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► To cite this version:

Christian Spreafico, Davide Russo, Daniele Landi. Combing TRIZ and LCA for a Better Awareness of the Sustainability of a Technical Solution. 22th International TRIZ Future Conference (TFC), Sep 2022, Warsaw, Poland. pp.328-339, 10.1007/978-3-031-17288-5_28 . hal-04449784

HAL Id: hal-04449784

<https://inria.hal.science/hal-04449784v1>

Submitted on 15 Feb 2024

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Combing TRIZ and LCA for a better awareness of the sustainability of a technical solution

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Abstract. A reflection about the evaluation of the environmental impacts arising from a technical solution obtained by applying some of the most common TRIZ (Russian acronym for Theory of Inventive Problem Solving) strategies is provided in this study. In fact, some of them provide suggestions to minimize the resources and make a device work better without adding additional substances or energy flows. However, the contained shortcomings for improving the environmental sustainability can only be fully understood only when applying a quantitative assessment such as Life Cycle Assessment (LCA). This was done in this study, by considering a selection of TRIZ strategies and collecting their pros and cons about environmental sustainability by applying LCA. To do this, the discussion of each strategy was supported by exemplary case studies about Comparative LCA, collected from the scientific literature. The intent of the authors is not to bring experimental evidence, but to provide a further and preliminary judging method to select the TRIZ strategies. In this way, problem-solvers can also base their choice on environmental sustainability.

Keywords: TRIZ; eco-design; Life Cycle Assessment (LCA)

1 Introduction

For several years, many researchers around the world have been trying to propose the use of TRIZ [1] and its tools within eco-design. Some authors (e.g. [2]) improved the design phase through mass reduction and geometry modification, while others (e.g. [3]) reduced the consumption during the use phase. Still others (e.g. [4]) ameliorated the product disassembly and dismantling during the end-of-life. Some efforts have also been spent in customizing TRIZ to favor its integration with eco-design. As consequence, frameworks (e.g. [5]), customizations of its tools (e.g. [6]) and novel usage modalities of the entire methodology (e.g. [7]) were proposed. [8] provided a new interpretive key of the TRIZ methodology from an environmental point of view, by distinguishing which tools and principles are most suitable for Eco-design and which must be properly adapted. This study was a first attempt to customize the TRIZ tools in relation to some typical eco-design problems and to integrate specific knowledge research databases to support eco-design (e.g. materials database). [9] and [10] proposed a new modality to use TRIZ evolutive trees and Macro-micro trend to organize the knowledge

about different pyrolysis techniques. The relation between the level of technological development and the environmental sustainability was investigated in these studies. The obtained framework could be a base for a problem-solving activity based on TRIZ, by providing the main elements to formulate the more strategic contradictions from an environmental perspective. [11] introduced a rigorous ontology to support the application of a specific TRIZ strategy to solve a specific problem, trying to make the user aware of the environmental consequences of her/his design choices. This ontology was organized in steps, following the LCA structure about the lifecycle phases (i.e. pre-manufacturing, manufacturing, use and end-of-life). The items generating the environmental impacts (e.g. logistic, maintenance, packaging) were also included, as well as TRIZ trends and principles (e.g. segmentation, local quality, trimming). The result of this work is a set of 59 guidelines that support designers in applying TRIZ in a targeted manner during eco-design. [12] provides a quantitative evaluation of some TRIZ-strategies based on LCA and involving only case studies, even if without providing a depth discussion about the method application in eco-design.

However, despite the best efforts, some gaps in the literature still need to be filled. The identification of the real benefits arising from TRIZ application on the reduction of the environmental impacts has yet to be specified. According to [2], [13] and [14], the application of TRIZ in eco-design can also lead to substantial environmental benefits even if some environmental criticalities emerge. This is because general-purpose idea generation tools do not usually show any specific preference to sustainable aspects. Therefore, the attention to sustainability is random and demanded to designers' sensibility about environmental and social issues.

