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Procedia CIRP 136 (2025) 444–449

www.elsevier.com/locate/procedia

35th CIRP Design 2025

The advanced TRIZ method for a sustainable lightweight design

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Abstract

As product variants increase and development times and costs decrease, speed and innovation become essential for success in today's competitive, sustainability-focused market. Therefore, this contribution introduces an advanced TRIZ method, demonstrated on the use case of a semi-mobile handling system, to systematically leverage lightweighting potentials while considering costs and CO2 emissions in a solution-oriented way. It involves defining key engineering parameters and deriving promising innovation principles based on the evaluation of expert surveys. The method provides a ranked list of innovation principles for generating targeted concepts and includes past implementation suggestions for a comprehensive approach to product, production, and material aspects.

Keywords: TRIZ; lightweight design; ecodesign; sustainability; product development

1. Introduction and Motivation

Due to the increasing acceleration of global networking and the economy as a whole, companies are forced to bring more and more products and services to market at ever shorter intervals in order to successfully compete against their competitors [1]. As a result, agile innovation methods are making their way into the corporate landscape [2], even if this implies a change or adjustment of the current business model. One of these methods is the "theory of inventive problem solving" (TRIZ), a systematic to reach new conceptual solutions faster and more efficiently by breaking down and analyzing the technical problem before creatively deriving specific concepts for different innovative principles based on knowledge-based engineering. Although the TRIZ method has nowadays spread worldwide and there have also been isolated further developments, the method still lacks a technical, economic and environmental evaluation to rank primary innovation principles for purposefully generating a lightweight design.

Thus, and after outlining the actual state of the art of innovation methods in the early phase of product development in Section 2, this contribution presents a novel systematic procedure of an advanced TRIZ method to purposefully generate lightweighting concepts with an integrated view on product, production and material aspects (Section 3). Exemplarily applied on the industry of machine and plant engineering, the approach is validated and further discussed in Section 4 before giving a conclusion and outlook (Section 5).

2. State of the Art in Literature

Within the generally well-known product development processes [3–5] based on the traditional problem-solving cycle [6], the transfer of functional units into solution principles and, finally, technical or physical components is a key aspect. Therefore, solution identification methods can be applied apart from the pure search in suitable solution catalogues (e.g., [7]). In order to make the complexity of the solution identification clear and conceivable, the solution identification methods can be fundamentally divided into

10.1016/j.procir.2025.08.077

intuitive, logical and systematic approaches, whereby intuitive and logical methods can be summarized as techniques that enhance the human creativity (see Table 1 for an overview).

Table 1. Overview of solution identification methods, collected from [3,8].

intuitive	logical	systematic
Brainstorming / Brainwriting	Osborn's checklist	Morphological box
KJ method	SCAMPER	TRIZ
NM method	Six thinking hats	Design catalogue
Look for opposites	Synectics	Creative Problem Solving (CPS)
Philipps 66	Analogy & Bisociation	SIT
Method 635	Bionics/Biomimetics	
Disney method		
Gallery method		
Delphi method		
TILMAG method		

Systematic solution-finding methods are characterized by a conscious step-by-step approach, which means they are discursive in their emphasis. Focusing on this type of methods, one representative is the TRIZ (Russian acronym for "теория решения изобретательских задач" = theory of inventive problem solving) method, which was pioneered by Altshuller [9] and forms a central part of this contribution.

Based on the fundamental idea that conflicts can be solved through the variation of the already existing, the main feature of problem solving via TRIZ is to analyze technical and physical contradictions, and, to derive innovation principles systematically based on an empirical patent analysis for the technical design. The TRIZ contradiction matrix is a fundamental component for this purpose. It enables the derivation of a universally applicable innovation principle when a known abstracted developmental contradiction is present. Traditionally, this approach employs a 39x39 contradiction matrix developed by Altshuller, where 39 parameters designated for improvement are juxtaposed with 39 parameters representing potential deterioration. Through an appropriate pairing of these parameters, 40 possible innovation principles can be evaluated.

However, over the years, this original matrix has revealed some limitations. It was based solely on patents up until 1985, raising questions about its applicability to modern products. Additionally, certain correlations between parameters for improvement and those for deterioration yielded no productive results in terms of possible innovation principles.

To address these shortcomings, a team led by Darrell Mann and Simon Dewulf aimed to refine the matrix, producing an updated version called "Matrix 2003" [10] based on patents filed between 1985 and 2002, with further revisions leading to the "Matrix 2010" re-update [11]. The core innovation principles remained intact, yet they were recombined and expanded into 42 combined and specialized principles. Simultaneously, the technical parameters under analysis were increased to 50, resulting in an expanded 50x50 matrix.

