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Method for Formulation, Selection and Application of Elementary TRIZ Inventive Principles for Automated Idea Generation

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Abstract. The proposed method includes identification and documentation of the elementary TRIZ inventive principles from the TRIZ body of knowledge, extension and enhancement of inventive principles by patents and technologies analysis, avoiding overlapping and redundant principles, classification and adaptation of principles to at least following categories such as working medium, target object, useful action, harmful effect, environment, information, field, substance, time, and space, assignment of the elementary inventive principles to the at least following underlying engineering domains such as universal, design, mechanical, acoustic, thermal, chemical, electromagnetic, intermolecular, biological, and data processing. The method includes classification of abstraction level of the elementary principles, definition of the statistical ranking of principles for different problem types, and specific engineering or non-technical domains, definition of strategies for selection of principles sets with high solution potential for predefined problems, automated semantic transformation of the elementary inventive principles into solution ideas, evaluation of automatically generated ideas and transformation of ideas to innovation or inventive concepts.

Keywords: Inventive Principles, Automated Idea Generation, Systematic Innovation, Inventive Problem Solving, TRIZ Methodology.

1 Introduction and Methodological Background

Among numerous components of the Theory of Inventive Problem Solving TRIZ [1, 2], the 40 Inventive Principles belong to the most frequently used tools, which help systematically enhance the ideation performance. These principles are simple to apply or modify for specific technical domains and can be easily integrated into brainstorming or daily engineers work [3]. Over the past decades, the 40 TRIZ Inventive Principles have been widely used to solve technical contradictions in various engineering domains and enhanced through adjustments, illustrations, and examples for specific fields of application [3]. Moreover, several studies on Inventive Principles have been conducted to improve the quantity and quality of ideation process for the various engineering domains. The study of Russo and Spreafico [4] classified the Inventive Principles through functional behaviour structure ontology. Mann [5] cate-

gorized the classical Inventive Principles based on three areas of intervention: space, time and interface. Livotov and Petrov [6] established specific groups of Inventive Principles for industrial and business practices. There are also many proposals of examples illustrating the breadth of application in specific engineering domains [3], such as electronics, chemical engineering, food processing, ergonomics, maintenance, software engineering etc. The Altshuller' original 40 Inventive Principles [1] contain in total between 86 and 90 sub-principles. The number of the sub-principles has been extended in the later versions by different authors, for example, up to 125 sub-principles in [6] and to 160 sub-principles in [9]. Furthermore, Petrov [7] presents the "universal" 40 Inventive Principles with engineering illustrations including changed or extended names or formulations of certain principles and sub-principles.

In accordance with [8] the sub-principles can be understood as "inventive operators" for transformation of technical systems or heuristics for idea generation. In this context, some of the inventive operators are more specific and can be clearly assigned to at least one of nine MATCEM-IBD domains: M - Mechanical, A - Acoustic, T - Thermal, C - Chemical, E - Electrical, M - Magnetic, I - Intermolecular, B - Biological and D - Data or Information processing. There is also a group of generally formulated sub-principles, which are independent of any engineering domain and hence may have a higher level of abstraction. Thus, the application of domain-oriented (specific) sub-principles and of universal (domain-independent) sub-principles can have different impact on ideation outcomes [9].

The practical application of Inventive Principles often requires a concentrated, creative, and abstract way of thinking that can be challenging for engineers or newcomers to TRIZ. For example, the abstract term "object" used in the principles may be understood as a system, system component, substance, process or process step, or any other material or virtual object. Also, the abstract definition of "action" can be understood as function, positive or negative effect or any interaction between the objects. Therefore, the outcomes of ideation work with the TRIZ Inventive Principles may depend on a certain interpretation of the abstract terms. As outlined in [10] and [11], the level of abstractness can be reduced by the modification of the principles through replacing the abstract terms "object", "action" or "function" with the context-specific name of a real system component, real function, or action. The experimental study [10] confirms that the less abstract and problem specific formulation of TRIZ Inventive Principles can visibly improve idea generation outcomes of engineering students and newcomers to TRIZ both in the quantity and variety of proposed ideas. In 194 experiments conducted at the Offenburg University the students generated nearly 1.5 times more ideas with the modified and less abstract inventive principles than with the classically formulated principles. Also, the breadth of the proposed ideas over the nine MATCEM-IBD fields has been essentially enhanced while applying the less abstract principles. This positive effect was observed by the students from different years of study independently of their knowledge level or difficulty of the problem.

