ENHANCING ENGINEERING CREATIVITY WITH AUTOMATED FORMULATION OF ELEMENTARY SOLUTION PRINCIPLES

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ABSTRACT

Several researchers have reported on the effectiveness of knowledge-based inventive stimuli, known in the Theory of Inventive Problem Solving (TRIZ), in enhancing engineering creativity, but few authors have focused on the comparative analysis of structured ideation in engineering design in terms of quantitative and qualitative outcomes. Previous studies have mainly concentrated on the investigation of exemplary selected single stimuli rather than on a critical assessment of the relationship between the structured application of inventive stimuli and their contribution to engineering design. The paper describes a method for the automated formulation of elementary creative stimuli for product or process design at different levels of abstraction and in different engineering domains. The experimental study evaluates the impact of structured automated idea generation on inventive thinking in engineering design and compares it with previous experimental studies in educational and industrial settings. The outlook highlights the benefits of using automated ideation in the context of AI-assisted invention and innovation.

Keywords: Creativity, Design methods, Innovation, New product development, TRIZ

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1 INTRODUCTION

A number of researchers have reported on the effectiveness of using tools of the theory of inventive problem solving TRIZ developed by Altshuller (1984) and co-workers to enhance the creativity of engineering students and engineers, but few studies have focused on the comparative analysis of TRIZ-based ideation in engineering design in terms of quantitative and qualitative outcomes. Instead of critically assessing the relationship between the structured application of TRIZ, as defined in the TRIZ standard VDI 4521 of the Association of German Engineers (VDI, 2016), and its inventive contribution to engineering design, previous studies have focused on the investigation of exemplarily selected simple creative stimuli. Among the many components of TRIZ, the 40 Inventive Principles are the most widely used tool for systematically improving ideation performance. These principles are easy to apply or modify for specific technical domains and can be easily integrated into brainstorming or the daily work of engineers (Borgianni et al., 2021). Over the past decades, the 40 TRIZ Inventive Principles have been widely used to solve technical contradictions in various engineering domains and have been enriched with adaptations, illustrations, and examples for specific fields of application. In addition, several studies on the Inventive Principles have been carried out to improve the quantity and quality of the ideation outcomes for the various engineering domains. The study of Russo and Spreafico (2015) classified the 40 Inventive Principles through functional behaviour structure ontology. There are also many proposals of examples illustrating the breadth of application in specific engineering domains (Borgianni et al., 2021), such as electronics, chemical engineering, food processing, ergonomics, maintenance, software engineering etc. The Altshuller' original 40 Inventive Principles (Altshuller, 1984) contain in total between 86 and 90 sub-principles. Petrov (2018) presents the "universal" 40 Inventive Principles with about 125 sub-principles and engineering illustrations. Finally, Chandra-Sekaran et al. (2019) extend the number of the sub-principles to 160 for their comprehensive application in the field of process engineering.

In general, the sub-principles can be understood as elementary inventive operators for the 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 the eight MATCEM-IB domains known in TRIZ: M - Mechanical, A - Acoustic, T - Thermal, C - Chemical, E - Electrical, M - Magnetic, I - Intermolecular, B - Biological. There are also generally formulated sub-principles that are independent of any engineering domain and can be assigned to the design heuristics or to the universal process-oriented inventive operators (Chandra-Sekaran et al., 2019).

The practical application of the Inventive Principles often requires a focused, creative and abstract way of thinking that can be challenging for engineers or newcomers to TRIZ. For example, the abstract term "object" often used in the principles can be understood as a system, system component, substance, process or process step, or any other material or virtual object. Similarly, the abstract definition of "action" can be understood as a function, positive or negative effect, or any other interaction between objects. Therefore, the results of brainstorming with the TRIZ Inventive Principles often depend on the individual interpretation. The level of abstraction can be reduced by modifying the principles by replacing the abstract terms "object", "action" or "function" with the context-specific name of a real system component, real function or real action. A comprehensive experimental study confirms that the less abstract and problem-specific formulation of TRIZ Inventive Principles can visibly improve the idea generation results of engineering students and newcomers to TRIZ, both in terms of the quantity and variety of ideas proposed (Livotov et al., 2019a). In 194 experiments, students generated almost 1.5 times more ideas with the modified and less abstract inventive principles than with the classically formulated principles. This positive effect was observed among students from different years of study, regardless of their level of knowledge or the difficulty of the problem.