However, without an objective assessment of the results of TRIZ application, its advantages in eco-design cannot be confirmed. Only very few authors expressed about this issue, mainly by proposing qualitative or partial judgments. [15] positively assessed the application of TRIZ in small and medium-sized enterprises. Experiments aimed at demonstrating its ability to find notoriously greener solutions were proposed in this study. [3] confirmed TRIZ ability to reduce the consumption during the functioning of the product even if without determining the resulting reduction of the environmental impacts. In addition, methods for measuring eco-innovation also supported by non-TRIZ methods (e.g. [16]) were also proposed, although without quantifying the environmental impacts of the resulting solutions. Consequently, the main limitation of the discussion regarding the applicability of TRIZ in eco-design is the lack of a metric and indicators to effectively evaluate whether and how TRIZ is able to reduce environmental impacts.

The main novelty of this paper is the introduction of the Life Cycle Assessment (LCA) methodology as a tool for evaluating the efficacy of some TRIZ strategies in eco-design. Their main advantages and disadvantages in reducing environmental impacts are discussed in relation with items (e.g. materials, energies) and phases (e.g. pre-manufacturing, manufacturing, use, end-of-life) of LCA. For each TRIZ strategy, an example was chosen from among the many available to highlight the specific aspects related to LCA, which should be considered to carry out its eco-evaluation. All the examples were selected in such a way as to provide a broad analysis overview both on

the fields of application and on all the topics of LCA (e.g. physical features, energy flows, logistic, electricity mix).

The main objectives of this study are two: (1) Verifying whether the results of the strategies are actually also the most sustainable in relation to the entire life cycle. (2) Investigating the correlations between the environmental advantages ensured by the strategies, the lifecycle phases and the environmental impact indicators (e.g. global warming, acidification, particulate matter formation).

2 Methodology

In this study, rather than reviewing all the TRIZ tools individually, a selection of strategies was analyzed, mostly transversal to multiple tools, which can be more geared towards eco-design. The considered TRIZ strategies are: (1) Improving the local quality, (2) Exploiting the resources, (3) Changing the state of aggregation, (4) Increasing control (macro-micro), (5) Increasing control (nesting), (6) Dematerialization/ideality. Each strategy has been analysed by following the same 3-step divided methodology, summarized in Figure 1.

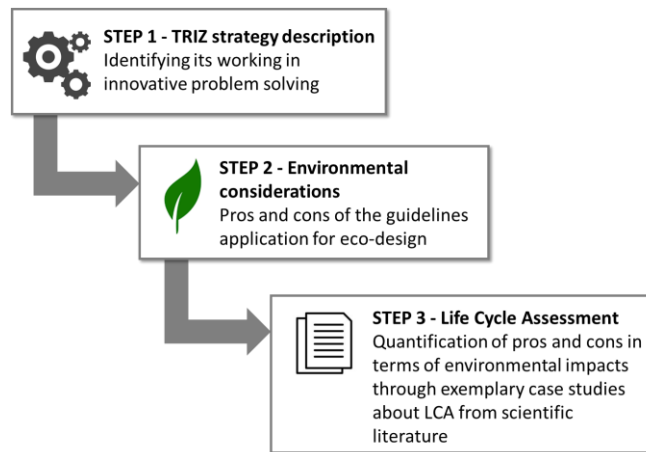


Figure 1. Flowchart of the followed methodology.

The steps of the followed methodology are:

1. Providing a brief description of its founding philosophy and its modality of application in the context of innovative problem-solving in general.
2. Investigating the specific repercussions of the TRIZ strategies in eco-design with reference to the advantages and disadvantages on the reduction of environmental impacts. These latter were found in the LCA studies from the scientific literature, associated with the considered TRIZ strategies.
3. Presenting a case study of Comparative LCA from the scientific literature, in which two products performing the same task are compared, with reference to the same functional unit and in the same operational scenario. Among them, the most

advanced product was seen as the result of the application of one of the TRIZ strategy on the other product. The typical LCA metric with its most common indicators is used to evaluate the effectiveness of the TRIZ strategy in relation to the objective of environmental sustainability: climate change (CO₂ eq.), Terrestrial and marine acidification (SO₂ eq.) and particulate matter formation (PM₁₀).

The case studies from the literature were carefully selected by following these criteria:

- All the considered papers propose a Comparative LCA between at least two different products.
- Exhaustive descriptions of the compared products, including all the data used during the LCA, were provided in the papers.
- The two considered products perform the same function in the same operating scenario, with a common and well-defined functional unit.
- The same calculation procedure was followed to assess the environmental impacts.
- The results were expressed through the same set of impact indicators.

