TEACHING AND LEARNING DESIGN METHODS: FACING THE RELATED ISSUES WITH TRIZ

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ABSTRACT

Design methods are claimed to support designers but, although they are largely taught in academia, their industrial uptake is still lacking. Many reasons have been identified about this flaw and some potential suggestions have been proposed and discussed in literature to overcome the problem. However, a further evidence is that although many students learn such methods from years, they partially or totally abandon the learned methods in their professional careers. This could partially explain the gap between academic and industrial diffusion of design methods. Literature provides suggestions for improving the learning experience of students but different didactical contexts may need more tailored solutions. The work shown in this paper exploits the problem solving potentialities of the TRIZ toolset to provide hints for improving a course focused on teaching a systematic conceptual design method. A set of suggestions has been obtained together some guidelines for applying the considered TRIZ tools to other didactical contexts.

Keywords: Creativity, Design education, Design learning, Design methods

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1 INTRODUCTION

The interest towards the complex and multifaceted mechanisms behind the design process led scholars to perform experiments and multidisciplinary studies for supporting practitioners, firms and companies in fulfilling the evolving needs of humanity in a more efficient way. Accordingly, a multitude of design methods have been proposed to support the different activities characterizing the design process (Van Boeijen *et al*., 2014), which operate in different ways and at different levels (Badke-Schaub and Voute, 2018; Wynn and Clarkson, 2017). However, literature highlights that methods from academia, although acknowledged as relevant tools to stimulate creativity and organize the design process, still suffer a poor diffusion in industry (e.g. Eder (1998); Geis *et al*. (2008); Tomiyama *et al*. (2009)). Several hypothesis have been formulated by scholars about the reasons behind this lack, and also many insights have been collected to improve methods' diffusion (Guertler, 2018; Reiß *et al*., 2017) but the issue is still open. Nevertheless, design methods are largely diffused in academia to teach design therefore academic courses still represent one of the most promising channels for methods diffusion, because today's students are likely to become the designers of tomorrow. However, learning and applying design methods are very hard tasks, especially when the taught methods require to compels the thinking styles of students along more systematic and structured processes (e.g. that of Pahl *et al.* (2007)). Moreover, the lack of a comprehensive industrial diffusion can affect students motivation in learning and using academic approaches (Gudur, 2016), also because many past successful products have been developed without an evident contribution of such methods (Geis *et al*., 2008). Six years of authors' experience in teaching systematic approaches for conceptual design confirm these evidences. In fact, students' opinions collected during these years highlighted that, on the one hand, students acknowledge interesting advantages of the learned methods but, on the other hand, they perceive learning and application like a non-sufficiently justified workload overall. Consequently, the authors believe that if teachers are unable to comprehensively overcome this problem, students will continue to abandon methods partially or totally in their future careers. In other words, it is necessary to improve the benefits perceived by students ("what the methods can do for me") and to reduce the efforts spent to learn and apply methods.
The identification of potential solutions to meet the objective requires the analysis and the resolution of several problems related to teaching and learning processes. Among the different techniques available in literature, authors infer that the toolset belonging to the TRIZ body of knowledge (Altshuller, 1984) could provide a useful support for that purpose, although TRIZ was originally conceived for technical problems. Accordingly, this paper presents the application of a subset of TRIZ tools for extracting potential suggestions to improve an academic course focused on teaching a specific design method. In particular, after introducing the problem (Section 2), Section 3 shows the adopted tools and the methodology followed for their application. The application to the case study is shown in Section 4, where a set of suggestions is presented for the considered course. Discussions and conclusion about the achieved results and the related limits are reported in Section 5, together with potential research hints and impact expected from this work.

2 BACKGROUND AND PROBLEM SPECIFICATION

The problem of the industrial uptake of academic design methods constitutes one of the most recurring debate from years (Eder, 1998; Frost, 1999; Tomiyama *et al*., 2009). Among the possible causes behind the lack of diffusion of methods in practice, Jagtap *et al*. (2014) highlighted that also an insufficient training of methods can play a crucial role. Similarly, Geis *et al*. (2008) assert that one of the possible reasons is that methods are often not taught properly.
More recently, Guertler (2018) provided a comprehensive list of requirements that methods should fulfil to be accepted by industrial practitioners. The list summarizes four categories (Performances, Presentation, Process and Data Collection), and especially the "Presentation" provides many interesting hints that can be used also for improving the learning experience of students (e.g. "provide a process overview", "allow tracking or process status", "clarify required input and expected output", etc.). However, these requirements (or hints) have been extracted mainly from the industry point of view, while didactical considerations need to be formulated and discussed for a successful teaching and learning experience of design methods "in academia". Indeed, although facing the problem of industrial diffusion of methods can potentially provide useful suggestions in the short and middle

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term, as highlighted in the introductory section of this paper, students constitute a potential important resource to be exploited in the long term to permeate the industry.

