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Preliminary studies on human approaches to inventive design tasks with a TRIZ perspective

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Abstract

Among the open research issues in the field of inventive design, a careful attention should be dedicated to the definition of means to measure and improve the efficiency of educational and training processes as well as to assess the benefits of the introduction of TRIZ expertise into R&D and engineering teams. In fact, while TRIZ methods and tools have gained a certain acknowledgment as a means to improve problem solving and inventive design skills, a dominant model about its introduction in an industrial organization is still missing. The paper presents a study aimed at measuring the impact of TRIZ learning (tools and logic) with respect to individuals' talent. The paper proposes an original methodology to investigate human approaches to inventive design tasks: definition of the test (Sample group and control group, Inventive problems); evaluation criteria (Aptitude to follow a logical problem analysis path; Aptitude to explore various perspectives of the problem; Aptitude to generalization; Overall correctness of the problem analysis task; Completeness of the analysis); comparison and correlation criteria (Pearson correlation). The proposed investigation methodology is clarified through the description of an exemplary application in design courses at Politecnico di Milano and at the Università di Firenze.

"Keywords: inventive design; problem solving; human behaviour"

1. Introduction

The 2009 survey accomplished by ETRIA on the TRIZ practitioners' perspective about TRIZ usage and benefits [1] revealed, among its relevant insights, that 70% and 90% of the repliers have directly appreciated a higher number and better quality of the developed solutions respectively. Nevertheless, TRIZ teachers, trainers and executives willing to introduce systematic practices for inventive problem solving regularly face high percentages of students/employees who skip absorbing a TRIZ way of thinking and stop adopting any TRIZ tool just after the training phase.

Therefore, measuring the impact of TRIZ education and training on the concrete capability to solve inventive problems faster, better and more exhaustively is a critical issue not just for the purpose to monitor and improve TRIZ educational practices, but most of all to plan the implementation of new TRIZ-based problem solving teams and to assess and customize their management according to the specific needs and resources of the organization.

Unfortunately, a direct measure of these figures is a tough and lengthy task, since it involves the evaluation of the whole product development process, possibly taking into consideration several innovative projects which typically occur within months if not years.

Within this context the authors intend investigating the possibility to define and measure indirect parameters of problem solving efficiency that could provide faster indications for a quick definition of suitable adaptations and corrections. The study is aimed at addressing two research questions: How to compare individual talent (in terms of thinking skills and aptitudes) with the impact of TRIZ learning (tools and logic)? Are there any correlations between individual thinking skills and the most suitable tools to improve problem solving capabilities?

This paper proposes an original approach to analyze and compare individuals' aptitude to problem solving, in a TRIZ perspective, with respect to natural (birth given) and acquired (after training) skills. The performed analysis also attempts to distinguish between spontaneous (i.e. assimilated) or induced (solicited by explicit questions) behaviours in terms of correctness and completeness of problem analysis, exhaustiveness of system thinking and their correlations with TRIZ education.

Therefore, the next section positions the proposed research with respect to complementary relevant studies on the analysis of designers' behaviour. The third section describes the approach proposed by the authors to provide a first response to the proposed research questions. The fourth section details and discusses the results of an exemplary testing campaign conducted with two samples of students from Politecnico di Milano and the University of Florence, both constituted by MS mechanical engineering students at the last year of their curriculum, but with a different level of acquaintance with TRIZ fundamentals.

2. State of the Art

The TRIZ community is debating since its earliest meetings and conferences about the impact of TRIZ training on problem solving capabilities, with dedicated studies and reports since 1979, as documented in [2]. Altshuller used to collect, through private mail exchange, feedbacks of colleagues and students, registering the number of patents (author's certificates in the former Soviet Union) achieved after TRIZ training in comparison with the past inventive activity of the same author. When data were available he also used to measure the profitability of innovations e.g. in terms of cost savings. A few examples of these documents are available on [3]. Despite the ultimate goal of problem solving for an engineer is indeed producing revenues through IP value generation and cost savings, these metrics strongly depend on context factors which go beyond individual problems solving skills.

In the English literature, most of the papers reporting the impact of TRIZ qualitatively describe the obtained benefits and/or present exemplary case studies developed by the TRIZ trainees. Besides, these contributions do not make any attempt to produce a quantitative assessment, nor try to investigate the relationships between individuals' talent and the influence of TRIZ tools on problem solving cognitive processes.