Even though many studies have extended and improved the TRIZ Inventive Principles and their sub-principles to a wider range of applications, another major challenge for engineers remains the precise selection of the strongest principles or sub-principles for specific problems. The Altshuller Contradiction Matrix in its classical form with 39 rows and 39 columns (Altshuller, 1984) or its later modifications can simplify the selection of appropriate solution principles for an engineering contradiction formulated with standard technical parameters. However, the author confirms through his own empirical findings from numerous case studies that statistically only about 10...15% of the problems can be satisfactorily described with the standard engineering parameters used in the matrix. Alternatively, one can apply the inventive principles in the order of their statistical frequency of use, 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 and others (Altshuller, 1984). A recent, slightly modified variant of the frequency of application of the 40 Inventive Principles has been proposed by Borgianni et al. (2021).

The publication by Livotov et al. (2019b) suggests the application of the sets of sub-principles as a more precise and productive ideation technique, adaptable to a wide 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 literature. Interestingly, the top ten strongest sub-principles often differ significantly from the statistically strongest parent Inventive Principles. This paper considers the application approaches of the 40 Inventive Principles mentioned above, including their advantages and disadvantages, describes a method for automated idea formulation based on elementary TRIZ inventive sub-principles and discusses its application to give a critical assessment of the creative TRIZ impact on engineering design in educational and industrial contexts, comparing it with previous studies.

The paper presents a formalized approach employing a semantic transformation function and compiling TRIZ knowledge database for automated idea generation using components of this function. In general, analogous procedures are quite common in the idea generation outside of the TRIZ domain. In a comprehensive survey Han et al. (2021) outline the importance of engineering-related semantic networks in engineering design. Georgiev et al. (2016) propose to support the design of products with innovative desired functions with an approach focused on thematic scenes or relations between two interacting objects. This specific procedure allows to create a new scene employing a database of existing scenes. Sarica et al. (2021) propose an ideation-assisting approach based on a large semantic network of technical terms for generating new design ideas. Han et al. (2018) outline that a computational tool based on analogical reasoning and ontology can significantly support creative idea generation and elaboration, improving the designer's ideation fluency, flexibility, and originality as well as the idea's usefulness.

In addition to the aforementioned approaches, the present work defines a new method of TRIZ methodology for the automated formulation of elementary invention principles for semantically predefined interacting objects, which are regarded as problem models. In its initial stage, the automated idea generation method does not require high computing power or specific TRIZ knowledge. In a second step, however, it can be enhanced with tools for AI-assisted invention, such as, for example, Generative Pre-trained Transformers, for post-processing the automatically generated solution principles.

2 METHOD FOR AUTOMATED FORMULATION OF IDEAS

The knowledge base for systematic ideation is primarily based on the 160 sub-principles (here defined as elementary inventive principles) of 40 TRIZ Principles, as proposed by Chandra-Sekaran et al. (2019). These elementary inventive principles have been enhanced and extended by some selected TRIZ tools (VDI, 2016), such as trends of technical evolution, standard solutions, selected physical, chemical, biological and geometrical effects, and other complementary heuristics. For example, the MATCEMIB heuristic, known as an efficient and easy-to-use ideation tool, was decomposed and integrated into the knowledge base. Overly complicated, overlapping or redundant classical inventive sub-principles known in (Altshuller, 1984) were avoided. The application of the knowledge base for automated idea generation can be done using a generic ad hoc problem definition or any systematic problem definition tools known in TRIZ (VDI, 2016) or in other problem solving approaches such as function analysis, cause-effect chain analysis or root conflict analysis. Automated idea generation can be carried out at different levels of problem analysis and understanding, such as

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- improving or transforming the system or its components,
- providing or increasing the useful action,
- elimination of harmful effects or undesirable characteristics,
- resolving engineering contradictions, characterised by a situation where improving one target parameter causes another target parameter to deteriorate.

