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Adaption of the TRIZ method to the development of electric energy storage systems.

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Abstract

The increasing competition in the automobile industry leads to intensified development activities regarding the next innovations of hybrid and electric vehicle technologies with acceptable costs, reduced weight and commonality. A survey carried out in the field of the automobile industry working on the electrification of drive trains analyzed the specific use of design methods. The industry survey revealed shortcomings in the industrial utilization of design methods which hinder their application and understanding. Besides the need for improved comprehension and a better balance between preparation and output, a lack of direct reference to the technical design task was observed.

A development project in a product generation development was accompanied with creativity workshops to specify the designers' needs. Therefore parts of the TRIZ (theory of inventive problem solving) concepts were chosen to stimulate new solutions.The goal of the presented approach was to facilitate the application of the inventive principles in this product generation development by customizing to the technological circumstances of electric energy storage systems (EESS).

The basis of the used approach was a patent search involving 150 patents (and patent applications) in the EESS field. These patents were selected by relevance for e.g. design of the battery's mechanical structure, cooling, electric contacting or assembly. Each of these patents was analyzed in detail regarding the used inventive principles and the technical contradictions solved thereby. After aggregating all identified combinations into an EESS specific contradiction matrix, this matrix was compared to Altshuller's matrix to evaluate the success rate of the given principles in these matrices for solving high voltage battery specific problems. The main result is a ranking of the most used inventive principles in this field. The benefits of the patents were moreover evaluated considering costs, lightweight and production. Hence, it was possible to create particular matrices and rankings for design tasks in these contexts. A first testing of these outcomes showed positive effects on the generated ideas and on the designers' comprehension. This design practice is focusing on the EESS and needs to be conducted and validated for further applications.

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1. Introduction

The electric energy storage system (EESS) is one of the key components in the electric drive train of passenger cars. Regarding future emission legislation there is an increasing competition between the automobile manufacturers in order to realize innovations in the markets on the one hand and to reduce the additional costs of the hybrid systems on the other hand. The EESS is a multi disciplinary and complex system including thermal management, mechanics, electrical contacting and battery management. Influencing requirements are caused by the surrounding vehicle, safety, service, performance, user behavior, legislation, modularity etc. As the first generations of high voltage systems for plug-in hybrid

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electric vehicles (PHEV) were focusing on the functionality and gaining development experience, the next generations of EESS need to be optimized regarding costs and weight [1]. The key aspects for the automobile industry are to improve the peripheral devices around the battery cells and the integration into the cars.

The integration of design methods could help improving future EESS concepts regarding e.g. iterations and development time. Therefore, the goal of the presented approach was to facilitate the access to design methods by adaption to a specific design task. This means to simplify the method application to designers of technical systems, in this case electric energy storage systems.

2. Theoretical background

TRIZ (also called TIPS) is the Russian acronym for the "Theory of Inventive Problem Solving" developed by Genrich Altshuller starting in 1946 by analyzing thousands of patents [2, p.28ff]. Altshuller claims, that due to the limitation of an individual's knowledge it is necessary to look beyond the developer's area of expertise for solving complex problems [2. p.28ff]. One of the basic ideas behind TRIZ is the systematization of the innovation process [3, p.32]. Therefore TRIZ offers a set of various design methods helping inventors to overcome psychological inertia, which induces them to search in the same direction for solutions while generating alternative solutions for very complex problems [2, p.15-18/30]. TRIZ therefore provides a systematic approach which helps experts to expand their knowledge over the borders of their own disciplines in order to find inventive and unexpected solutions [3, p.32-55], see Fig. 1.

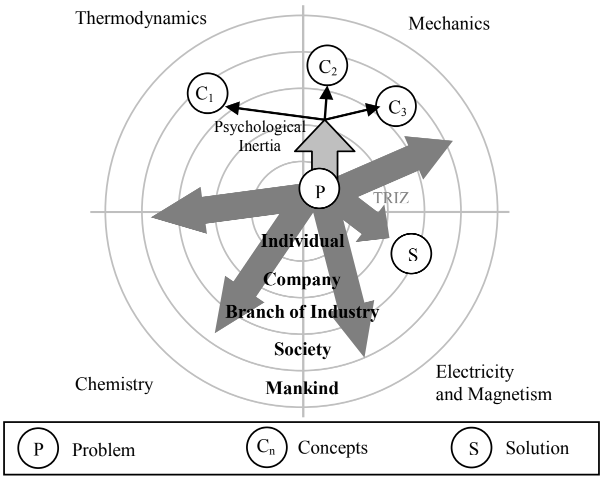


Fig. 1. The four main identified categories and the direction while developing concepts due to psychological inertia (illustration based on [3, p.52-55]).