Even though many studies have expanded and enhanced TRIZ Inventive Principles and its sub-principles to a broader range of applications, another major challenge for the engineers remains a precise selection of the strongest principles or sub-principles for specific problems. The Altshuller Contradiction Matrix in its classical form with

39 lines and 39 columns [1] or in extended form with 50x50 entries [13] can considerably simplify the selection of suitable solution principles. The matrix proposes a group of several appropriate principles that can often deliver more satisfactory ideation outcomes for an engineering contradiction, formulated with the standard technical parameters. However, statistically only about 10...15% of problems can be satisfactorily described with the standard parameters used in the matrix [12]. Formulation of several contradictions for one problem situation improves the ideation outcomes with a set of “strongest” solution principles, which were proposed by the matrix more than once. Alternatively, one can apply the innovation principles in the order of their statistical frequency of use [6], such as: (35) Transform physical and chemical properties, (10) Prior useful action, (1) Segmentation, (28) Replacing mechanical working principle, (2) Leaving out / Trimming, (15) Dynamism and adaptability, (19) Periodic action, (3) Local quality, (17) Shift to another dimension, (13) Inversion, (18) Mechanical vibration, (26) Copying etc. According to the application experience in more than 250 industrial case studies moderated by the author, the first 10 principles from this list provide useful solutions for about 50...60% of all tasks [6]. A slightly different variant of application frequencies of 40 Inventive Principles is presented in [3].

A series of studies [9, 14, 21] proposes the application of the sub-principles groups as a more precise and productive ideation technique, adaptable for a large variety of problem situations. The identified sets of sub-principles for process innovation, eco-innovation, design, or cost reduction are based on the analysis of 155 new technologies, 200 patent documents, numerous industrial case studies and TRIZ literature. Interesting that the strongest top ten sub-principles often significantly differ from the statistically strongest parent Inventive Principles.

This paper takes into consideration the application approaches of 40 TRIZ Inventive Principles mentioned above, including their advantages and disadvantages, and describes the method and a corresponding computer application [15] for formulation, selection, and application of elementary TRIZ inventive sub-principles for automated idea generation and discusses the modes of its application in ideation, systematic inventive problem solving and engineering education. The method includes

- identification and documentation of the elementary TRIZ inventive principles from the TRIZ body of knowledge,
- extension and enhancement of elementary inventive principles by patents and technologies analysis, avoiding overlapping and redundant principles,
- classification and adaptation of elementary inventive principles to the at least following categories such as working medium, target object, useful action, harmful effect, environment, information, field, substance, time, space,
- assignment of the elementary inventive principles to the at least following underlying engineering domains such as universal, design, mechanical, acoustic, thermal, chemical, electromagnetic, intermolecular, biological, data processing,
- classification of abstraction level of the elementary inventive principles,
- definition of the statistical ranking of elementary principles for different problem types, specific engineering or non-technical domains and requirements,
- definition of strategies for selection of elementary inventive principles sets with high solution potential for predefined problems,

- automated semantic transformation of the elementary inventive principles into solution ideas,
- idea evaluation, selection and creation of the inventive solution concepts.

2 Approach to Automated Idea Generation

2.1 Knowledge Base for Idea Generation

The knowledge base for systematic ideation is primarily based on the 160 sub-principles (here defined as *elementary inventive principles*) of 40 TRIZ Inventive Principles initially proposed in [9]. These elementary inventive principles have been enhanced and extended by some selected trends of technical evolution, standard solutions, and some chosen physical, chemical, biological, and geometrical effects as well as by the operator for elimination of harmful effects [6]. For example, the MATCEM-IBD heuristic, known as an efficient ideation tool of the Substance-Field Analysis [16], has been decomposed and integrated into the knowledge base. Too complicated, overlapping, or redundant elementary inventive principles has been avoided.