Towards an improved application of TRIZ, algorithms such as the ARIZ (Russian acronym for "Алгоритм решения изобретательских задач" = algorithm of inventive problem solving) are used to automate the searching in any form of the contradiction matrix and proposing innovation principles.

2.1. TRIZ for Lightweight Design

Gaining a general understanding of fundamental systematic solution-finding methods, particularly the TRIZ approach, offers considerable potential for identifying structured solutions in lightweight design. The most straightforward way to achieve this is by using the parameters "weight of a moving or stationary object" found in the contradiction matrix to explore the innovation principles and derive new solutions. This approach has been implemented in several case studies documented in the literature, where weight reduction is analyzed in conjunction with other optimization goals to identify the most suitable innovation principle.

As a first example for this, Butdee and Vignat [12] identified a conflict between the weight of a moving object and its strength within the TRIZ contradiction matrix and thus performed a topology optimization for a body bus structure at a given stiffness resulting in a reduced weight. Besides, Jinturkar et al. [13] achieved the weight reduction of a FSAE vehicle by looking at improvement of the physical parameter "weight of a moving object" against the deteriorating technical parameters "length", "area" and "volume of the object". Similar results were achieved by Ishak et al. [14] aiming to reduce the weight of a car front hood despite a decrease in strength via TRIZ. Here, "composite design" has emerged as the best innovation principle, which was realized using natural fibers resulting in a significant weight reduction. More recently, Guo et al. [15] considered besides the TRIZ parameters of "weight" and "volume of a stationary object" also the object's "shape". Therefore, they reinterpreted the innovation principles in view of bionics. It can therefore be observed that applying the TRIZ method in real-world contexts for weight reduction often results in innovation principles yielding a topology optimization as well as conscious material selection as recommended solutions.

In addition to this straightforward possibility, the TRIZ methodology could also be applied to investigate all other technical parameters in the contradiction matrix regarding their effects on an object's weight. Similarly, each innovation principle presents a distinct potential for weight reduction. For instance, the innovation principle "segmenting" could be linked to the differential construction technique regarding lightweight design, likely offering a higher potential for weight reduction. In contrast, the principle of "counterweight" would likely imply additional mass within the system, rendering it less favorable for achieving weight reduction. Such considerations have not yet been addressed in literature.

2.2. TRIZ for Design for Sustainability

Apart from single application examples of TRIZ for lightweight design, first methodological approaches have also emerged to incorporate sustainability aspects within the TRIZ method. Since there exist no specific TRIZ parameters for sustainability in the contradiction matrix of Altshuller or in the Matrix 2010 re-update like the parameters "weight of the moving/stationary object" for lightweight design, investigations of TRIZ for design for sustainability frequently include the systematic choice of appropriate optimization or deterioration parameters.

Some methodological approaches for this include the combination of the "environmental quality function deployment" (E-QFD) or the Kano model with the TRIZ method like it has been done in [16–20]. Another way to explore the benefits of TRIZ for a sustainable product development is to assess the results derived from the innovation principles using the "life cycle assessment" (LCA) [21] as it is done in [22].

A completely new method arises if only the systematics of TRIZ remain unaltered. Thereby, for example, the algorithm of recommending innovation principles is transferred to sustainable practices. In such cases, however, the resulting method is only based on TRIZ and almost completely loses its original content like the TRIZ parameters or the intended innovation principles. Examples of such practices can be found in [23–25].

2.3. Need for Action

In conventional, discipline-specific development processes for lightweight design such as [26,27], there is significant potential within the conceptual design phase to identify and realize functional principles that can support weight, cost, and sustainability goals. After establishing and outlining the key functional as well as operating principles, the subsequent process generally involves detailing physical components and their implementation in production.

Thus, the TRIZ method has been identified as a highly promising method for generating innovative solutions in the early design phases, as the presented and documented investigations in literature show its potential. However, the aforementioned approaches do still not sufficiently cover the topic of a technical (lightweight specific), economic and environmental (our main focus when mentioning sustainability) evaluation to first analyze the technical parameters in the contradiction matrix and, secondarily, rank the innovation principles for purposefully generating a lightweight and sustainable design. Thus, the following Section 3 presents an advanced TRIZ method, which focusses exactly on the ranking of the innovation principles based on expert interviews.