Altshuller considered other conventional creativity methods like brainstorming, morphological analysis or synectics as insufficient in this context [2, p.15-18]. Brainstorming for example uses the direct way from the specific problem to a specific solution, TRIZ on the other hand offers a bypass by using analogy [3]. The developer transforms his specific problem into a standard problem that can be solved by a TRIZ standard solution and then again transforms this standard solution to the specific solution [3].

2.1. Altshuller's contradiction matrix

During his patent search Altshuller identified 39 technical parameters like mass, volume and stability. According to Altshuller's early publications it is common in product development that improving one parameter leads to worsening another [2, p.24]. These so called technical contradictions can be solved by one of the elements of TRIZ - the contradiction matrix, which gives a suggestion on which of the 40 identified "Inventive Principles" should be used to overcome the contradiction. The improving parameters are listed vertically, the worsening parameters horizontally, see Fig. 2.

Improving Parameter / Worsening Parameter	Weight of moving object	Weight of stationary object	Length of moving object	…
Weight of moving object		-	15, 8, 29, 34	…
Weight of stationary object	-		-	…
Length of moving object	8, 15, 29, 34	-		…
⋮	⋮	⋮	⋮	⋱

Fig. 2. Altshuller's Contradiction Matrix [2].

Although Altshuller himself already doubted the usefulness of the matrix in 1975 (commentary with Filkovski GL: 'СОВРЕМЕННОЕ СОСТОЯНИЕ ТЕОРИИ РЕШЕНИЯ ИЗОБРЕТАТЕЛЬСКИХ ЗАДАЧ') as well as the principles in 1985 (letter 'ПИСЬМО 19' from 31.01.1985), they are still included in most of the TRIZ-teaching literature today. The identification of the appropriate contradictions is difficult and time consuming. Anyway the authors included them in the subsequent investigation in order to check their utility and to align the approach. As to the authors' they seem to be helpful for the development of the EESS, their usefulness was investigated in the current approach.

2.2. Adaptions and variations of the classical contradiction matrix

In 2003 an update of Altshuller's classical contradiction matrix was published by Mann. For this purpose he analyzed 150.000 patents (issued 1985-2003) [4]. An approach to identify those of the 40 principles with the most influence to decrease costs for manufacturing products was conducted by Schlösser in 2006 [5]. Therefore, at first Schlösser subjectively chose those of the principles that seem to have potential for decreasing costs among the 40 principles. Subsequently further 'cost principles' were identified in an empiric analysis. For that purpose the 39 technical parameters were classified according to their relevance to costs into four groups: *negligible*, *in a wider context* and *of relevance* for costs either during utilization or manufacturing phase. Based on this classification Schlösser created two adapted matrices by the removal of all columns and lines that were not relevant (see Fig. 3).

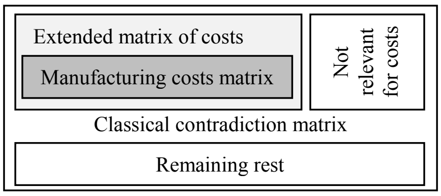


Fig. 3. Venn diagram [5].

Within these two specific and the classical contradiction matrices Schlösser subsequently calculated the relative frequency of occurrence $H_{rel,i}$ of the 40 principles in the classical contradiction matrix as well as in the cost matrix. He then evaluated the normalized deviate Δ_{norm} in analogy to (1).

$$\Delta_{norm} = \frac{H_{rel,i}^{cost\ matrix}}{H_{rel,i}^{classical\ contradiction\ matrix}} - 1 \qquad (1)$$

All principles with a normalized deviation greater than 33% were additionally considered as relevant for cost improvements. Schlösser's idea behind this was that by reducing those parameters from the matrix, which are less relevant for costs, the changes in the relative frequency of the occurring of the principles in the matrix must subsequently be cost related, too.

3. Approach

In the first step, the conducted approach of this paper consisted of an online survey asking about development tasks, technical challenges, benefits and disadvantages as well as further subjective circumstances like method knowledge. The second step included the TRIZ customization regarding the survey results according to the described theoretical background. The third step was to test the application in the specific environment of a research project dealing with new EESS.