The association of the results from the literature and the different TRIZ strategies were performed by the same authors. In this case, we exploited the TRIZ ontology (i.e. the Minimal Technical System model) as a linkage to research the application of the TRIZ strategies to describe the differences between the two compared products. In other words, the second product is seen as an improvement of the first one resulting from the application of one of the considered TRIZ strategies.

In the following sections the different strategies are described in detail.

3 Evaluated TRIZ strategies

3.1 Improving the local quality

This strategy derives mainly from the TRIZ Principle N. 3 - Local quality, by also involving the concept of the operational area and the Principle of Separation in Space to favor its more targeted application during eco-design. The improvement of the local quality is used for reducing mental inertia when considering space and materials too homogeneous and continuous. It suggests to “Change an object's structure from uniform to non-uniform, make each part of an object function in conditions most suitable for its operation, and make each part of an object fulfil a different and useful function”. **Environmental consideration.** The advantages related to the increase of the local quality of a component may depend on the reduction of the mass and the energy or resources used by the same component. The more targeted and optimized use of the component only where and when is needed is also more economically convenient.

The reduction of the environmental impacts arising from the reduction of the expended energy and/or the mass to be produced, moved, and disposed. In particular, the impacts of disposal can be particularly significant especially in the case of auxiliary materials such as lubricating and cooling fluids, oils, and paints. In addition, the improvement of the local conditions of an auxiliary material can also lead to benefits for environmental sustainability. In fact, the useful life the product can be increased and the consumptions can be reduced.

On the other hand, through the application of this strategy, the introduction of additional processes to increase the quality of the component, e.g. a longer milling in the areas where better roughness must be ensured, can increase the impacts. In addition, higher energy consumption during the product use should also be considered to ensure the local increase its performances. For instance, a more powerful pump to increase the flow speed of a lubricating fluid in the area to be cooled. Sometimes, to increase local quality, inserts or additives, difficult to be disposed, are also introduced into the technical system, e.g. the abrasive water jet which contains solid particles.

Example: “cutting fluids”. The evolution of cutting fluids in recent years points towards increasing their heat removal performances in the cutting area. This is possible through the increase of the local flow velocity and pressure, to concentrate their action more effectively within the cutting area.

The comparative LCA of two cutting fluid systems (conventional vs high pressure), proposed by [17], shows the validity of the increase of the local quality of the second compared to the first one. A reduction of 25% of global warming potential (CO₂ eq.), 30% of acidification potential (SO₂ eq.), and 25% of the equivalent energy consumption (MJ) over the entire life cycle were estimated. These advantages were due to the drastic reduction of the impacts of cutting, since through the introduction of the more advanced cutting fluid system, the productivity of the machinery increases. At the same time, the energy consumption is maintained, which abundantly compensates for the increase in the impact of electricity consumption required by the new high-pressure pump of the cutting fluid.

3.2 Exploiting the external resources

This strategy mainly derives from the TRIZ Law of Technical System of Evolution N. 6 - Switch to supersystem, which points out the use of the resources available in the external environment. From an environmental point of view, the product reaches the minimum consumption of its energy resources, drastically reducing its environmental impact. The use of external resources usually does not contribute to increase the environmental impacts since they are already present in the environment and they are unexploited.

According to this law, when a technical system evolves by exhausting the possibilities of further significant improvements is included in a super-system as one of its parts. As a result, new development of the system become possible. When thinking of resources, in this strategy the energy consumed during either the product use or its manufacturing was highlighted. However, TRIZ considers more resources than those typically considered according to the environmental perspective. A special attention is provided also to those resources that are commonly considered as negative, e.g. hot exhaust fumes.

Environmental considerations. The environmental advantages arising from a greater exploitation of the resources and directly ascertainable through an LCA study are different. Among them, one of the most obvious concerns the reduction of energy consumption, by replacing or integrating the most impacting energy sources with natural resources. Examples are the solar cooling cycles with trigeneration and the reuse of the waste energy in order to reduce energy consumption in turbocharged engine and the cogeneration. Furthermore, there is a reduction/elimination of the conventional energy system and its components, e.g. the boiler size in a domestic heating system that also combines solar thermal. Finally, there is also the reduction of the impacts of materials

if resources are used to reduce the mass of the product, e.g. plastic components loaded with shavings and scrap metals to replace the virgin metal.