3. The Advanced TRIZ Method

Having identified the need for an advanced TRIZ method for lightweight design, the objective of applying the advanced TRIZ method lies in addressing a classic fundamental conflict common to many areas of product development: a problem in the current design exists that requires a new solution, while no clear solution path or concept is evident. More specifically for the advanced TRIZ method, this generic problem must be characterized by an engineering design challenge that involves a target conflict between weight, cost, and environmental sustainability and is encountered in the early phases of development. Thus, the conflict may be resolved by implementing a novel solution, the search for which can be supported by the advanced TRIZ method.

Therefore, the systematic procedure follows the steps illustrated in Fig. 1. The general procedure of the advanced TRIZ method is based on the latest "Matrix 2010" re-update [11]. Thereby, the user of the method must first select the technical parameter(s) to be improved (step 1). Subsequently, the weighting of the individual technical parameters to be improved is determined in a pairwise comparison (step 2). Once this has been done, the determination of the technical parameters that must not be deteriorated follows (step 3). With this given set of technical parameters, the algorithm of the advanced TRIZ method is executed, so that for all innovation principles the amount of their designation is counted and summed up (step 4).

For each parameter pair (improving versus worsening technical parameters), the cells in the contradiction matrix are examined, and all suggested innovation principles are collected. The first-listed innovation principle in each cell is awarded 5 points for the specific parameter combination, the second-listed principle receives 3 points, and the remaining principles each receive 1 point. Subsequently, the points allocated to each innovation principle across all parameter combinations are summed to generate a "weighted number of occurrences" for the parameters. Next, the list of all innovation principles is reduced to those that are in the top ten of the designation (step 5) based on the number of occurrences.

In order to check the violation of the technical parameters not to be deteriorated, the listed potentially worsened parameters are written down for each innovation principle in its occurring order (step 6). Thus, the list of preferably applicable innovation principles can be further reduced. In step 7 of the methodology, the influence of the potentially negatively affected technical parameters by an innovation principle are assessed and summed up regarding their influence on lightweight design, costs, and environmental sustainability. With the valued transfer of the best innovation principles into a ranking list as a compromise between potential benefit and conflicts (additionally indicating the previously determined frequency and all potentially worsened parameters, step 8), different concepts can finally be elaborated via the additional depiction of corresponding sample images from previous projects (step 9).

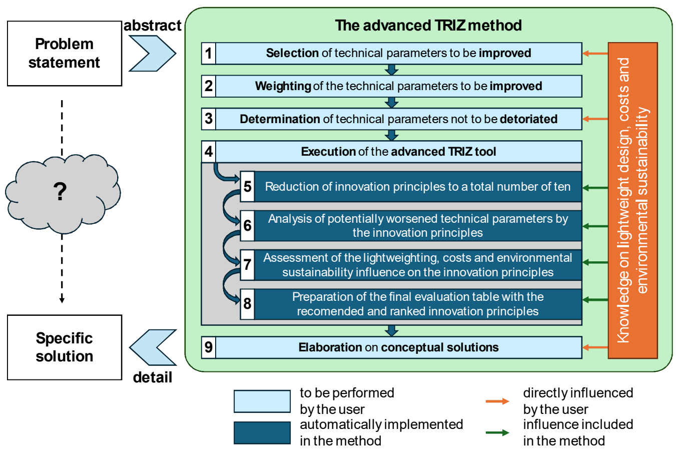

Fig. 1. Methodological procedure of the advanced TRIZ method.

Getting a deeper look at the steps described, input as expert knowledge is required for determining the effect of the technical parameters and innovation principles on weight reduction, costs and environmental sustainability (steps 5-8). Therefore, in the initial methodological approach, a project team (mutually weighting of lightweight, cost and environmental impacts relevancy exemplarily transferred from the description of the target system) or experts (valid evaluation of impacts of technical parameters to assessment criteria (here: lightweight, cost and CO2 emissions) – analogous to the considerations in [28] only for the sustainability dimension) are used. In Fig. 1 their input is indicated as knowledge of lightweight design, costs and environmental sustainability. For the presented case study in this contribution, a group of 14 experts from industry and science with diverse areas of expertise were asked to fill out their point of view which in sum ended in the following tabular overview for the influence of technical parameters on weight, costs and environmental impacts, see Table 2.

Table 2. List of technical parameters and their influence on lightweight, cost and environmental impacts (the direction of change is indicated for a worsening of parameters).