2.1 Semantic transformation function of the elementary solution principles

For the selection of the elementary inventive principles and the 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, and finally D - undesirable property or harmful effect. For each problem definition category, A, B, C and D, the corresponding specific elementary inventive principles can be automatically pre-formulated as solution ideas using a semantic transformation. For example, it is reasonable that the categories A (working tool) and C (useful action) require different definitions and interpretations of inventive principles. Furthermore, the number of elementary inventive principles varies across the problem definition categories. At the same time, the number of the system attributes (components, functions), in each problem definition category is not limited. Thus, several working tools, target objects, useful actions or undesirable properties can be used for the selection of elementary inventive principles for automated idea generation. The following semantic transformation function T_i (Equation 1) illustrates the proposed method for compiling a knowledge database for idea generation using n elementary inventive principles for k working tools, l target objects, m useful functions and t harmful effects.

$$IPi \rightarrow Ti\,\{\,Aj(j=1,k)\,,Bj(j=1,l)\,,Cj(j=1,m)\,,Dj(j=1,t)\,\} \rightarrow Si,r \quad (1)$$

In this method, a semantic transformation function T_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, $i=0,r$. The semantic transformation is not limited to the four categories of problem definition A, B, C, D, and can be formally extended to the higher number of categories. The exact formulation of the same elementary inventive principle may vary for different problem formulation categories. In other words, a semantic procedure integrates the problem-specific working tool(s), target object(s), useful action(s) and harmful effects(s) in the bodies of the elementary inventive principles and transforms them into less abstract solution ideas.

Table 1 illustrates the procedure of the automated idea generation for the Ship Hull Cleaning problem on how to intensify the cleaning of the hulls of large ships from marine organisms (algae and shell layers) by means of high-pressure water jetting without damaging the paint layer. In this example the following four categories were used as input for the problem definition: A. Water jet (working tool), B. Marine organisms (target object), C. Surface cleaning (useful action), D. Paint layer damage (harmful effect).

Table 1. Example of automated idea generation for four problem definition categories

Automatically generated idea or recommended solution principle	Problem category	Statistical Ranking	Abstraction level	Working principle
10. Use water jet in form of solid particles or granules	A. Working tool	High	Medium	Mechanical
89. Change the aggregate state of marine organisms to solid, liquid, gas, or plasma	B. Target object	High	Medium	Thermal
134. Perform a part of surface cleaning process in advance as a preparatory step (e.g., pre-treat)	C. Useful action	High	Low	Universal
193. Use condition monitoring and modelling to predict paint layer damage and avoid it	D. Harmful effect	Medium	Medium	Digital

The knowledge base for automated idea generation in the current state of development can propose a total of 200 ideas to the users, including 88 ideas for the problem category A. Working tool, 45 ideas for B. Target object, 56 ideas for C. Useful action and 11 ideas for the problem category D. Harmful effect. Table 1 shows as an example four ideas No 10, 89, 134 and 193, one idea for each problem definition category.

2.2 Variety of the elementary solution principles

Among the typical objective metrics of ideation effectiveness, such as quantity, variety, novelty, quality and feasibility of the proposed ideas (Shah et al., 2003), only the quantity and variety (breadth) of ideas can be directly influenced by the ideation or creativity techniques. Novelty, quality (value) and feasibility can also be influenced by the personal creativity, motivation, knowledge level and professional skills of the professionals. According to Diehl and Stroebe (1991), there is a positive correlation of $r = 0.82$ between the number of high-quality ideas and the total number of ideas. Thus, increasing the quantity of ideas 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 most common approaches to increase the variety or breadth of ideas is to provide a more uniform distribution of the inventive principles across the technical domains. For this purpose, the applied elementary inventive principles represent nine MATCEM-IBD technical domains, where "D" stands for digital or information processing ideas, as well as the categories "Design" and "Universal". The "Universal" category includes the elementary inventive principles that can be assigned to any of the MATCEM-IBD fields or to non-technical domains. The generation of ideas with the design or universal elementary inventive principles does not necessarily lead to a change in the working principle of a technical system. A diagram in Figure 1 illustrates the variety of the 200 solution principles proposed in the current knowledge base for automated idea generation.