A first attempt to measure the impact of a TRIZ course has been proposed by Belski in [4], where the assessment is based on students' self-confidence about problem solving capabilities before and after TRIZ training. This student survey approach, further developed in [5], brings relevant insights about students' perception of their abilities in problem solving. It is also claimed that TRIZ thinking tools impact students' problem solving skills much more than discipline-based courses. Besides, it can be argued that such skills are not directly measured, since the assessment is substantially based on students' feedbacks.

With a complementary perspective, one of the authors in [6] had analyzed students' behaviour at using TRIZ tools in different case studies, looking for correlations between the degree of education, the formal correctness of tools application and the usability of the outcomes of the case studies. Still the authors, within a project aimed at developing a computerized dialogue-based system capable to coach an inexperienced designer in the analysis of inventive problems [7] have recently faced the need to measure the advantages of the proposed system with respect to design tasks performed by the same people without any supervision. The promising results achieved have pushed the authors to the development of an updated implementation of the methodology [8] which enhances the recourse to a TRIZ multi-screen search for resources both for contradiction formulation and problem solution.

The assessment criteria adopted for measuring the impact of the computerized system have been further developed, as described in the following section, in order to thoroughly investigate the mechanisms behind the application of TRIZ concepts within a problem solving session.

Beyond the TRIZ literature it is worth reminding that there's a quite intense debate about the possibility to improve creative thinking versus schools of thought anchored to a vision as a God-given ability, something an individual either possesses or does not possess, but can only be slightly learned or improved. An interesting investigation is proposed in [9], which demonstrates the potential of inventive heuristics and the benefits of their introduction since the youngest age of the pupils. The paper also observes that these heuristics shouldn't be considered as rigid algorithms, since the most effective results are obtained if any individual develops his/her own thinking method.

An important source of inspiration for the present work is the approach to the analysis of design protocols proposed in [10]: despite the authors have not assumed in this study Gero's Function - Behaviour - Structure ontology as a reference framework, students' problems solving processes have been investigated through a segmentation of the analysis task into elementary steps and by analyzing their thinking path through a pre-defined coding in order to highlight the most interesting TRIZ-related issues as described in the following chapter.

3. Methodological approach

The authors have defined a tailored investigation path aimed at investigating which individuals' capabilities and features of the TRIZ thinking process better support a correct problem analysis task within inventive design. Table 1 illustrates the proposed steps to achieve preliminary outcomes regarding the relationships across individual approaches and skills in inventive problem investigation. Each step is widely discussed in the following subsections.

Table 1. Methodological framework to investigate individual problems setting and problem solving capabilities

| Task | Tools and criteria | (partial) Results |
|--|--|---|
| 1 - Definition of the issues relevant for inventive problem analysis | ARIZ logic, OTSM-TRIZ models | Set of features related to individual aptitudes and skills within inventive problem analysis process according to a typical TRIZ approach |
| 2 - Proposition of the test and of the case studies | Analysis of Design Protocols ARIZ steps (Parts 1-3) Criteria and evaluation parameters defined at step 1 | Reference test (list of questions regarding problem analysis) and a set of case studies related to inventive problems |
| 3 - Testing experiment and correlation analysis | Test rules and statistical analysis criteria Pearson correlation analysis | Observations about the correlation degree among the parameters defined at step 1 Evaluation of the role played by TRIZ education |

3.1. Definition of the issues relevant for inventive problem analysis

Since the proposed research is aimed at mapping the role played by TRIZ thinking features in the execution of a correct problem analysis, the objective of this task is to define suitable parameters by which to assess the impact that TRIZ tools have on the individual capabilities regarding inventive problem analysis. The attention has to be focused on those features belonging to TRIZ body of knowledge that substantially differ from other problem solving skills more conventionally mapped as for example those surveyed in [11]: convergent/divergent thinking; preferred learning style; quality and originality of problem solving outcomes.