The application of the knowledge base for automated idea generation can be performed using a generic ad hoc problem definition or systematic tools known in TRIZ [2] or in other approaches to problem solving, such as function analysis, cause-effect-chains analysis [2] or root conflict-analysis [17]. For example, a fast TRIZ-based method of problem definition and identification of contradictions for the interdisciplinary problems is presented in [18]. The automated idea generation can be accomplished on the different level of problem analysis and understanding, such as

- enhancement of the useful action or function, including situation with a lacking or deficient useful function,
- elimination of the harmful effect or undesired properties,
- resolving of the engineering contradictions or elimination of the trade-offs, characterized by a situation at which an improvement of one target parameter causes the worsening another target parameter in a system.

For the selection of the elementary inventive principles and automated ideation is essential that at least one of the following categories has been identified in the phase of the problem definition:

- A. *Working Tool* or working medium.
- B. *Target Object* or workpiece affected by the Working Tool.
- C. *Useful Action* or main function.
- D. *Undesired Property* or harmful effect.

For each problem definition category, A, B, C and D, the specific elementary inventive principles can be assigned and preformulated. For example, it is reasonable that the categories A Working Tool and C. Useful Action require different definition and interpretation of inventive principles. Moreover, the number of elementary inventive principles varies over the problem definition categories. At the same time, the number of the system attributes in each problem definition category is not restricted. Thus, several working tools, target objects, useful actions or undesired properties can

be applied for selection of elementary inventive principles for automated idea generation. The following Table 1 illustrates the proposed method for compiling a knowledge database for idea generation using n elementary inventive principles. The coefficients A_j , B_j , C_j and D_j are equal 1 if a corresponding elementary principle is applicable for the problem formulation category and equal 0 if it is not applicable. The exact wording of the same elementary inventive principle may vary for different problem formulation categories. In accordance with recommendations in [10, 11], a semantic procedure integrates the problem-specific working tool(s), target object(s), useful actions(s) and harmful effects(s) in the body of the elementary inventive principles and transforms them into less abstract solution ideas.

Table 1. Matrix for compiling a knowledge database for idea generation with n elementary solution principles for k working tools, l target objects, m useful functions and t harmful effects or properties: 1 – inventive principle is applicable, 0 – not applicable (fragment).

Elementary inventive principle IP_i	A. Working Tool $A_j, j=0,k$	B. Target Object $B_j, j=0,l$	C. Useful Action $C_j, j=0,m$	D. Harmful Effect $D_j, j=0,t$
1. Principle IP_1	1	1	0	0
2. Principle IP_2	1	1	0	0
3. Principle IP_3	1	1	1	0
...				
i. Principle IP_i	0	0	1	0
...				
n. Principle IP_n	0	0	0	1

In this approach, a semantic transformation function τ_i is defined as a collection of rules that specify how an elementary inventive principle IP_i , $i=0,n$ can be represented in a less abstract form as a finite number of solution ideas S_i , $i=0,r$:

$$IP_i \rightarrow \tau_i \{ A_j, B_j, C_j, D_j \} \rightarrow S_{i,r} \quad (1)$$

The semantic transformation is not restricted by only four categories for problem definition A , B , C , D , and can be easily extended to the higher number of categories.

For example, the Automatic Idea Generator tool disclosed in [15] proposes 170 solution ideas distributed over the problem definition categories as follows: Working Tool (83 solution principles); Target Object (30 solution principles), Useful Action (47 solution principles), Harmful Effect (10 solution principles). An illustration of its application is presented in the section 3.