On the contrary, the introduction of components dedicated to the exploitation of the resources, especially the natural ones, in some cases may also include materials more difficult to be disposed. For instance, the impacts of photovoltaic modules could be significant and difficult to be mitigated, especially for some specific indicators, e.g. toxicity. On the other side, they can also lead to large reductions of other indicators, such as CO₂ eq. Furthermore, the exploitation of renewable resources is still not sufficient for many systems to fully perform their functions, which must therefore resort to less optimized and sometimes more impactful back-up systems than an ad hoc system.

Example: “wastewater elimination”. In the context of wastewater elimination from manure, a recent evolution of traditional digestion systems is based on gas injection inside the silos where the manure is stored. This is possible through the use of algae activated by sun which have a more effective chemical action compared to the injected gas.

The comparative LCA of the two wastewater elimination systems in a pig farming proposed by [19] resulted in a reduction, going from the first to the second technology, of 31% of the global warming potential and of about 5% of the marine and terrestrial eutrophication, over the entire life cycle. These advantages mainly depend by the drastic reduction of the environmental impacts arising from the preparation of the digesters, passing from the gaseous mixture, prepared ad hoc, to algae, available in nature and processed in a much more sustainable way. Secondly, a further advantage is obtained through the elimination of the gas injection circuit and the energy consumption for its handling, by using solar radiation to activate the algae. The disadvantages to switch to the algae concern the partial reduction of the fertilizing power of the manure at the end of the process. This requires an overproduction of the same to fulfil the same function and involves a minimum increase of the impacts, which are below 1% in both impact indicators.

3.3 Changing the state of aggregation

This strategy embodies part of the founding philosophy of TRIZ by suggesting the designer to exploit the resources obtainable from the change in the state of aggregation of a substance. This concept is included in the TRIZ Principle N. 35 - Parameters change and in TRIZ Principle N. 36 - Phase transition. Its application does not necessarily require a phase change, since Principle N. 36 suggests to exploit also the effects deriving from the phase transition, such as the latent heat released, but is also limited only to the simple substitution. For instance, a hard shell that does not adequately absorb shocks can be replaced by bubble wrap.

Environmental considerations. From an environmental point of view, the advantages of the change of the state of aggregation depend by different aspects. The reductions of the volume of the product can optimize the logistics and reduce its impact. The energy consumption during manufacturing can be reduced, e.g. obtaining a component from foundry casting is cheaper than machining it from solid to machine tools. The environmental contamination can be reduced, e.g. if the oil escaping from a tanker stranded in the rocks could be solidified, it would undoubtedly be easier to recover. On the other hand, in the analysis of the impacts, the energy spent on heating or cooling during the phase transition must also be considered, if it is assumed to use this option. In addition, it could be an increase in environmental contamination, e.g. a solid fuel is usually more

explosive than a liquid one. Finally, the construction of plants, structures and the energies dedicated to maintaining a substance in a state of aggregation other than the natural one in the environment should also be considered. For instance, cryogenic tanks with large thicknesses and coatings and refrigeration cycles.

Example: “CO₂ sequestration”. In recent years, the evolution of CO₂ sequestration systems, inside the special collection tanks, has seen the alternation of solid membrane adsorption systems with gaseous oxidizing agents. The main advantage deriving from the adoption of gaseous oxidizing agents concerns the increase in efficiency in intercepting the CO₂ molecules within the entire volume of the tank. While the solid membranes, which, however densely arranged, always leave empty volumes. In addition, with gaseous oxidizing agents, processing times are also reduced since the use of gas avoids the replacement of the membranes once saturated, ensuring continuous cycle operation. The comparative LCA of the two systems proposed by [20], confirms the advantages of the technology with gaseous oxidizing agents also from the environmental point of view. A reduction of the impacts, compared to the membrane system, of 73% of CO₂ eq., of 36% of SO₂ eq., and of 36% of PM₁₀ eq. over the entire life cycle can be reached in this way. The reasons for this reduction in impacts are mainly due to the elimination of the production of the membranes, which consist of particularly impacting material (e.g. activated carbon). In this case, the avoided impacts abundantly compensate for those deriving from the energy spent for the production and the supply of the gaseous oxidant inside the reactor, as well as the construction of its recirculation plant.