The high breath of available underlying solution principles allows systematic ideation in different engineering and non-technical domains. One can systematically analyse 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 can start with the evaluation of the design and mechanical solution ideas, step-by-step extended with acoustic, electromagnetic, thermal, digital, chemical, and other solution principles. A typical ideation session in process engineering can start with the universal solution principles.

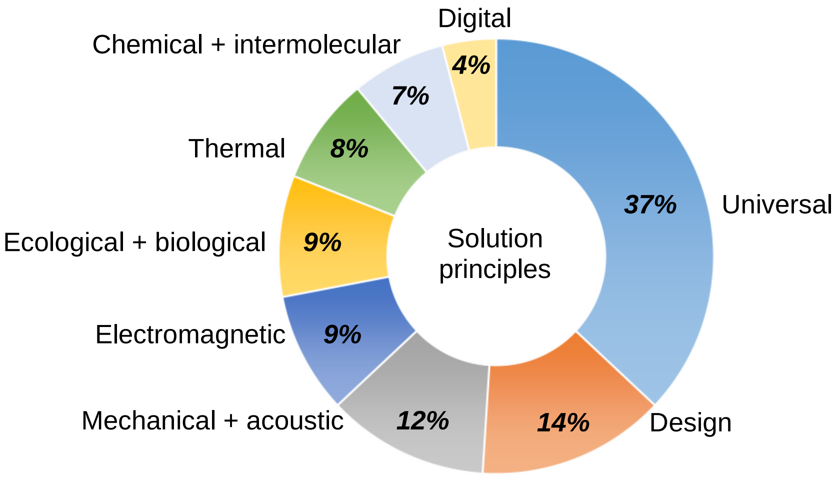

Figure 1. Variety of the underlying elementary solution principles

2.3 Statistical ranking and abstraction level of elementary solution principles

As shown by Borgianni et al. (2021), the 40 classical TRIZ Inventive Principles and their sub-principles can be ranked according to the statistical frequency of their application. However, this ranking has more the character of a recommendation. The ranking of the TRIZ Inventive Principles and sub-principles can vary in different engineering domains, as shown for example in (Livotov et al., 2019b) in the field of process and environmental engineering. It is also noteworthy that, compared to the general ranking of parent inventive principles, which is of rather limited informative value, the ranking of the statistically strongest inventive sub-principles is more meaningful. According to

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Chandra-Sekaran et al., (2019), both ranking approaches can be used complementarily in practice to select the stronger elementary inventive principles using an analogue scale and fine- or coarse-grained scales, such as: High - for frequent use in all engineering domains, Medium - for frequent use in some engineering domains, Low - for specific or difficult problems.

As mentioned in the review in Section 1, a major challenge for the engineers and users of the 40 TRIZ Inventive Principles remains the fast, reproducible and, if possible, precise selection of the promising inventive principles and corresponding solution ideas for a given problem. A recent comprehensive experimental study outlines that the higher level of abstraction of TRIZ principles negatively affects the ideation performance of undergraduate and graduate engineering students (Livotov et al., 2019a). In numerous ideation experiments the students generated on average 1.2 times fewer ideas with the more abstract universal elementary principles than with the field-oriented elementary principles corresponding to one of the MATCEM-IBD domains.

The level of abstraction of the elementary solution principles can be related to the feasibility of the automatically generated ideas, e.g., using the following scale: Low - a ready-to-use idea, Medium - implementation of the idea requires additional knowledge, High - interpretation and implementation of the idea requires additional analysis. Figure 2 shows the distribution of 200 automatically generated ideas according to the statistical ranking and the level of abstraction of the underlying elementary solution principles. The ideas highlighted in Figure 2 with a medium to high statistical ranking and a low to medium level of abstraction are suitable for a fast and targeted search for high quality solutions. The ideas with low rankings are also valuable, but their underlying elementary inventive principles are less frequently used in all engineering domains. However, in a specific field of work, the opposite may be true. The ideas with a high level of abstraction usually require additional analysis of the problem. Moreover, these ideas often lead to non-obvious inventive solutions and therefore need to be treated carefully and without haste. Different strategies for selecting and evaluating automatically generated ideas can be explored in this context.