2.2 Variety of the Elementary Solution Principles

Among typical objective metrics of ideation effectiveness such as quantity, variety, novelty, quality, and feasibility of proposed ideas [19], only the quantity and the variety of ideas can be directly affected by the ideation or creativity techniques. The novelty, quality (value) and feasibility can be also influenced by the personal creativity,

motivation, knowledge level, and professional skills of the specialists [10, 16]. In accordance with Diehl and Stroebe [20], there is a positive correlation of $r=0.82$ between the number of high-quality ideas and the total ideas number. Thus, increasing of ideas quantity helps to generate more ideas of higher quality. The high quantity of ideas can be ensured by the high number of applied elementary inventive principles. One of the common approaches to increase the ideas variety or breadth stipulates a more uniform distribution of the inventive principles over the engineering domains [9, 16]. For this purpose, the applied elementary inventive principles represent nine MATCEM-IBD, “Design” and “Universal” categories. The category “Universal” includes the elementary inventive principles which can be assigned to any of MATCEM-IBD fields or also non-technical domains. The idea generation with the design or universal elementary inventive principles does not compulsorily lead to a change of the working principle in a technical system. A diagram in Fig. 1 illustrates the variety of the 170 elementary solution principles in the Automatic Idea Generator presented in [15].

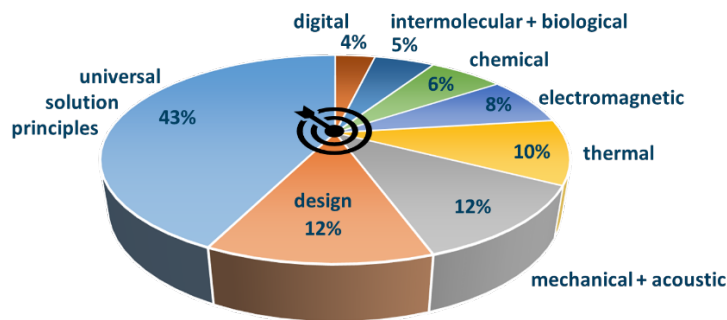


Fig. 1. Variety of the 170 elementary solution principles in the Automatic Idea Generator [15].

The high breadth of available underlying solution principles allows systematic ideation in different engineering and non-technical domains. One can systematically analyze possible solution ideas in the MATCEM-IBD order, select or discard specific engineering domains, look for solutions based on design or universal principles only, etc. For example, a typical ideation process in mechanical engineering will start with the evaluation of the universal, design, and mechanical solution ideas, step-by-step extended with acoustic, electromagnetic, thermal, digital, chemical, and other solutions.

2.3 General Statistical Ranking and Abstraction Level of Solution Principles

As illustrated in [3, 6], the classical 40 TRIZ Inventive Principles and their sub-principles can be ranked in accordance with the statistical frequency of their application. However, this ranking has rather the character of a recommendation. The ranking of the TRIZ Inventive Principles and sub-principles can vary over different engineering domains as, for example, revealed in the studies [6, 14, 21] in the field of

process and environmental engineering. It is also noteworthy that the ranking of the statistically strongest elementary inventive principles is more meaningful in comparison with the general ranking of the parent inventive principles which is rather of limited informative value. In accordance with [9] both ranking approaches can be complementary applied in the practice for selection of the stronger elementary inventive principles using an analogue scale [14] and finely or coarsely [15] graded scales, such as for example:

- High - frequent use in all engineering domains.
- Medium - frequent use in some engineering domains.
- Low - for specific or difficult problems.

As mentioned in the review in the section 1, a major challenge for the engineers and users of 40 TRIZ Inventive Principles remains a fast, reproducible, and whenever possible precise selection of the promising inventive principles and solution ideas for a particular problem. The recent comprehensive experimental study [10] outlines that the higher abstraction level of TRIZ principles negatively affects the ideation performance of the undergraduate and graduate engineering students. In numerous ideation experiments the students generated on average 1.2 times less ideas with the more abstract universal elementary principles than with the field-oriented elementary principles corresponding to one of the MATCEM-IBD domains.

The abstraction level of the elementary inventive principles can be connected to the feasibility of the automatically generated ideas using, for example, the following scale:

- Low - a ready-to-use idea.
- Medium - idea implementation requires additional knowledge.
- High - idea interpretation and implementation need additional analysis.

Figure 2 presents a distribution of 170 automatically generated ideas in accordance with the statistical ranking and abstraction level of the underlying elementary solution principles in the Automatic Idea Generator [15].