ID	category	technical parameter	influence / change	lightweight	costs	env. impacts
1	physical	weight of moving object	increased ↗	-3	-2	-2
2		weight of stationary object	increased ↗	-2	-1	-1
3		length of moving object	increased ↗	-2	-1	-1
4		length of stationary object	increased ↗	-1	-1	-1
5		area of moving object	increased ↗	-1	-1	-1
6		area of stationary object	increased ↗	-1	-1	-1
7		volume of moving object	increased ↗	-2	-2	-2
8		volume of stationary object	increased ↗	-2	-1	-1
9		shape	more complex	1	-2	0
10		quantity of substance	increased ↗	-2	-2	-2
11		quantity of information	increased ↗	0	-1	-1
12	performance	duration of action (moving obj.)	decreased ↘	1	1	-2
13		duration of action (stationary obj.)	decreased ↘	1	1	-2
14		speed	decreased ↘	1	1	1
15		force (intensity)	increased ↗	-1	-1	-1
16		use of energy (moving object)	increased ↗	-1	-2	-3
17		use of energy (stationary object)	increased ↗	-1	-2	-3
18		power	decreased ↘	1	1	1
19		stress or pressure	increased ↗	-2	-1	-1
20		strength	decreased ↘	-1	0	0
21		stability of object's composition	decreased ↘	-1	1	0
22		temperature	increased ↗	-1	-1	-1
23		illumination intensity	decreased ↘	0	0	0
24	efficiency	efficiency of function	decreased ↘	-1	-2	-2
25		loss of material	increased ↗	0	-2	-2
26		loss of time	increased ↗	0	-2	-1
27		loss of energy	increased ↗	-1	-2	-3
28		loss of information	increased ↗	-1	-1	-1
29		noise or roaring	increased ↗	0	0	-1
30		harmful emissions	increased ↗	0	-1	-3
31		object-generated harmful factors	increased ↗	0	-1	-3
32	non-functional	adaptability or versatility	decreased ↘	1	0	-1
33		compatibility or connectivity	decreased ↘	0	0	-1
34		convenience of use	decreased ↘	0	0	-1
35		reliability	decreased ↘	0	0	-2
36		ease of repair	decreased ↘	1	0	-2
37		safety	decreased ↘	0	0	-1
38		vulnerability	decreased ↘	0	0	0
39		aesthetics	decreased ↘	1	1	0
40		object-affected harmful factors	increased ↗	-1	-2	-1
41	manufacture	ease of manufacture	decreased ↘	0	-2	-1
42		manufacturing precision	decreased ↘	-1	-1	-1
43		extent of automation	decreased ↘	-1	-2	-1
44		productivity	decreased ↘	0	-2	-1
45		complexity of device	increased ↗	-1	-2	-1
46		complexity of control	increased ↗	-1	-2	-1
47		positive intangible factors	decreased ↘	0	-1	-1
48		negative intangible factors	increased ↗	0	-1	-1
49		detectability or measurability	decreased ↘	-1	-1	0
50		measurement accuracy	decreased ↘	-1	-1	0

This weighing based on the group of 14 experts has also been performed regarding the 40 innovation principles. As a result, a lightweight, costs and environmental sustainability weighed contradiction matrix as well as recommendation of innovation principles follows. They are used in the process steps 4-8 illustrated in Fig. 1. For getting a better understanding of the resulting methodological process of implementation, the advanced TRIZ method is implemented in a case study within the following subsection.

4. Application Example: Handling System

As validation example for ensuring the practical applicability of the method in an industrial context, the identification of a lighter solution of a gripping unit in front of a robot (as part of a handling system) is examined. The application example has already been discussed and presented in earlier studies [29,30]. Since the moving mass of an industrial robot including the gripping unit has a significant impact on energy consumption, a weight reduction of the system offers optimization potential not only for enhancing environmental sustainability (e.g., CO2 emission reduction as a consequence of the electricity mix), but also for costs during operation.

The aim of implementing the presented approach is characterized by finding a new lightweight solution for the gripping unit illustrated in Fig. 2. Thereby, a target conflict between three key technical parameters has been identified, which are weighed in Fig. 2 (steps 1 and 2 of the advanced TRIZ method).