The authors have essentially individuated the need to map the testers':

- unconscious aptitude to follow a systematic problem analysis process (as in ARIZ),
- unconscious aptitude to describe the phenomena by concepts that are not constrained in the specific problem context (as with the Hill model),
- unconscious aptitude to observe the elements and features that interact with the system (in hierarchical and temporal logic as with the System Operator),
- unconscious aptitude to formalize the elements that ground a contradiction, i.e. control and evaluation parameters.

Moreover, all the above-listed aptitudes should be compared with the individual capability in carrying out a correct and comprehensive problem analysis.

3.2. Proposition of the test and of the case studies

The task is related to the definition of a suitable test to assess the individual aptitudes defined at the first methodological step. The authors propose a repeatable experiment, in order to allow other scholars to perform similar tests aimed at sharing and comparing the obtained results. The experiment was thought to be performed through administering a set of written questions regarding the most relevant aspects of an inventive problem, which stimulate the individual cognitive approach towards the analysis of a technical

system. Any inventive problem can be employed as a case study to be administered and analyzed through the reported list of questions.

The provided answers and the sequence, through which the questions are faced, supply relevant indications about the parameters to be investigated. More in detail, the list is composed by the following 6 questions (labelled respectively as A, B, C, D, E, F) aimed at describing the overall problem emerging in the system, its main function and goal, the conflicting issues that characterize the case study:

- A. Synthetically describe the core problem of the technical system under investigation (maximum 30 words).
- B. What technical function should be carried out in order to satisfy the needs of the end users employing the device under study?
- C. Remark who or what undergoes the modifications carried out by the technical system that is described.
- D. Describe the most impacting undesired/harmful effect/condition (including underperformances and further missing functions) that emerges in the described situation.
- E. With reference to the undesired phenomenon or unsatisfactory aspect of the case study, clarify who or what mostly perceives the bad consequences that arise.
- F. Which element(s) cause(s) the problem described in the case study? Clarify if such component performs any positive function.

As mentioned above, it is suggested to deliver these questions to the students in a random order and to invite them first to define the most suitable sequence of questions to be addressed and then to answer. In fact, it is possible to recognize three small clusters of questions which are supposed to be answered together and not jumping from one subset to another: questions B and C are indeed related to the description of the main useful function of the system under study; D, E and F are focused on the undesired effect, analyzing in details the negative action, its carrier and its receiver; question A is somehow independent from the others.

The path followed by the students is considered good if the block dealing with the main useful function and the group of questions facing the undesired effect are considered separately in a logical order (B-C and D-E-F or F-D-E), as well as the query A comes out at the beginning of the analysis as an introduction to the problem or at the end of the investigation as a summary of the raised issues. An intermediate score is assigned to those testers who just correctly separate the blocks A, B+C, D+E+F. Besides, a student mixing questions from different clusters will gain the lowest score in terms of logic of the problem analysis path they tend to follow.

A second parameter here proposed for the analysis measures the aptitude towards the generalization of the provided description and it is evaluated by surveying the contents of each answer with respect to the text that describes the case study. Each answer has the highest score if the tester describes the problem employing terms depicting the relevant system features without mentioning the system itself, thus producing a description by attributes with minimal references to specific system elements, which result capable to illustrate situations referable to different contexts and industrial domains. An intermediate score is assigned whether the tester introduces more general terms than those introduced in the provided text, e.g. through the employment of hyperonyms (such as metal instead of iron, animal instead of dog, etc.). The lowest score is attributed if the provided answer includes just words introduced along the text or their closer synonyms.

The aptitude to explore various levels and conditions of the system, its environment and components is evaluated by assessing the number of detail levels (i.e. SuperSystem, System, SubSystem) and operation time intervals (i.e. Past, Present, Future) according to the classical multi-screen view of the System Operator framework, involved across the description provided by answering the questionnaire.

The correctness and completeness of the analysis is estimated by considering how well the tester has reported across the questionnaire answers the information that is crucial to problem solving, through which to form the primary problem representation [12]. The evaluations provide a high, intermediate and low score.

Eventually, the aptitude to introduce the terms of a contradiction is evaluated with reference to the basic overview of the problem that should be provided through the answer to the question A. The highest score is attributed if a control parameter and two conflicting evaluation parameters are delineated, even if in a narrative form. An intermediate score is assigned to those answers capable to focus on at least two of the aforementioned items (typically two conflicting engineering characteristics, or in the form of positive consequence on a certain evaluation parameter by introducing a certain modification in a design variable but without mentioning the negative consequence on another system feature). In the other cases the lowest score is supplied.