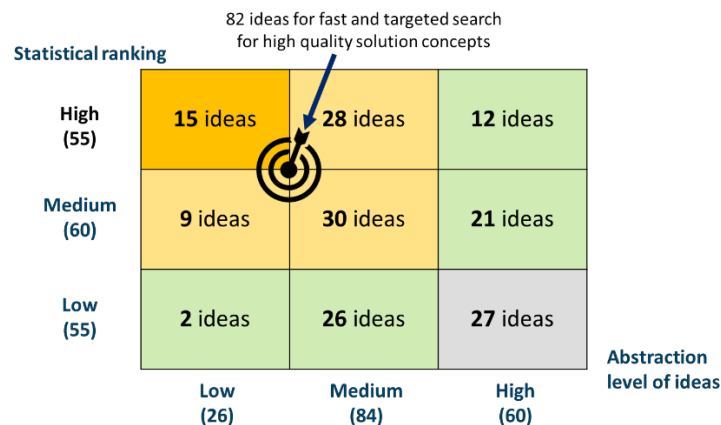


Fig. 2. Statistical ranking and abstraction level of the 170 automatically generated ideas in [15].

The in Figure 2 highlighted 82 ideas with the *medium to high* statistical ranking and *low to medium* abstraction level are suitable for the fast and directed search for the high-quality solutions. The ideas with the *low* ranking are also of value but their underlying elementary inventive principles are rarer used in all engineering domains. However, it can happen that the exact opposite is true in a specific field of work. The ideas with a *high* abstraction level usually require an additional analysis of the problem. Moreover, these ideas often lead to the non-obvious inventive solutions and therefore must be treated carefully without haste. Different strategies for selection and evaluation of automatically generated ideas can be explored in this context.

2.4 Strategies for Automated Idea Generation

A recent comprehensive literature analysis of application, selection, and modification of the 40 TRIZ Inventive Principles [3] outlines the importance of refined approaches and strategies for identifying “appropriate” inventive principles depending on the type and engineering domain of a problem. The process for automated ideation, described in this paper, can be started if at least one of the problem definition categories is defined: A. *Working Tool*, B. *Target Object*, C. *Useful Action* or D. *Harm*. In each category the ideas are initially sorted according to the statistical ranking of the underlying elementary principles. Selection of the statistical ranking, abstraction level and engineering domains of the elementary inventive principles offers the following approaches to the identification of valuable ideas:

1. Selection of top 10...15 ideas with *high* statistical ranking and *low* abstraction level which immediately delivers 2...3 feasible and easy-to-implement solutions. If no appropriate ideas are found in this group, it is highly likely that the problem is defined incorrectly, and the problem definition categories must be revised.
2. Selection of the ideas with *high* statistical ranking and *low to medium* abstraction level helps to identify 5...10 inventive solutions in 10...20 minutes.
3. Evaluation of all automatically generated ideas with *high to medium* statistical ranking and *low to medium* abstraction level allows one to identify on average 30...50 implementable solutions for a given problem within 60 minutes.
4. Enhancement and completeness check of the idea pool with the solution ideas with *high* abstraction level and *low* statistical ranking.
5. A systematic identification of strong solution ideas can be performed in accordance with the engineering domains of the underlying elementary solution principles starting with universal and design principles, and step-by-step extended with mechanical, acoustic, thermal, electromagnetic, intermolecular, digital, and biological principles. The engineering domains order can be defined by the users.
6. Different alternative or complimentary variants of the problem definition categories A. *Working Tool*, B. *Target Object*, C. *Useful Action* or D. *Undesired Property or Harm* can be successively applied to achieve an optimal problem formulation or to enhance ideation outcomes.
7. Automated knowledge-based identification of statistically stable and frequently repeatable groups or chains of elementary inventive principles in different engineering domains, using adaptive algorithms and artificial intelligence AI.

8. Automated idea generation can be executed in accordance with the cause-effect-chains: starting with the identified causes of the problem and continuing with the problem itself and its effects.
9. Automated idea generation can be executed on different system levels: for the technical system, for its sub-systems or components, and for the super-system.
10. Automated idea generation for the predefined partial problems, complementary or contradictory engineering attributes, as explained in the section 2.5.