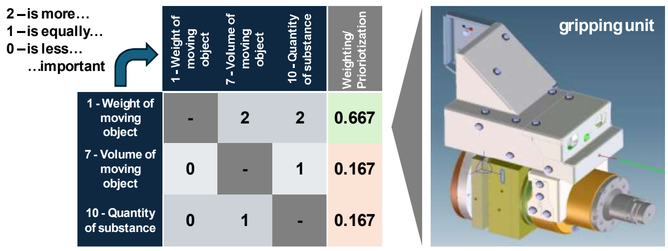

Fig. 2. Weighting of technical parameters to be improved for the gripping unit of the handling system by means of using a pairwise scheme.

The result of the pairwise comparison is that the most important technical parameter is "1 – weight of moving object", followed by the equally important parameters "7 – volume of moving object" and "10 – quantity of substance".

Apart from the selection of the technical parameters to be improved the user must also select technical parameters which must not be downgraded (step 3). In the presented use case, the strength of the gripping unit is a very important requirement. The required strength is affected by the weight and length of the gripper, the handling object as well as the accelerations of the industrial robot. Therefore, in this case study, the technical parameters "20 - strength", "1 - weight of moving object", and

"3 - length of moving object" are chosen to be maintained without deterioration.

After these selections are done, the user executes the advanced TRIZ algorithm (step 4) with included weightings of the technical parameters and innovation principles indicated as knowledge in Fig. 1 based on the expert surveys. In this step, all cells of the contradiction matrix are analyzed based on the selected technical parameters, and the innovation principles are scored according to their chronological occurrences in the cells (as part of step 5 in Fig. 1). Furthermore, to consider the weighting of the parameters from step 2, each count of the innovation principle is multiplied by the weighting of the technical parameter it optimizes. As a result of this step, the ten innovation principles with the highest scores are ranked, as visualized in Fig. 3 for the case study.

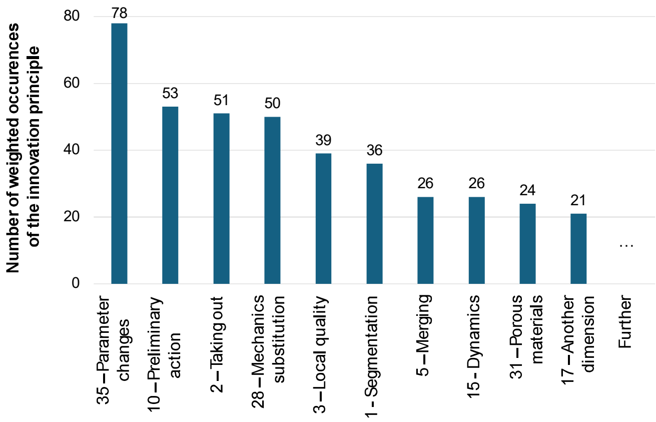

Fig. 3. Top ten results of the assessment of innovation principles based on their number of weighted occurrences.

In addition, for each innovation principle, any potentially deteriorated technical parameters are recorded and analyzed in step 6 of the methodology. The negative sum of all technical parameters downgraded by the innovation principle, considering the influence of lightweight design, costs, and environmental sustainability, is calculated and shown for the case study in the column 'deterioration rating' in Fig. 4 (step 7). The more negative a rating is, the greater the adverse impact of the worsened parameters on lightweight design, costs and environmental sustainability when implementing the corresponding innovation principle.

Finally, step 8 of the methodology addresses two main aspects. First, unsuitable innovation principles are excluded based on the following rules:

- The innovation principle appears only in cells where it downgrades selected technical parameters that must not be deteriorated.
- The innovation principle is listed first (as the most suitable) in a parameter combination in which the corresponding worsened technical parameter must not be deteriorated.

As a result, the innovation principles "35 – parameter change", "17 – another dimension", "2 – taking out", and "31 – porous materials" were excluded in our case study. The remaining parameters with potential deterioration are listed as warnings in the final evaluation table and should be considered when redesigning the system.

Rank	Innovation principle	Number of weighted occurences (positive)	Deterioration rating (negative)	TRIZ index (sorted)	Technical parameters with exlusion criteria	Technical parameter downgrade warning
1	**10 - Preliminary action**	52	-21.4	**-0.41**	-	17, 27, 19, 24, 43
-	**35 – Parameter changes**	78	-32.7	**-0.42**	1	7, 17, 27, 2
2	**28 – Mechanics substitution**	50	-22.6	**-0.45**	-	7, 10, 17, 27, 3
3	**5 – Merging**	26	-13.5	**-0.52**	-	10, 2, 24, 40, 45
4	**1 – Segmentation**	36	-19.0	**-0.53**	-	17, 2, 24, 40, 45
-	**17 – Another dimension**	21	-11.2	**-0.53**	3	19, 45, 4, 5
5	**15 – Dynamics**	26	-15.5	**-0.6**	-	7, 17, 27, 3, 45
-	**2 – Taking out**	51	-30.7	**-0.6**	1	7, 10, 17, 27
6	**3 – Local quality**	39	-23.9	**-0.61**	-	10, 17, 27, 2, 3
-	**31 – Porous materials**	24	-17.2	**-0.72**	1	7, 10, 2, 19

Fig. 4. Ranking of the recommended innovation principles based on the TRIX index (deterioration rating against number of weighted occurrences).