3.3. Testing experiment and correlation analysis

In order to pinpoint the contribution of TRIZ teaching in the aptitude towards problem analysis tasks the test has to be administered to two different groups of experimenters (a sample group and a control group), differing just with regards to the treatment whose effect has to be evaluated. The tests have to be performed under the same administering conditions (e.g. written topic under investigation and singular leaves in a random order containing one the six questions on which to answer).

After the tests are conducted and the results analyzed, the data are gathered in order to assess the links among the involved parameters and the role played by TRIZ fundamentals teaching. Thus, the arrays of scores related to each evaluation parameter are compared by employing Pearson correlation criteria [13], which express the extent two sets of parameters are directly related. In the current research the Pearson correlation method is thus employed with the aim of individuating dependencies among the recalled evaluation parameters (logical path, generalization, levels exploration, analysis correctness, contradiction formulation).

4. Application of the methodology and outcomes

4.1. Description of the performed test

The first exemplary testing activity is built upon manifold experimental rounds carried out by Master Degree students in Mechanical Engineering. All the pupils have similar background and, with regards of experience in inventive design, they differ predominantly in terms of their knowledge about TRIZ notions. With reference to the objective of the research the thorough set of carried out tests is split according to the background of the testers, whereas the control group is constituted by the students unaware of TRIZ basics and systematic problem solving. As a whole the test was performed by the following groups, both representing a sample of convenience:

- the control group constituted by 23 students attending the course in Product Development and Engineering at Università di Firenze;
- a test group composed by 24 students attending the courses in Methods and Tools for the Innovation at Università di Firenze and in Modelling and Simulation Methods for Product Development Processes at Politecnico di Milano, both after 32 lecturing hours on TRIZ fundamentals and systematic problem solving (to be considered a short introductory course).

The questionnaire presented in section 3.2 has been administered to each student, delivering the leaves containing the queries in a random way, in order to avoid any bias towards the logical path followed for

answering. The whole testing campaign encompasses the analysis of three industrial examples, allowing therefore to appreciate the main differences in the results according to a specific topic. The assigned case studies, thoroughly reported in the Appendix, concern:

- case 1, the wear of the fringes covering the entry and the exit of a X-ray inspection system for foodstuff;
- case 2, the heat losses of anodizing tanks that have to allow the introduction of aluminium beams to be treated;
- case 3, the difficulties to regulate the inclination of the blade of a circular saw according to different cutting exigencies.

However, due to constraints related with the organization of the University courses, the topics weren't completely randomly assigned and just the case 1 was analyzed by students belonging to both the testing samples.

The described experiment allows to preliminarily evaluate the links among individual capabilities and unconscious aptitudes in terms of the issues recalled in Section 3.2: such estimation can be performed by taking into account the overall sample of testers, thus delineating general approaches regardless the students' background (see 4.2). Taking into account the same all-comprehensive sample, a further parameter depicting the individual involvement in some TRIZ course (getting value "0" for the sample group and "1" for the other testers) has been introduced. In such a way the correlation analysis has led to the identification of further benefits emerging by basic education about systematic problem solving (see 4.3). Such analysis can be better performed with reference to the testers that have analyzed the case study 1, since such subset presented no bias referable to the specific problem and its description; nevertheless, it is worth to admit that these results are affected by a lower reliability due to a smaller sample size.

The analysis of the two groups in a separate way, allows to highlight the different patterns followed by each sample and sheds light about further particularities referable to TRIZ education (see 4.4).

Additionally a further examination regards observations related to the single case studies, viable to highlight the variability of the outcomes according to the specific problem to be addressed, as illustrated in 4.5.

Thence, each collection of answers provided by the students has been analyzed in order to assess the parameters defined in 3.1 according to the criteria defined in Section 3.2. The correlation degree among these parameters has been evaluated by using the Pearson correlation criteria, as recalled in section 3.3, taking into account both the overall sample of experiments, the control and test groups, the subsets pooled by the same industrial problem.