2.5 Statistical Ranking of Solution Principles for Predefined Engineering Attributes and Automated Resolving of Engineering Contradictions

In addition to the general statistical ranking of the elementary inventive principles, discussed in the section 2.3, the estimated partial ranking of elementary principles for specific predefined engineering attributes helps to automatically identify the corresponding solution ideas of statistically higher value. To such attributes can belong various technical requirements and the engineering parameter known from the Altshuller matrix [1, 12, 13], as exemplarily presented in Table 2.

Table 2. Predefined engineering attributes for problem definition and statistical ranking of elementary solution principles (examples).

Cost reduction [15]	Reduction of ecological impact [14]	Process Intensification [22]	Parameter of the Altshuller matrix [1]
Energy consumption and energy losses	Environmental pollution: air, water ...	Reliability and quality of process	Stability of the object
Raw material consumption and losses	Chemical waste disposal	Size of equipment	Mechanical strength of the object
Manufacturing and production costs	Energy consumption	Complexity of process and equipment	Power or capacity
Personnel costs	Acidification	Safety and controllability of process	Speed, velocity of the object
Time losses	Depletion of abiotic resources	Process flexibility and adaptability	Accuracy of measurement
Operating, service and maintenance costs	Reduction of CO ₂ emission	Energy and material consumption	Complexity of the structure
...

The major benefit of applying strongest elementary principles for predefined attributes is a timesaving and more precise ideation. Moreover, a simultaneous selection of two or more attributes allows one to identify stronger ideas which fulfil different complementary or contradictory requirements. Figure 3 illustrates how six cost cutting attributes can be applied for the systematic cost reduction in the Automatic Idea Generator [15]. For example, the idea 1 satisfies with high probability all cost reduction attributes, whereas the ideas 2, 3 or 4 show a lower overall cost cutting impact.

	Energy costs	Material costs	Manufacturing	Complexity	Maintenance	Eco-Impact
Idea 1	High	High	High	High	High	High
Idea 2	Medium	High	High	High	Low	High
Idea 3	Medium	Medium	Medium	High	Medium	Medium
Idea 4	High	Medium	Medium	Low	High	High

Fig. 3. Example of automatic identification of strong ideas for cost reduction based on their statistical ranking for six cost cutting attributes [15].

In general, automated generation and comparison of ideas for contradictory attributes or requirements offers a fast approach to identify a group of elementary solution principles and ideas for resolving a given engineering contradiction or even a network of contradictions. This feature can be considered as a novel way for overcoming of technical and non-technical trade-offs without application of the Altshuller contradiction matrix or its derivatives. Moreover, a combination of ideas for the independent partial problems or contradictory requirements can be used for creation of the innovative solution concepts.

2.6 Creation and Optimization of Solution Concepts

In accordance with the Advanced Innovation Design Approach a comprehensive problem analysis leads to transformation of the initial problem situation to the finite number of partial problems $P_1 \dots P_n$, which must be appropriately defined and prioritized [22]. To develop a new solution concept the suitable complementary ideas must be generated and selected for each partial problem. The creation of solution concepts in a situation comprising several partial problems remains one of the challenging phases in the innovation design. Each partial problem P_i can have several complementary or competitive solution ideas S_{i1}, S_{i2}, S_{i3} etc. Moreover, the preferred partial solutions of different partial problems may be incompatible to each other.

Table 3 illustrates exemplarily possible results of the automated ideation with more than one preferred solution for each partial problem. Each solution concept C_k can be represented in the solution matrix as an integration and adaptation of partial solution ideas S_{ij} :

$$C_k = \{ S_{i1}, S_{2j}, \dots, S_{nm} \} \quad (2)$$

Table 3. Solution matrix for automated concept creation and optimization, with an example of the solution concept $C_1 = \{S_{13}, S_{22}, \dots, S_{n3}, \dots, S_{nm}\}$.