4. Results

4.1. Online survey

To analyze the current situation 114 people in the field of EESS development were questioned in an online survey. The survey was carried out mainly within the development and production departments of electric drive trains within the BMW Group but also suppliers including small-scale companies. Some of the results were the motivation for the following method adaption, by calculating the portion of the considered answers to the entire number of given answers:

- 76% of the respondents experience design methods in general as theoretical and thus not use-oriented (medium to high approval)
- for 73% the preparation and execution of design methods in general is too time-consuming (medium to high approval)
- 30% apply design methods for finding new and only 18% use methods in the subsequent embodiment of concepts
- only 48% are satisfied with the general effectiveness after the application of methods (satisfied and highly satisfied)
- 73% have reasonable skills in methods for finding alternative solutions (extended basic knowledge to expert knowledge), but only 38% use them regularly (regular to very often)
- the main benefit of applied methods are stated by 39% to be a structured approach, but only 6% see new stimuli as the main benefit
- for 18% of the respondents the main intention therefore to use methods is assessment and selection and only for 8% to gather creativity stimuli.

4.2. Patent search and generation of adapted EESS matrix

For this study a number of 150 German, European and worldwide patents and patent applications (in the following short referred to as patents) regarding EESS systems were analyzed. The number of German (and European) patents regarding EESS filed increased rapidly over the last few years [6]. Since it takes time for a patent to be granted, the limitation to granted patents only would have excluded valuable newer knowledge which is revealed in patent applications as well as in patents.

Two-thirds of the analyzed patents were submitted by OEMs like BMW, Audi, Daimler, Toyota and Tesla, the other third by automotive suppliers for EESS subcomponents. Patents referring to all different parts of the EESS were selected (position within the car, connection to the vehicle body, housing and mechanical safety, cooling, cell module, gas venting, cell, electrical contacting, production of any of the previous, etc.). A group of EESS experts familiar with TRIZ made sure that no 'fake' (consciously misleading competitors) patent applications or patents of poor value were chosen. The chosen patents were then investigated on technical contradictions, the relating technical parameters of the contradiction and the Inventive Principle used for solving it by a person familiar with TRIZ. Later this analysis and classification was re-examined, discussed and adjusted by the group of experts if necessary. This multiple evaluation of a patent by different persons lead mostly to the same classification result, but in this context an entire objectivity is difficult to achieve.

With this information a new and at the beginning of this study empty contradiction matrix (with the same parameters as Altshuller's) was generated by filling in the contradictions found in the analyzed patents. All contradiction-fields which contain one or more Inventive Principles were highlighted. To increase its clearness, empty lines and columns were deleted which lead to a matrix with a dimension of 29x27 instead of 39x39, see Fig. 4 for an extract.

		Weight of Moving Object	Weight of Stationary Object	Area of Stationary Object	Volume of Moving Object	Volume of Stationary Object	…
		1	2	6	7	8	…
⋮	⋮	⋮	⋮	⋮	⋮	⋮	…
13	Stability	3, 5, 6, 11, 15, 17, 35, 39	35		3, 11, 15, 17, 25, 39	40	…
14	Strength	1, 3, 4, 40	3, 6, 40		6	40	…
17	Temperature	5	5, 6, 7, 40			6, 7, 14, 17, 24, 25, 30, 37	…
22	Loss of Energy		3	5, 17		7	…
23	Loss of Substance	2, 30				3, 39	…
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋱

Fig. 4. Contradiction matrix adapted to the EESS patent analysis.

Within the derived matrix, some contradiction-fields which were left empty by Altshuller could be filled, while others remained empty. Altshuller's matrix only contains up to four principles per field due to the limitation on the most frequently occurring ones. Since in this approach only 150 patents were analyzed, all identified principles for a contradiction show up in the matrix and therefore some fields of the new EESS matrix contain up to twelve suggestions of Inventive Principles. Furthermore there were no "new" Inventive Principles, so the matrix still contains only the original 40. It should be noted though that by analyzing only a number of 150 patents, some of the Inventive Principles didn't show up at all. Even though the contradiction matrix is quite controversial and just a small part of TRIZ, the patent analysis was additionally used to review the usefulness of the contradictions in the EESS case, by trying to identify the mitigated contradictions.