3.4 Changing the state of aggregation

This strategy summarizes the philosophy of the static TRIZ laws of technical system of evolution, which suggests that the evolution of a system is often tied to the evolution of its control. According to this law, any working system must have four parts: the supply, the transmission, the tool (working organ) and the control element. The supply generates the needed energy, the transmission guides this energy to the tool, which ensures contact with the outside world (processed object), and the control element makes the system adaptable. According to the same law, among the four elements, the control element is where innovation can make the biggest leap. One way to increase control is by miniaturizing the tool to reduce its interaction with the object on which it acts, from a macro level to a micro level. This is possible by reducing the interface between tool and object and by changing the interaction mode, from mechanical to electromagnetic. In this way, the action of the tool on the object can go from superficial/massive to molecular: for example, the drilling with a laser tip instead of a common drill bit.

Environmental considerations. Often, increasing control over the system and the tool, or replacing the operating principle of the system with a more controlled one, could require the technological complication of the system. This is due to the introduction of a new structure that has a more impact on the environment. Although, in most cases, the increase in environmental impacts is justified by the greater efficiency of the use phase which is more controlled in execution and therefore less energy intensive. When the miniaturization of the tool suggests the transition from a mechanical to an electromagnetic mode. This presupposes the change of the energy source from fossil to electric, then the sustainability of the latter in relation to the operating scenario must be carefully considered. In fact, unlike fossil sources (e.g. natural gas or oil) which have emission factors due to their extraction and distribution substantially stable in various parts of the world, in the case of electricity the specific impact per kWh produced is

much more variable from state to state, regions and provinces. It depends on the electricity mix, i.e. on the characteristic distribution of the means of electricity production (i.e. coal, natural gas, nuclear, renewable). Other factors to be considered are the technological level of the used plants, the environmental characteristics and the political factors. However, recently, much progress has been made to reduce electricity generation emissions and forecasts call for its greater use in the future as a replacement for fossil energy sources.

Examples: “gas hob vs induction hob”. Induction hobs are a more advanced than gas hob and are believed to replace them in the coming decades. However, today their diffusion in many states is comparable or even much higher than the first ones.

The induction hob, thanks to its operating principle, i.e. electromagnetic induction generated by wound electric coils, can guarantee a much more precise control on the energy consumption. This is due to higher heating/cooling ramps, as well as greater efficiency in energy transmission. The comparative LCA proposed by [21] between gas hob and induction hob, shows the environmental limitations of the induction technology (compared with gas) in Italy. The reason is the disadvantageous electricity mix, since the energy consumption of the induction hob is significantly lower. The authors determined an increase in the impacts on the entire life cycle of the induction hob compared to gas hob, by 51% of CO₂ eq., in this scenario. However, the situation is different in France, where the electricity mix is clearly more favorable. In this case, the induction hob is more sustainable than the gas hob over the entire cycle of life, with a reduction of CO₂ eq. equal to 58%.

3.5 Increasing control (nesting)

Another way to increase the control over the technical system is to introduce additional elements with active function in the realization of the function and/or sensors with monitoring function. Often when there is no other possibility, their introduction must be studied carefully. Among the suggestions that TRIZ provides us in this regard, there is also Principle N. 7 - Nesting.

Environmental considerations. From the environmental point of view, the introduction into the system of additional components and sensors must deal with the impacts due to their production, use, disposal. In addition, also control or data acquisition structure must be considered. Furthermore, the introduction of additional components within the materials of the product makes its disposal more impactful, due to the complications arising from its disassembly. As consequence, there is the possibility of invalidating the recycling of the constituent materials, especially when particles are embedded within the material and welded by chemical bonds (e.g. doping). Therefore, in order to achieve environmental sustainability through the application of this strategy, the beneficial control action carried out by additional components must reduce the impacts on the product life cycle to compensate for their increase due to their introduction. This can therefore be ensured by the control over the operating mode of the product, to increase efficiency and reduce consumption or to reduce waste, by extending the operational life of the product.