<i>Partial problems</i>	<i>Solution ideas and Innovation concepts</i>				
Problem P_1	S_{11}	S_{12}	S_{13}		
Problem P_2	S_{21}	S_{22}			
...
Problem P_n	S_{n1}	S_{n2}	S_{n3}	...	S_{nm}

The automated concept creation can be performed with the help of multiple evaluation criteria, optimization algorithms and compatibility analysis of selected solution ideas. The development of the appropriate multi-objective optimization algorithm for concept creation in the framework of the proposed approach for automated idea generation is a subject of further research work.

3 Application Example and Experimental Verification

3.1 Application Example of the AIDA Automatic Idea Generator

Figure 4 illustrates the proposed method for automated idea generation using the current functionality of the AIDA Automatic Idea Generator [15] for the problem of ship hull cleaning on how to intensify the hull cleaning of big ships from maritime organisms (algae and shell layers) with high pressure water jetting without paint layer damage? The illustrated approach includes the following 7 steps:

1. Brief problem description and definition of the goal(s) for idea generation.
2. Definition of at least one category to activate automated ideation: A. Working Tool = *Water jet* (83 ideas); B. Target object = *Maritime organisms* (30 ideas), C. Useful action = *Surface cleaning* (47 ideas), D. Harm = *Maritime organisms on hull* (10 ideas).
3. The automatically generated ideas are presented in accordance with their statistical ranking of the underlying inventive principles and displayed for each problem definition category A - B - C - D separately.
4. Selection of valuable ideas with the *high to medium* statistical ranking.
5. Filtering ideas by their abstraction level: ideas with abstraction level *low to medium* are easier to implement.
6. Optionally, application of the solution domain filter to select engineering domains of solution ideas and optionally of other filters.
7. Definition of the idea potential and other evaluation criteria; selection, enhancement, and adaptation of ideas for the solution concepts.

The example shows that the first elementary solution principles for the working tool “Water jet” deliver 5 suitable solution ideas.

Problem name and brief definition:		Fill the fields below to activate the idea generation:						
Ship hull cleaning. How to intensify the hull cleaning of big ships from maritime organisms (algae and shell layers) with high pressure water jetting without paint layer damage ? <div style="text-align: center; border: 1px solid black; width: 100px; height: 100px; margin: 0 auto; display: flex; align-items: center; justify-content: center; border-radius: 50%; font-size: 2em; font-weight: bold;">1</div>		A. Working tool or working medium:	<div style="border: 1px solid black; border-radius: 50%; width: 20px; height: 20px; display: flex; align-items: center; justify-content: center; margin: 0 auto;">2</div> WATER JET					
		B. Target object or workpiece:	MARITIME ORGANISMS					
		C. Useful action or main function:	SURFACE CLEANING					
		D. Undesired property or harmful effect:	MARITIME ORGANISMS ON HULL					
<div style="display: flex; justify-content: space-around; margin-bottom: 5px;"> <div style="border: 1px solid black; border-radius: 50%; width: 20px; height: 20px; display: flex; align-items: center; justify-content: center; font-size: 0.8em; font-weight: bold;">3</div> <div style="border: 1px solid black; border-radius: 50%; width: 20px; height: 20px; display: flex; align-items: center; justify-content: center; font-size: 0.8em; font-weight: bold;">4</div> <div style="border: 1px solid black; border-radius: 50%; width: 20px; height: 20px; display: flex; align-items: center; justify-content: center; font-size: 0.8em; font-weight: bold;">5</div> <div style="border: 1px solid black; border-radius: 50%; width: 20px; height: 20px; display: flex; align-items: center; justify-content: center; font-size: 0.8em; font-weight: bold;">6</div> <div style="border: 1px solid black; border-radius: 50%; width: 20px; height: 20px; display: flex; align-items: center; justify-content: center; font-size: 0.8em; font-weight: bold;">7</div> </div> Currently displayed rows: 170 out of total 170								
N	Solution ideas: 170 out of total 170	Idea category	Statistical ranking	Abstraction level	Solution principle	Define idea potential	Refine or comment ideas	
1	Use WATER JET in other aggregate state: change it to solid, liquid, gas, or plasma	A. Working tool	High	Medium	Thermal	High	Use gas, steam or solid dry ice (carbon dioxide) to enhance cleaning	
2	Change mechanical or surface properties of WATER JET like strength, hardness, density, viscosity etc.	A. Working tool	High	Medium	Mechanical	Low		
3	Change physical properties of WATER JET like conductivity, magnetism etc.	A. Working tool	High	Medium	Universal	Low		
4	Change the temperature of WATER JET by heating or cooling	A. Working tool	High	Low	Thermal	Medium	Use of very hot or very cold working agents to remove maritime organisms.	
5	Change chemical properties of WATER JET like chemical formulation, pH, solubility etc.	A. Working tool	High	Medium	Chemical	Medium	Environmentally friendly chemical detergent	
6	Pre-arrange WATER JET so it can come into action at the most convenient position and without losing time	A. Working tool	High	Medium	Universal	Medium	Apply water jet in a tilted position with highest cleaning effect	
7	Divide WATER JET into several independent parts or sections.	A. Working tool	High	Low	Design	Medium	Use two or three water jets simultaneously, which are amplifying each other	
...								
84	Change mechanical or surface properties of SHIP HULL like strength, hardness, density, viscosity etc.	B. Target Object	High	Medium	Chemical	Medium	Modify the surface properties of the ship hull after or during cleaning to prevent the adhesion of algae and	
...								
114	Perform a part of SURFACE CLEANING process beforehand as a preparatory step	C. Useful Action	High	Medium	Universal	High	Use a preparatory step to remove shells before removing algae	
...								
170	Remove or compensate MARITIME ORGANISMS ON HULL with another harmful effect	D. Harmful Effect	Low	High	Universal	Low		