Within the analyzed patents the frequency of occurrence of all 40 Inventive Principles was determined to see, which principles are the most important and most promising for developing the EESS, see Fig. 5.

Additionally the association to lightweight, costs and manufacturing topics was evaluated. Thus, three more specific matrices for these disciplines could be created.

Within these three matrices the frequency of occurrence of the Inventive Principles was evaluated as well. As a consequence a developer, who wants to optimize the complete EESS or a part of the EESS regarding light weight, costs or manufacturing, can use the corresponding simplified matrix to identify the most relevant parameters and the most relevant Inventive Principles.

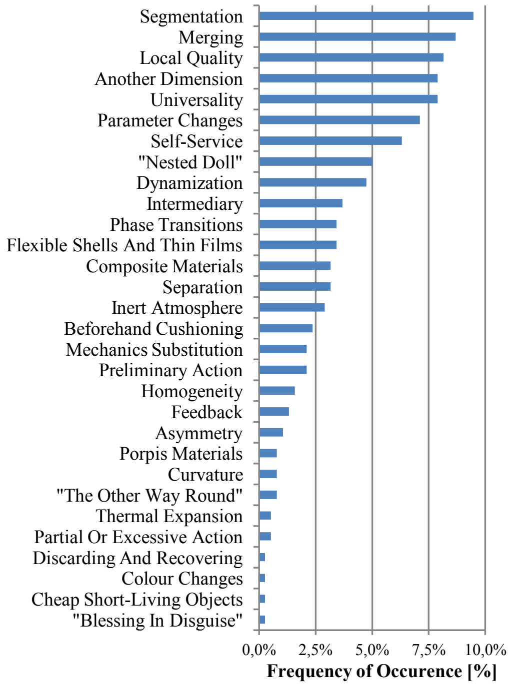


Fig. 5. Frequency of Occurrence of the Inventive Principles in the analyzed EESS patents.

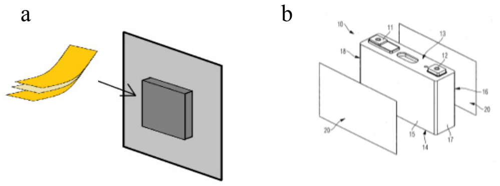
4.3. Improving the understanding of the parameters and the principles

During the survey the authors identified difficulties in the transformation and comprehension of the parameters. To avoid misunderstandings, a "technical dictionary" providing a translation of the technical parameters into corresponding vocabulary used by the developers was generated. This dictionary contains the common terms in German and English and the common definitions in both languages. An additional column offers examples from the specific context of EESS development.

In some cases the understanding of the principles was considered insufficient because the abstraction level was too high. Therefore examples, which were identified during the patent analysis, were added to the common description of the 40 principles, so the developers now have specific examples of the usefulness of the principle in the EESS development. An example is shown in Fig. 6.

The shown classification example represents the problem of how to improve the heat transportation process between the battery cells without using much space. According to Altshuller's matrix the contradiction of improving temperature and decreasing stationary volume is to be solved using principle 35 (Parameter Change), 6 (University) or 4 (Asymmetry).

a b



Fixing objects to the wall with sticky tape.

Fixing cells to one another with an isolating and heat transporting sticky tape. (DE 10 2010 020 065 A1)

Fig. 6. (a) Common example of Inventive Principle 30; (b) EESS specific example.

Based on the German patent application DE102010020065A1 the designers fixed the cells to one another with a sticky tape so the cells cannot move relatively to one another and the heat transfer is improved while realizing an electrical insulation, see Fig. 6b. Hence, in the synthesized EESS matrix, one proposed solution is principle 30 (Fig. 6a). This principle suggests the usage of flexible shells or thin films.

As this example also enhances the manufacturing process of the cell stacks due to a simplified handling of the cells (without glue) it was also assigned to the manufacturing matrix.

4.4. Comparing the EESS matrix to existing matrices

Since on a first view the derived EESS matrix and Altshuller's matrix showed a great difference, these differences were investigated subsequently. For example the comparison of the ranking of frequency of appearance of the 40 principles in the EESS matrix and the classical respectively the Matrix 2003 showed great changes between the matrices, see Fig 7. The accordance between Mann's ranking of the principles in his updated Matrix and the EESS matrix is slightly better than the one between the EESS matrix and Altshuller's matrix.