4.2. Correlation analysis

As depicted in Table 2, the first outcome of the experiment lies in the evidence that, as a whole, no parameter is negatively correlated with other matching issues. However the links among the various measures of individual aptitude do not always show high Pearson correlation values, ranging from 0,07 (logical path vs. generalization) to 0,46 (correctness vs. levels exploration and correctness vs. generalization). By an overview of the results the role of individual skills in problem analysis (measured through the parameter concerning the correctness of the analysis) seems to be consistently influent in determining the aptitudes related to the other coefficients. A great impact is played also by the individual approach in exploring manifold levels of the systems, which seems to be a key capability in the investigation of inventive problems.

Table 2. Overall correlations among individuals' aptitudes and skills

| | TRIZ Course | Logical path | Levels exploration | Generalization | Correctness | Contradiction |
|--------------------|-------------|--------------|--------------------|----------------|-------------|---------------|
| TRIZ Course | - | 0.13 | 0.06 | 0.21 | 0.33 | 0.11 |
| Logical path | | - | 0.20 | 0.07 | 0.18 | 0.18 |
| Levels exploration | | | - | 0.34 | 0.46 | 0.29 |
| Generalization | | | | - | 0.46 | 0.17 |
| Correctness | | | | | - | 0.33 |
| Contradiction | | | | | | - |

4.3. Contribution of TRIZ training

With reference to the parameters described in Section 3.1, TRIZ training plays a positive role in influencing the various unconscious aptitudes, as shown in Table 2. Indeed, it is worth to highlight that both the test groups have been assigned the same set of questions which includes neither specific TRIZ terminology, nor any suggestion about suitable TRIZ tools to produce the most appropriate answers. Surprisingly, a short term TRIZ training has a marginal impact with respect to the instinctive tendency to explore different detail levels and resources pertaining the overall system lifecycle.

Looking at the correlation of TRIZ education with the capability to follow a logical path and the aptitude to identify contradictory issues in the problem scheme, a more remarkable influence of TRIZ teaching is observed: the Pearson coefficients assume the value 0,13 and 0,11 respectively, with even higher values registered in case study 1 (0,33 and 0,22).

Besides, not-negligible correlations subsist among TRIZ fundamentals awareness and the correctness of the analysis (Pearson coefficient equal to 0,33 for the overall experiment, 0,19 if considering just the problem about the X-rays). As mentioned above, due to courses constraints it was not possible to investigate more deeply the influence of the case study on the outcomes of the experiment.

4.4. Comparing the aptitudes of the test and the control group

The observations arisen from the comparison between the sample constituted by the students which have been introduced to TRIZ fundamentals (test group) and the control group, can be summarized as follows (see Table 3):

- for the students submitted to the teaching of TRIZ basic knowledge, the correctness of the problem analysis exercise is noticeably correlated with the aptitude to generalize the description of the systems and to illustrate the parameters for formulating a contradiction; with regards to the control group the skill of properly investigating the problem is mostly connected with the approach in the levels exploration and in the generalization process (i.e. to the personal talent, rather on the acquired methodological tools);
- with respect to the students belonging to the test group the logical path which is followed presents an appreciable relationship with the individual aptitude to formulate contradictions; the analyzing process

shows marginal correlation with the other parameters, even a weak reverse correlation with the generalization aptitude;

- for both samples the correlation between the levels exploration and the generalization of the problem description is considerable, in each case greater for the test group;
- the dependence between the parameters regarding the levels exploration and the contradiction formulation is appreciable for both samples, slightly greater for the control group;
- within the control group, the aptitude towards the contradiction definition is poorly correlated with the other parameters, but the levels exploration aptitude; the students that have received TRIZ training show a remarkably different behaviour, given the considerable link of such coefficient with the logical path and the correctness of the analysis.

