Concrete structures	None	Recycled concrete	Recycled	Generic substitution	-13%					-10%	-12%
Yazdanbakhsh et al. (2018)	Concrete	Standard concrete	Concrete with recycled coarse	Recycled	Nesting	-4%	-19%	-16%	-10%			-12%
Young et al. (2019)	CO_2 sequestration	None	Post combustion	Recycled	Dematerialization	-7%	-6%	-1%		7%		-2%
Zakuciová et al. (2020)	CO_2 sequestration	Activated carbon sieve by adsorption	Gas oxidizers	Natural	Dematerialization	-73%	-36%	-36%				-48%
Zanchi et al. (2016)	Suspension arm	Steel	Aluminium	Synthetic	Generic substitution	-3%						-3%
Zea Escamilla et al. (2018)	Bamboo buildings	Bricks and concrete	Bamboo glue laminated	Natural	Segmentation	-80%						-80%
Zea Escamilla et al. (2018)	Bamboo buildings	Bricks	Bamboo glue	Natural	Segmentation	-70%						-70%
Zea Escamilla et al. (2018)	Bamboo buildings	Concrete hollow	Bamboo	Natural	Generic substitution	-50%						-50%
Zhang et al. (2010)	Wastewater reuse industrial process	None	Wastewater reuse	Recycled	Generic substitution					-13%		-13%
Zhang et al. (2015)	Food packaging	Modified atmosphere packaging	Active packaging (with internal coating)	Natural	Segmentation	-20%	-4%		-2%		-1%	-2%
Zhang et al. (2017)	Greenhouse lighting	Incandescence	LED	Synthetic	Dematerialization	-38%	-39%	-40%	-42%		-39%	-40%
Zhang et al. (2020)	Power plants cooling	Heat exchanger	Heat exchanger with encapsulated phase-change materials	Synthetic	Nesting, Phase change	-13%					-72%	-43%
Zhu et al. (2015)	Ethanol synthesis	Direct thermochemical conversion	Indirect thermochemical conversion	Recycled	Dematerialization	-10%	-23%		-17%			-17%

Conflict of 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.

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