Statistical ranking			
High	**17 ideas**	**32 ideas**	**15 ideas**
Medium	**11 ideas**	**45 ideas**	**28 ideas**
Low	**2 ideas**	**23 ideas**	**27 ideas**
	Low	*Medium*	*High*

Level of abstraction

Figure 2. Statistical ranking and level of abstraction of 200 automatically generated solution principles and corresponding ideas

2.4 General application approach and practical recommendations

A recent comprehensive literature analysis of the application, selection, and modification of the 40 TRIZ Inventive Principles by Borgianni et al. (2021) outlines the importance of refined approaches and strategies for identifying "appropriate" inventive principles depending on the type and engineering domain of a problem. The automated idea generation process described in this paper can be started when at least one of the problem definition categories is defined: A. Working tool, B. Target object, C. Useful action, or D. Harmful effect. In each category, the ideas are first presented according to the statistical ranking of the underlying elementary principles.

The following basic techniques for identifying valuable ideas are recommended by selecting the statistical ranking, the level of abstraction and the technical domains of the elementary principles:

1. Selecting the top 10...15 ideas with a high statistical ranking and a low level of abstraction that immediately provides 2...3 feasible and easy to implement solutions. If no suitable ideas are

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found in this group, it is highly likely that the problem is poorly defined, and the categories A, B, C or D used to describe the problem need to be revised.

2. Selecting the ideas with a high statistical ranking and a low to medium level of abstraction helps to identify 5...10 inventive solutions in 15...20 minutes.
3. Evaluating all automatically generated ideas with a high to medium statistical ranking and a low to medium level of abstraction makes it possible to identify on average 30...50 implementable solutions for a given problem within about 60 minutes.
4. A systematic identification of strong solution ideas can be carried out according to the engineering domains of the underlying elementary solution principles, starting with universal and design principles and progressively extending to mechanical, acoustic, thermal, electromagnetic, intermolecular, digital, biological and ecological principles.
5. Finally, the completeness of the idea pool can be checked by analysing solution ideas with a high level of abstraction and a low statistical ranking.

3 EXPERIMENTAL VERIFICATION

This section presents the results of the experimental application of automated ideation in educational and industrial settings in 2022-23 and compares them with the published experimental studies on enhancing engineering creativity. In the experiments conducted, several design problems were offered to the interdisciplinary groups of mechanical and process engineering students in different semesters of their studies. The ideation sessions in the experiments lasted 15...30 minutes in order to limit fatigue and still allow a high number of ideas to be generated. In each group, the participants sat together in familiar places in a large seminar room. They were supervised by the same person. The problems were new to the participants and had been explained by the supervisor just minutes before the idea generation session. All participants used the same idea generation form with automatically formulated elementary solution principles, prepared by the experimenter. The number of different ideas proposed by each participant and the number of different ideas within each group were estimated by two independent evaluators. The evaluation of the brainstorming sessions was anonymous. After a 4-5 minute introduction to the problem, the participants were allowed to think about the automatically suggested ideas in silence and to select and comment on the ideas suitable for solving the problem using the distributed idea generation forms.

3.1 Experimental results

The main point of reference for the experimental verification of the automated ideation was the series of experiments on enhancing engineering creativity using the interdisciplinary MATCEMIB heuristic for the problem of how to remove a hard lime (calcium carbonate) deposit on the inner surface of water pipes. (Belski et al., 2019). This ideation technique is using Mechanical, Acoustic, Thermal, Chemical, Electric, Magnetic, Intermolecular and Biological (MATCEMIB) working principles for a systematic idea search, resulting in generating of more novel ideas in various engineering domains. Students were invited to generate and to record ideas in period of 16 minutes with 2 minutes for each of the 8 MATCEMIB working principles. The number of independent ideas proposed by each individual student for eliminating the lime build up as well as the distribution of these ideas over the MATCEMIB domains have been evaluated for the students enrolled into the master's degree in mechanical engineering (7th and 8th study semesters). Students in the Control group spent 16 minutes individually generating solutions without creative stimulation. (Belski et al., 2019).