To better motivate students in learning methods, there are several literature contributions providing useful knowledge and suggestions. For instance, it has been observed that substantial differences exist between experts and students in approaching design (Björklund, 2013; Ozkan and Dogan, 2013). Therefore, making students aware of the lacks of their design approach is certainly a first important step that could prepare them for a more efficient learning process. In particular, Cardella (2007) observed non-negligible differences between experts and novices in terms of problem scoping and information gathering. Moreover, it is acknowledged that while experts often rely in problem decompositions, students are not capable to perform this task without a sufficient teaching support (Song and Becker, 2014). As a further example, Barak (2013) observed that students involved in learning engineering and technology, need to acquire a certain procedural knowledge to understand problem solving approaches. Furthermore, while students often believe that mathematics is the language of engineering, it is important to show them that many other types of human cognition are involved in the design process (Dym *et al*., 2005). Consequently, students should be motivated to learn methods because methods provide a valid procedural support for novices to shorten the distance between them and the expert designers.

According to the above-introduced context, the authors' experience in teaching design methods (see Section 4 for further details) highlighted the following general problems, which require solutions in order to improve the experience of students in learning the taught method:

1. How to increase the advantages perceived from using academic methods?
2. How to improve the learning capabilities of students?
3. How to reduce the learning effort?
4. How to reduce the effort perceived by students in practical applications?
5. How to improve the learning quality of students?
6. How to improve the amount of information learned by students?

Problem 1 is focused on the possibility to allow students to better understand the advantages offered by the design method (perceived benefits). Problem 2 concerns the possibility to allow students to learn the method in a more efficient way. Similarly but in a dual formulation, Problems 3 and 4 concern the possibility to reduce efforts perceived by students. Eventually, Problem 5 and 6 are focused on the improvement of respectively quantity and quality of the information learned about the method.

To overcome the recalled problems, useful suggestions can be collected from the literature to better structure the didactical activities. For instance, it has been observed that the "teaming" (in particular, students working in dyads) affects the quality of design outcomes of students (Henderson *et al*., 2018). As a further example, it has been demonstrated the importance of comprehensive feedback from teachers, because they affect the correct use of divergence through the design process (Yilmaz and Daly, 2016).

Concerning the teaching approaches, the classical and maybe the most diffused one is characterized by frontal lessons alternated with tutorials and practical exercises (Cascini *et al*., 2017). In this case, text-based learning material constitutes an important part of the different media exploited for sharing knowledge to students. Accordingly, it has been observed that reading and studying theoretical bases of methods from books improve the problem solving skills of students (Atman and Bursic, 1996).

Other approaches exist, which can be potentially used for a more effective learning experience of students, as, for example, inductive approaches like problem-based learning (Northwood *et al*., 2003) or project based learning (Bell, 2010). Moreover, also the use of additive manufacturing technologies is claimed to be helpful and can also support creativity (Mantelet *et al*., 2018). However, certain circumstances may hinder a successful application of these approaches, e.g. when teaching fundamental theoretical knowledge is required to apply a specific design method but the available course time is not sufficient for performing both comprehensive theoretical lessons and purposeful practical applications.

Summarizing the background presented above, many hints can be extracted from literature but their general validity for the plethora of different didactical and ethnological contexts is unclear. In particular, different issues may hinder the applicability of the literature proposals. Consequently, tailored and context-specific solutions should be developed for both improving learning effectiveness and reducing learning efforts. However, testing different teaching approaches and/or improvement

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suggestions from literature in a trial-and-error way can be barely feasible, especially when there are very limited opportunities to test them.

3 EXTRACTING HINTS WITH TRIZ

3.1 Why TRIZ?

The generalized problems listed in Section 2 are often related each other, hiding a complex net of relationships that makes the problem-solving activity a difficult task. For instance, trying to solve Problem 3 (see Section 2) by reducing the theoretical burden of the course and leaving more space on practical activities leads to the reduction of the efforts perceived by students. However, without providing the sufficient theoretical foundations of the taught design method, it is impossible for students to learn and apply it, and then it is impossible for them to perceive the related advantages (thus turning back to Problem 1 cited in Section 2). In other words, the nature of the problems to be solved is conflicting since a solution to a problem leads potentially to create other problems. Such a kind of conflicting situations can be modelled by TRIZ in form of "contradictions", i.e. one of the key-concept of TRIZ Theory, which is acknowledged to provide valid support for innovative solutions development, troubleshooting and failure prevention, incident management, new products-services-business concepts definition and administrative/management conflict resolution (Souchkov, 2007). Therefore, TRIZ has been used in this research to deepen the analysis of the generalized problems listed in Section 2 and to define possible solutions by solving the underlying contradictions, making use of the tools briefly explained in the following sections.