In a reverse engineering study of 100 patents Mann suggests that his Matrix 2003 has an accuracy rating of 96%, meaning that for 100 sample patents the identified technical contradictions and the used Inventive Principles to solve them fitted into his Matrix 2003 in 96 % of the cases [7]. A comparison between the adapted EESS matrix and Altshuller's matrix revealed an accordance of 23%. This might be because Altshuller only investigated patents with a high level of innovation, whereas some of the EESS patents might not be considered as innovative enough. Another reason might be that the EESS solutions in the current patents (and patent applications) do not yet represent the best or ideal solution.

Inventive Principle	Classical TRIZ Ranking	EESS Matrix Ranking	Deviation	Matrix 2003 Ranking	EESS Matrix Ranking	Deviation
1	3	1	2	7	1	6
2	5	13	-8	5	13	-8
3	12	3	9	2	3	-1
4	24	20	4	10	20	-10
5	33	2	31	12	2	10
6	20	5	15	27	5	22
7	34	7	27	17	7	10
8	32	31	1	37	31	6
9	39	31	8	24	31	-7
10	2	18	-16	8	18	-10
11	29	13	16	39	13	26
12	37	31	6	19	31	-12
13	10	22	-12	3	22	-19
14	21	22	-1	15	22	-7
15	6	12	-6	14	12	2
16	16	25	-9	28	25	3
17	19	6	13	9	6	3
18	8	31	-23	25	31	-6
19	7	31	-24	11	31	-20
20	40	31	9	40	31	9
21	35	31	4	32	31	1
22	22	27	-5	36	27	9
23	36	20	16	33	20	13
24	18	9	9	6	9	-3
25	28	7	21	13	7	6
26	11	31	-20	23	31	-8
27	13	27	-14	35	27	8
28	4	15	-11	4	15	-11
29	14	31	-17	26	31	-5
30	25	10	15	22	10	12
31	30	22	8	16	22	-6
32	9	27	-18	21	27	-6
33	38	19	19	38	19	19
34	15	27	-12	31	27	4
35	1	4	-3	1	4	-3
36	27	15	12	30	15	15
37	26	25	1	20	25	-5
38	31	31	0	34	31	3
39	23	15	8	29	15	14
40	17	10	7	18	10	8
Sum of absolute change values			460			356

Fig. 7. Comparison of Classical Matrix, EESS Matrix and Matrix 2003, in analogy to [4].

The analysis shows for example a big change at the principles 5 (Merging) and 7 ("Nested Doll"), which are ranked higher in the EESS study. Both principles encourage a compact construction of the EESS which is important due to the limited space. Other principles like 18 (Mechanical Vibration) and 19 (Periodic Action) seem to be less useful for the electric energy storage. In the latter case this could be explained by the mostly static states of EESS. This leads the authors to the conclusion to preferably use the generated ranking of the principles in the special context of the EESS. Nevertheless the matrix can be used to start out with at the innovation process, but the given principles should not be considered as the only possible ones to solve the problem. Moreover it should be pointed out, that at least one (or more) of the 40 Inventive Principles could be identified in each of the analyzed patents. The comparison with an empiric analysis for cost improvements revealed partly different suggested principles. This could justify the large effort of a product specific patent analysis.

A negative aspect of creating a product specific matrix though is that by using the same principles for the same specific contradiction might lead to similar ideas as in the patents. This is especially counterproductive for designing around patents. The presented approach must be confirmed regarding other products, considering more patents and a wide validation before transferring it widely.

4.5. First validation of the results

For a first validation of these results a design workshop was held. The discussed problem contained a current challenge of an inventive EESS concept. Therefore the goal was to find technical feasible solutions for one of its components. As the number of contradictions could not easily be limited, the previously created rankings were used. These principles were a combination of the ranking of the principles within the adapted EESS matrix and the production specific matrix. The workshop was split into two sequenced phases to determine the helpfulness of the used TRIZ elements. Within the first phase the established brainwriting was used by the engineers. The chosen Inventive Principles for the specific problem were introduced before the second phase. For the comprehension a common description, pictures of a common example and pictures of EESS specific examples of each principle were handed out to the participants.