Example: “cheese packaging”. In the field of cheese packaging and, more generally, the packaging of highly perishable food products, various strategies have been implemented to increase the shelf life of the product, so as to reduce waste. An evolutionary line points towards active and sensorized packaging, including bactericides (e.g. [22]) and/or micro-sensors of light, pressure and temperature (e.g. [23]) within the thickness

of the package and in contact with the product. The LCA studies of [24], [25] and [26] showed that the increase in the environmental impacts resulting from the modification of the packaging to increase the shelf life of the contained compensate for those resulting from the waste of food. This fact was confirmed by the introduction of both bactericides and sensors, where the extra impacts associated with them are due both to their production and to the greater difficulty in disposing of the packaging. In many cases, bactericides consist of metal oxides and they affect the recyclability, the decomposition and the compostability of the packaging. The missed impacts due to the extension of the shelf life and therefore to the reduction of food waste were instead calculated by quantifying the missed overproduction and distribution that would also be necessary.

3.6 Dematerialization/ideality

This strategy is mainly related to the kinematic laws of evolution. Among them, TRIZ outlines the steps toward ideality and the dematerialization of the product, which can be translated into the concept of zero impact. The evolution of the answering machine is a good example. The product was eventually dematerialized into a service that is now provided without the need for a dedicated system. According to TRIZ, the dematerialization of a product coincides with its Ideality. The TRIZ Ideal Product is that which does not exist while continuing to perform the function for which it was conceived. It is not associated with any energy flow, material, packaging, etc., and cannot produce environmental impacts. It consists in eliminating all useless product components, reducing toward zero auxiliary materials, consumable. When the complete elimination of the structures is not possible, a partial elimination is then suggested, through a greater involvement of the fields in replacement of some structures, e.g. magnetic coupling.

Environmental considerations. From an environmental point of view, the most obvious advantages of dematerialization concern the elimination of product components and the impacts related to their production. This is possible though the replacement of the components that are much smaller and with a lower impact during production. Furthermore, the behaviour of the dematerialized technology is generally more efficient, especially when electromagnetic fields are involved. This is because the typical inertias of mechanical mechanisms and fluid-dynamic systems is avoided. This can significantly limit the consumption and the impacts arising from the use phase. However, the new technology could include a fluid in place of a mechanical means, which, if not properly managed, could have a lot of impact during disposal. This is the case of medium and high voltage switches that use Sulphur hexafluoride (SF₆) gas to extinguish the electric arc instead of compressed air. In this case, SF₆ has a very high impact of over 23500 kg of CO₂ eq.

Example: “metal cutting”. For many years, the evolutionary trend of cutting materials has been outlined with the elimination of mechanical systems (i.e. blades) in favor of the use of electromagnetic waves, with electro-erosion and lasers. The study of [27] compares the environmental impacts of the various technologies, based on an analysis of several LCA studies proposed in the scientific literature. It emerges from it that, although there are significant differences in terms of environmental impacts in relation to the type of material processed, over the entire life cycle, both EDM and laser prove to be a more sustainable alternative in many cases compared to the mechanical cutting.

Considering the LCA impact categories, the electromagnetic cutting systems are more energy-intensive during the cutting operation, mainly due to their poor operating efficiency. However, the lack of impacts of the elimination of the mechanical tool, of

its replacement and maintenance as well as of the dedicated machinery are such as to compensate for this aspect.

4 Evaluated TRIZ strategies

In this paper, six macro directions of intervention inspired by TRIZ laws and principles have been presented, which more than others help to improve a product by making the use of resources more efficient. According to this logic, an improvement in its environmental sustainability should also be achieved. This impression was also confirmed through a careful analysis about the modalities to present the results in those papers proposing Eco-design methods based on problem-solving, where the link between sustainability and energy efficiency is considered almost automatic. However, the situation is much more complex. In fact, this article demonstrates with a series of practical cases how the evaluation of a problem-solving activity could be challenging, especially if a specific evaluation metric for sustainability, such as LCA is not applied.

In order to contribute to increase the level of awareness in the problem-solver about the effects that a new solution can produce on the product sustainability, a double level of conviction was proposed. First TRIZ suggestions were contextualized according to an environmental perspective. Then, through LCA a product and a variant obtained through the application of a TRIZ suggestion were compared. The planned future developments of this work consist of an extensive analysis of a large number of contributions in order to quantitatively verify whether the observations identified in this study can be confirmed. In addition, new TRIZ strategies and new observations for each of them will be considered to increase the knowledge basis.

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