Table 3. Correlation coefficients of individuals' aptitudes and skills for the test (underlined) and the control group (italic)

| | Logical path | Levels exploration | Generalization | Correctness | Contradiction |
|--------------------|--------------|----------------------------|-----------------------------|----------------------------|----------------------------|
| Logical path | - | <u>0.20</u> <i>0.19</i> | <u>0.21</u> <i>-0.15</i> | <u>0.12</u> <i>0.18</i> | <u>0.26</u> <i>0.08</i> |
| Levels exploration | | - | <u>0.41</u> <i>0.27</i> | <u>0.26</u> <i>0.59</i> | <u>0.22</u> <i>0.34</i> |
| Generalization | | | - | <u>0.37</u> <i>0.46</i> | <u>0.08</u> <i>0.21</i> |
| Correctness | | | | - | <u>0.58</u> <i>0.10</i> |
| Contradiction | | | | | - |

4.5. Outcomes according to the analyzed problems

The examination of the single case studies reveals a strong variability of the correlations among the investigated parameters. The extent of the poor repeatability of certain links jeopardizes the predictability of the actual nature of certain dependencies. Through the separate analysis of each case study it is possible to reject the hypothesis of generalizing the essence of the following correlations:

- logical path vs. generalization;
- correctness vs. generalization;
- correctness vs. contradiction;
- generalization vs. levels exploration.

However the variability of the previous listed interdependencies can be explained on the basis of the testers' background, as highlighted in Section 4.4. On the other hand, some correlations show a good degree of stability as different problems are considered. More specifically:

- levels of exploration vs. logical path presents permanently a direct correlation, although the extent of such correlation results modest;
- levels of exploration vs. contradiction shows a direct correlation at a significant extent.

5. Discussions

The described methodological proposal represents a preliminary approach dedicated to the assessment of the individual aptitudes and capabilities in facing an inventive problem analysis task. As recalled, the

absence of acknowledged models to extract, within engineering design field, the main relevant factors related to TRIZ thinking influencing the cognitive processes during problem-solving activities, has pushed the need to introduce an original method of investigation. In such preliminary work, the authors have concentrated their efforts mainly on the definition of the overall framework on which to ground the logic of investigation. According to this objective, some aspects related to the pertinence and completeness of the defined evaluation parameters have not been carefully investigated so far. Moreover the adopted correlation model requires further investigations in order to verify its appropriateness in highlighting the existent relationships. This implies that the set of measured evaluation parameters could result incomplete for a tailored examination of design practices and patterns, even from the viewpoint of analyzing key cognitive aspects of problem solving with TRIZ. Additionally, the estimation of the parameters extents could be affected by biases regarding the measuring criteria described in Section 3.2 and concerning subjective evaluations.

Despite such limitations, the outcomes arising from the current research are capable to establish preliminary relationships among capabilities and aptitudes related to the investigation of inventive problems, with a particular focus on those issues that characterize TRIZ way of thinking. The impact of TRIZ basics learning is also widely investigated. The results are affected by two major flaws, consisting in the limitation of the sample size within the wide scope of the survey and in the poor repeatability of the correlations according to different analyzed case studies. However some evidences emerge with a particular emphasis on the key role played by certain features in the problem analysis process.

At first, TRIZ training has demonstrated to positively influence the performance of problem analysis tasks, given its observed contribution to enhance the correctness of the investigations. On the other hand the effect of tutoring about systematic problem solving results to be weak with regards to unconscious individual aptitudes towards the other parameters recalled in section 3.1. The motivations of this matter of fact could be due to the limitation of the lecturing hours, that does not allow to deeply assimilate TRIZ thinking process. This hypothesis is supported by the positive evaluation of the proficiency results of the pupils involved in TRIZ courses when explicitly asked to apply TRIZ techniques, focusing more specifically on those concerning the capabilities of performing a correct analysis path, the contradictions formulation, the generalization, the multi-screen exploration.

With reference to the investigated evaluation parameters, through which to describe the problem analysis, the exploration of several levels of the systems results to be a pivotal key feature in the design task. Incidentally the contribution of TRIZ teaching to this aspect is the most marginal if no explicit requests are made towards the use of System Operator; this means that a particular attention should be paid in developing students' skills regarding broad-scheme thinking.

Interesting insights can be drawn with regards to the aptitude of generalizing the problem description through the provided answers. The correlations of such issue with the other parameters have shown great variability according to the faced industrial case studies. In the authors' vision this circumstance sheds light to the fuzziness of abstracting processes in design tasks and to their limited performance in achieving valuable results when not systematically organized and directed. In order to validate the advanced hypothesis, detailed considerations should be drawn by relating together more than two parameters.