Secondly, the remaining innovation principles are ranked using an index calculation ('TRIZ index'), which compares the 'deterioration rating' (= indicator of the negative impact of potentially worsened technical parameters affected by the innovation principle on lightweight design, costs, and environmental sustainability) with the 'number of weighted occurrences' (= indicator for the positive effect of an innovation principle on the described target conflict). The less negative the TRIZ index is, the greater the potential of the innovation principle for improvement in the respective case. Subsequently, based on the recommended innovation principles listed in the evaluation table in Fig. 4, in step 9 of the methodology, appropriate solution concepts can be elaborated. For the case study, Fig. 5 summarizes the entire procedure, including potential solution concepts, for the three most promising innovation principles.

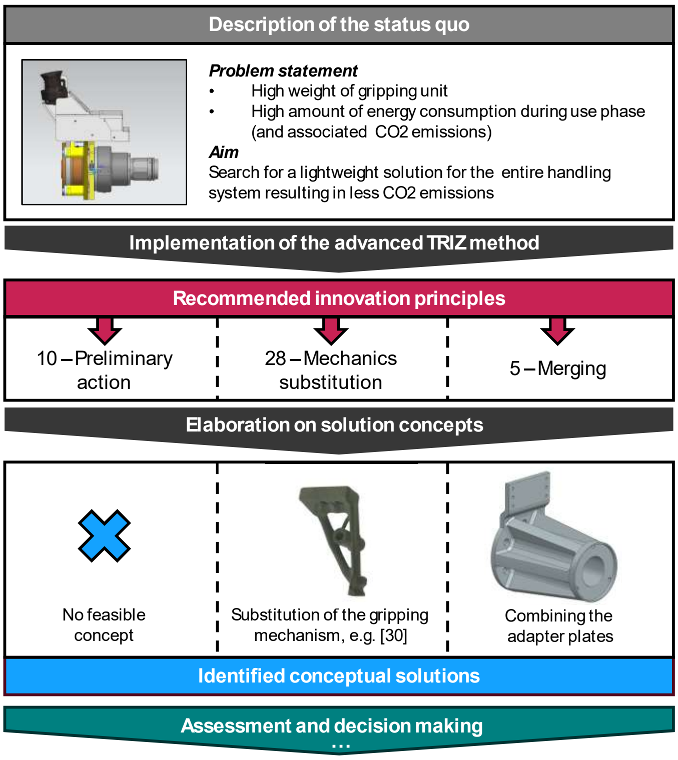

Fig. 5. Results of the case study including possible solution concepts.

5. Conclusion and Outlook

Based on the need for rapid, systematic solution finding in lightweight design, this paper proposes an advanced TRIZ method, evaluated through a case study. The uniqueness of the method lies in its consideration of the influence of lightweight design, costs, and environmental impacts on the technical parameters and innovation principles – determined through expert surveys. In the case study, as most suitable innovation principles "28 – mechanics substitution" and "5 – merging" were identified. Corresponding solutions include exploring a new gripping mechanism (e.g., discussed in [31]), or performing topology optimization of the gripping unit with function integration. However, no feasible solution concept emerged for the innovation principle "10 – preliminary action".

This study demonstrates that the advanced TRIZ method can accelerate the innovation process and inspire novel lightweight design concepts. As the results are based on expert knowledge, the methodology's applicability in different contexts or industries requires further investigation. Additionally, a deeper exploration of its potential to improve environmental sustainability is needed. Future research could also explore how the advanced TRIZ method could leverage the capabilities of artificial intelligence and data-driven approaches to optimize the innovation process, enhance solution generation, and further increase the method's efficiency and adaptability across diverse design challenges.

Acknowledgements

The authors thank the "Technologietransfer-Programm Leichtbau (TTP LB)" of the Federal Ministry for Economic Affairs and Climate Action (BMWK) for supporting their research within their project "SyProLei" (03LB2007H).

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