The same problem was used in the automated idea generation experiment with the mechanical engineering students in the 8th semester of their master's degree. The automated idea generation procedure was carried out for the problem category C. Useful function "Limescale removal" with a total of 25 pre-formulated elementary solution principles corresponding to 3 mechanical, 1 acoustic, 4 thermal, 5 chemical, 7 electrical or magnetic, 3 intermolecular and 2 biological domains, as shown in Table 2. Participants were given 16 minutes to select feasible and useful solutions from 25 automatically suggested ideas, and an additional 10 minutes to comment on or improve selected ideas. Table 3 shows the results for the average number of independent ideas proposed by students in both experiments using the MATCEMIB heuristic (Groups 1 and 2, see Belski et al., p. 256) and using the Automated Ideation approach for the same problem. The "Mean" column in Table 3 shows the average

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number of independent ideas proposed by a student in a given group and its standard deviation. It shows the breadth (variety) of these ideas, the average ideation productivity in ideas per minute, and includes information on group size and semester of study.

According to Belski et al. (2019), the breadth or variety of ideas for each group was calculated as the sum of eight terms, each corresponding to a fraction of students who proposed ideas for each domain of MATCEMIB. For example, the breadth of ideas proposed by students in the Automated Ideation group was as follows: 100% of students proposed mechanical ideas; 86% - acoustic; 86% - thermal; 100% - chemical; 86% - electrical; 86% - magnetic; 86% - intermolecular; 93% - biological. Therefore, the breadth of ideas proposed by this group is equal to 7.22:

$$Breadth = 1.00 + 0.86 + 0.86 + 1.00 + 0.86 + 0.86 + 0.86 + 0.92 = 7.22 \quad (2)$$

Table 2. Examples of automated idea generation in for different MATCEMIB domains with 8 ideas out of total 25

Automatically generated idea or recommended solution principle	Working principle	Example of student's comments and interpretation
Use mechanical friction, vibration or ultrasonic vibration, pressure, deformation, shocks, explosion for lime removal	Mechanical	Rotating brush or cutting tool
Use ultrasound, infrasound, sound, cavitation for lime removal	Acoustic	Loosening of the lime in the pipe with ultrasound vibrations
Use fluids and gases for heat and energy transfer in lime removal process	Thermal	Hot boiling water, steam, or other gas
Use chemical reactions, reactants, additives, elements, compounds for lime removal	Chemical	Chemical reaction, use of acids
Use ionisation, electrical discharge, sparks, electric arc in lime removal	Electric	Crumble and crash lime with electrical discharge
Use magnetic field, magnets, magnetic particles and fluids, electrical drives for lime removal	Magnetic	Mini-robot inside of the pipe
Use capillary and pores, evaporation, surface tension, surface-active substances for lime removal	Inter-molecular	Use lime porosity for its faster removal
Apply biotechnologies and microorganisms in lime removal-process, e.g., enzymes, bacteria, fungi, insects, etc.	Biological	Microorganisms dissolve lime

Table 3. Outcomes of the automated ideation in comparison with earlier experiments (*) of Belski et al. (2019), illustrating mean numbers of different ideas per person, breadth, and average ideation productivity [ideas/min] of students

Group	Students	Mean (SD)	Breadth	Productivity
Control *	16 (semester 7,8)	4.4	2.80	0.28
MATCEMIB 1*	18 (semester 7,8)	6.4	4.70	0.40
MATCEMIB 2*	15 (semester 7,8)	8.1	6.10	0.51
Automated Ideation	14 (semester 8)	17.9 (SD=5.8)	7.22	1.12 (0.69)

The results of the experiment show a significant difference between the control group (mean=4.4), two MATCEMIB groups (mean=6.4...8.1) and the Automated Ideation group (mean=17.9; SD=5.8). The Automated Ideation group also shows the higher breadth value of 7.22 compared to the MATCEMIB groups with 4.70...6.10 and the Control group with 2.80. If the students in the Control and MATCEMIB groups generate on average 0.28 and 0.40...0.51 ideas per minute respectively, the automated idea generation allows to increase the ideation productivity by up to 1.12 ideas per minute with a test duration of 16 min. The ideation productivity can be well applied to evaluate the ideation results with the different idea generation time in the experiment (Saliminamin et al., 2019). Table 3 shows the automated ideation productivity for the idea selection time in the first 16 min of the

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experiment. Adding 10 minutes for idea enhancement or commenting results in a lower ideation rate of 0.69 ideas /min.