On the one hand the resulting ideas and on the other hand the feedbacks of the designers were considered to validate the results. Regarding different metrics for the evaluation of ideas [8] the quantity of the generated ideas increased by 27%. In comparison to an existing Pugh Matrix of the provided task, the novelty and variety improved but the quality considering applicability and acceptability was heterogeneous. Thus, a deeper analysis within further applications in terms of the concept space variety and different abstraction levels [8, p. 255-260] is necessary. An anonymous survey (two open questions, 17 questions with a five-step scale) among the participants revealed a subjective usefulness of the specific EESS examples given and an improved comprehension of the method. In order to consider the possibility of biased answers, the questions included the individual expectations, previous knowledge and the option not to answer. Those designers, who had already known the Inventive Principles prior to the workshop, used them subconsciously during the brainwriting phase. This shows that knowing the principles can influence the designer's way of problem solving. Nevertheless, this was just the first test of the presented approach and a broader implementation is needed for further validation.

The acknowledgment of the given examples competed with feedback about too abstract general descriptions. In order to intensify the perception of the pre-selected inventive principles a TRIZ-Box was composed for further EESS workshops. This set of artifacts represents the specific principles in a functional, technical or physical way [9]. Different small products representing the principles in a vivid way should stimulate the designers even more and help to remember the abstract principles in a practical example.

5. Conclusion

The method adaption presented in this paper indicates that it is useful to analyze system specific patents and patent applications in order to identify the most commonly used design principles. These could subsequently be utilized to reduce obstacles identified in a survey among EESS designers. On the one hand the results can help to create more efficient procedures in solving problems in the embodiment process. On the other hand this convergence leads to a less abstract approach that is more focused on existing solutions of the considered system.

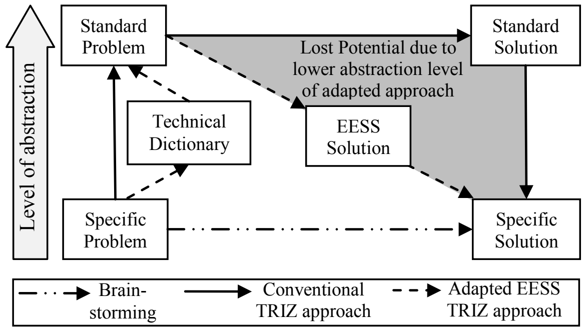


Fig. 8. The way from the specific problem to the specific solution.

The authors suggest considering the most relevant principles (based on an analysis for the specific system) for a more focused problem solving. This could bypass the controversial identification of contradictions. The suggestion for an own, field related patent search also derives from the comparison of the 10 identified principles most relevant for reducing costs with those cost principles of other authors like Schlösser [5] and TriSolver [10]. But since there is a lost potential (Fig. 8) it is crucial to consider the benefits and also the limits of this adaption when choosing the right method for a design phase.

References

[1] Albert A, Wagner D, Ruckpaul A, Hessenauer B, Burkardt N, Matthiesen S. Target Weighing – a new approach for conceptual lightweight design in early phases of complex systems development. Seoul: 19th International Conference on Engineering Design ICED13; 2013.
[2] Altschuller G. Erfinden – Wege zur Lösung technischer Probleme. Berlin: VEB Verlag Technik; 1984.
[3] Herb R, Terninko J, Zusman A, Zlotin B. TRIZ – der Weg zum konkurrenzlosen Erfolgsprodukt. Landsberg: Modern Industie AG; 1998.
[4] Mann D. Comparing The Classical and New Contradiction Matrix - Part 1- Zooming Out. TRIZ Journal; 2004.[5] Schlösser T. Herstellkosten senken mit Hilfe der Widerspruchsmatrix. In: Innovation mit TRIZ – Konzepte, Werkzeuge, Praxisanwendungen. Düsseldorf: Symposion Publishing; 2006. p. 289-331.
[6] Karl F. Trends bei den Patentanmeldungen für Elektromobilität. In: eCarTec Magazin 2013. p. 68-69.
[7] Mann D. Comparing The Classical and New Contradiction Matrix - Part 2- Zooming In. TRIZ Journal; 2004.
[8] Verhaegen PA, Vandevenne D, Peeters J, Duflou JR. Refinements to the variety metric for idea evaluation. In: Design Studies 34/2; 2013. p. 243-263.
[9] Albers A, Lohmeyer Q, Schmalenbach H. TRIZ-Box in design education – a study on supporting creativity. London: 18th International Conference on Engineering Design and Product Design Education ICED11; 2011.
[10] Livotov P, Petrov V. TRIZ Innovationstechnologie:- Produktentwicklung und Problemlösung – Handbuch. 2.nd ed. Hannover: TriSolver GmbH; 2005. p. 44.