6. Concluding remarks

The original contribution of the paper is represented by a preliminary methodological proposal by which to support the investigation of relevant features related to the individual approaches in problem analysis tasks. The achieved results, if confirmed by wider testing activities, are capable to point out which individual capabilities to stress in order to enhance the inventive design initiatives. Given the

testing sample, constituted by Master Degree students, the specific outcomes of the survey are mostly relevant within engineering education and TRIZ fundamentals training.

Besides, the results of further experiments conducted with the presented methodology could be exploited in order to outline the definition of appropriate working teams, both in the academics and in the industry, whose members are characterized by complementary backgrounds and individual skills. Thus, the present work can represent a preliminary contribution even to the field of collaborative problem solving with the aim of fostering creativity in inventive design, as with [14]. Tailored tests involving groups rather than individuals are viable to provide further indications in this sense.

The current research has envisaged multiple directions of development which require further investigations. At first, measures have to be taken in order to overcome the limitations recalled in the previous section, with a particular focus on those related with the methodological approach and the process for the parameters evaluation. Then, novel tests should be carried in order to statistically assess the emergences of the preliminary experiment. Further on, statistical instruments and other acknowledged models could be implemented in order to characterize the interplay among the evaluation parameters, hence building a comprehensive representation of design aptitudes (e.g. through Artificial Neural Networks).

Whoever wishes to repeat the test and to integrate the obtained data is kindly requested to contact the corresponding author of the present paper. Alternative approaches and experiments, aimed at exploring the key aspects of individual approaches leading to proficient problem solving tasks, would be beneficial to the current research, so to work on different outcomes to be compared against.

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Appendix A. Test cases

A.1. Case 1

An X-ray inspection system checks the presence of foreign bodies inside foodstuff, in order to select and remove non compliant items. In order to protect the workers and onlookers from X-rays, the device is internally lined by lead layers. Obviously the input and outputs for the items to be inspected cannot be screened in the same way. Such inputs and outputs are configured as rectangular windows that allow the flow of the conveyor belt and consequently of the foodstuff. The protection of the windows is performed by curtains with fringes, which embed the lead layers viable to absorb the X-rays. The external shell of the fringes is usually made of a polymer. The needed flexibility of the fringes doesn't represent any problem, due to the extreme ductility of the lead; once the item to be examined has crossed the passage, the curtain elements come back by themselves to their position.

However each object impacting the curtain produces wear. The fringes are normally replaced once a year, but in some cases the substitutions are necessary within few days. The items causing the greatest wear are the lollipops. Arrays of 3 lollipops are carried inside the inspection system, with the sticks being fitted in a support moved by the conveyor.

A.2. Case 2

The aluminium is subjected to the anodizing process in order to increase the resistance against corrosion, wear and abrasion, as well as the surface hardness. The workshop of a company that produces aluminium beams comprises an array of anodizing tanks. The average dimensions of the tanks are 3 m in height, 4m in length, 1m in depth. The tanks contain cleaning acids and other chemical substances meant to work as fixing agents. Some tanks must be kept at the temperature 96°C.

A suspended tray conveyor catches the holders on which the beams are hanged and moves them from one tank to another with the variable pace of 5-20 minutes. The problem concerns the conservation of the higher temperatures of the pools, minimizing energy waste, avoiding the usage of lids that would provide complications for the movement of the conveyor.

A.3. Case 3

Circular saws are commonly constituted by a housing, that hosts the engine coupled with the circular blade, and a base mounted on the housing itself to support the saw on the piece to be cut. The base is mounted on the housing in such a way to allow the turning movement around a horizontal axis, so to adjust the inclination of the blade with respect to the base, according to the desired cutting angle. The range of the adjustment angle is commonly 45°; as a consequence the relative angle between the blade and the base can vary between 90° and 45°. However it is often necessary to perform different cuts, that require inclinations until 38,5° and thus needing an adjustment range of 51,5°. The adjustment mechanism includes the base with a reference hinge (around which to allow the turning movement of the housing and the rest of the saw), a connection beam with an eyelet for the adjustment, a blocking nut. The ends of the eyelet act as a stop for the adjustment.

The most common cutting angles (90° and 45°) have to be easily and accurately adjusted. However eyelets with a range greater than 45° (like those of the saws allowing the cuts until 38,5°), don't allow to position the blade at 45° with respect to the piece in a quick and accurate way.