3.2 Further verification through educational and industrial applications

In a series of industrial applications in 5 engineering companies, automated idea generation was used in five independent projects by teams of 2...3 specialists. All teams started with 75 automatically generated ideas with a higher statistical ranking, selected in the next step on average 44 useful ideas for a given problem, among them 33 ideas with higher value and 12 ideas for implementation or/and patenting. The average total time spent by the teams was 48 minutes. The results of the individual application of the method can be characterised by its high productivity and diversity of ideas, with an average of 31 independent ideas per person for a given problem within 60 minutes, without special skills in the application of creativity stimulation using TRIZ-based methods.

In another case study, 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 persons applied the method for automated formulation of solution principles and documented 66, 42, 54 and 34 appropriate solution ideas respectively within a time of about 60 minutes.

The increasing diffusion of rapidly developing AI technologies led to the idea of the experiment to combine TRIZ-based automated idea generation with the natural language processing tool ChatGPT3 (https://chat.openai.com/chat, last accessed on 28.02.2023), using the chatbot to interpret the automatically generated elementary solution principles. For a problem on how to intensify the cleaning of the hulls of ships from marine organisms using high-pressure water jetting, the chatbot proposed 35 different ideas for 10 elementary solution principles, as shown in Table 4. The elementary solution principles were processed within seconds in separate chats, while each chatbot response was regenerated 3 times without changing the text of the requests.

Table 4. Automatically generated solution principles and some examples of corresponding interpretations by ChatGPT

Automatically generated elementary solution principles	Examples of ChatGPT proposals
1. Use water jet in other aggregate state	cavitation cleaning, high-pressure steam, ice particles, dry ice, …
2. Change mechanical or surface properties of water jet	increase pressure, add abrasives, …
3. Change electromagnetic properties of water jet	electrolysis, electromagnetic fields, …
4. Change the temperature of water jet	combine water and steam cleaning, …
5. Change chemical properties of water jet	altering the pH, enzymes, biocide, …
6. Pre-arrange water jet so it can come into action at the most convenient position and without losing time	optimal angle and pressure for areas under waterline, propeller and rudder
7. Divide water jet into several independent parts	nozzle with multiple outlets, …
8. Design the water jet to be dismountable	better accessibility of ship elements,…
9. Replace the water jet by several smaller units	independent jets, synchronized jetting
10. Use water jet in form of solid particles or granules	re-use particles in water stream,…

4 CONCLUDING REMARKS AND OUTLOOK

The overall results of the experiments confirm that the proposed method for the automated formulation of TRIZ-based elementary solution principles can significantly improve the quantity, variety and, consequently, the quality of idea generation, even if its practical results still require further quantitative validation. Extension of the knowledge base, automated problem formulation, development of adaptive multi-objective optimisation algorithms for automated idea generation and concept creation, systematic identification of limitations and refinement of the method are the topics of the current research work. The paper also supports the assumption that automated TRIZ-based ideation will positively influence the frequency of TRIZ use by newcomers and contribute to a wider dissemination of TRIZ invention techniques in practice. The author would like to suggest that

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professionals, inventors, patent engineers, innovation facilitators and engineering educators should consider incorporating this approach into their professional activities. The proposed approach to automated ideation can be used individually or in creative meetings and brainstorming sessions. It also helps to improve internal and external crowdsourcing of ideas and can be used to check the completeness of invention claims in patent applications. The approach allows specialists, engineers and students to explore the significant part of the TRIZ inventive knowledge base according to their creativity skills, technological experience and available time without extensive preparation or training. Furthermore, in the near future, AI-based technologies can significantly improve automated ideation by processing a large number of applied elementary solution principles.

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