Fig. 4. Application Example of the AIDA Automatic Idea Generator [15].

3.2 Validation through Educational and Industrial Applications

This section briefly summarizes the outcomes of the experimental application of the method for automated ideation in educational and industrial settings in 2020-21. In the initial experiment performed by the author at the Offenburg University, an interdisciplinary mechatronic problem has been offered to the graduate students enrolled into the Master's Degree in Mechanical Engineering. The student's groups of 4, 3, 4 and 2 participants applied the AIDA Automatic Idea Generator tool [15] and documented 66, 42, 54 and 34 appropriate solution ideas respectively within a time of 42...55 minutes.

In a series of industrial applications in 5 engineering companies, the AIDA Automatic Idea Generator [15] has been used in five independent projects by teams of 2...3 specialists. All teams started with 75 automatically generated ideas with higher statistical ranking, selected in the next step averagely 44 useful ideas for a given problem, among them 33 ideas with higher value and 12 ideas for implementation and patenting. The total mean time expenditures of the teams were 48 minutes.

The outcomes of individual application of the method can be characterized by its high ideation productivity and variety with on average 31 independent ideas per person for a given problem within 60 minutes without special skills in TRIZ methodology. This assessment is based on evaluation of 59 industrial applications reported by the users.

4 Concluding Remarks and Outlook

The proposed approach for automated ideation can be applied individually or in the creative meetings and brainstorming sessions. It also helps enhance the internal and external ideas crowdsourcing and can be used for a completeness check of invention claims of the patent applications. The approach allows the specialists, engineers, and students to explore the significant part of the TRIZ inventive knowledge base in accordance with their creativity skills, technological experience and available time without an extensive preparation or training in applying TRIZ. The paper supports the assumption that the automated TRIZ-based ideation will positively affect the frequency of TRIZ usability by the newcomers and contribute to the wider dissemination of the TRIZ inventive techniques in the practice. The author wishes to suggest that specialists, inventors, patent engineers, innovation facilitators and engineering educators need to consider embedding this approach into their professional activities.

The overall results of the experiments confirm that proposed TRIZ-based universal ideation method can substantially improve the ideation quantity, variety, and quality even if its practical outcomes still require further quantitative validation. Extension of the knowledge base, automated problem formulation, development of the adaptive multi-objective optimization algorithms for automated idea generation and concept creation, systematic identification of limitations and refinement of the method belong to the subjects of the current research work.

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