3.2 Short introduction to the TRIZ tools used in this work

In order to allow the reader to understand the contents of this paper, a short introduction about the fundamentals of the considered TRIZ tools is provided in the following subsections.

3.2.1 Physical contradiction modelling

Problems in TRIZ can be formulated in terms of contradictions. More specifically, two kinds of contradiction exist: Technical and Physical. A Technical Contradiction (TC) occurs when two different Evaluation Parameters (i.e. the parameters used to evaluate the performances of the system) are in conflict with each other. Otherwise, a Physical Contradiction (PC) arises when two mutually opposed requirements on the same Control Parameter (i.e. the parameter the problem solver can manage) of the system are imposed. In particular, the contradiction model depicted in Figure 1 comes from a development of classical TRIZ, i.e. the so called OTSM-TRIZ, where OTSM is a Russian acronym that stands for "General Theory of Powerful Thinking" (Khomenko *et al.*, 2007). On the "right part" there are the two Technical Contradictions, and on the "left part" there is the Physical Contradiction.

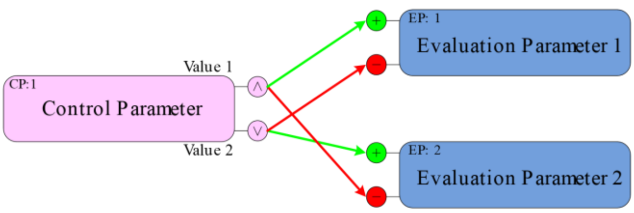

Figure 1. Physical contradiction model (Becattini et al., 2011)

3.2.2 Separation principles

The Separation Principles (SPs) are intended to be used for solving Physical Contradictions, and can be resumed as it follows (Gadd, 2011):

- Separation in Time: a solution is valid at one time, and the opposite one at another time.
- Separation in Space: a solution is good in one place, and the opposite one at another place.
- Separation on Condition: Opposite solutions in the same place at the same time. One solution for an element, the other solution for another element.
- Separation by System: Separate solutions by scale; switch to an inverted system; switch to another system.

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3.2.3 Inventive principles

Inventive Principles (IPs) were extracted from the analysis of thousands of patents, and formed a list of 40 principles for overcoming technical contradictions (Altshuller, 1984). They appear as short titles, followed by a list of simple examples for their explanation. A comprehensive description of them is out of the scope of this paper, but the reader can easily find the required information on almost all TRIZ textbooks (e.g. those cited in this paper) and/or on the world-wide-web (e.g. 40 Inventive Principles (2018)). A subset of IPs can be used as further stimuli to apply SPs (Gadd, 2011).

3.2.4 System operator

The System Operator (SO), or Nine Boxes, or Multiscreen, is a matrix (at least 3x3) where the initial problem (central box of the matrix) can be translated into eight different problems. The rows represent a hierarchical decomposition of the system from its parts to the environment where it is inserted. More specifically, the central row of SO represents the System, the bottom row represents the parts constituting the System (i.e. Sub-systems) while the upper row represents the elements of the environment to which the System belongs (i.e. Super-system). The columns represent the time dimension, i.e. the central column of the matrix represents the Present, the left column represents the Past and the right column represents the future. Therefore, even if the tool was originally developed for performing problem analysis, the SO can be used also for performing structured brainstorming processes (Frillici *et al*., 2015). Considering the SO shown in Figure 2, the cell number five can be interpreted as it follows: "what can be done to the system when the problem appears?". Similarly, the cell number one can be interpreted as "What can be done to what is surrounding the system, before the problem actually appears?". To give a generic example, suppose that a mechanical device produces the problem related to undesired noise. Cell number five of Figure 2 means "What can be done to the mechanical device in order to reduce the noise level?", while Cell number 1 means "What can be done to the environment surrounding the mechanical device, in order to prevent or attenuate the generation of the noise (e.g. room walls, doors, supports, etc.)?".

What can be done	Before the problem appears	When the problem appears	After the problem appeared
Outside the system	1	2	3
To the system	4	5	6
Within the system	7	8	9

Figure 2. Illustrative representation of the system operator (Gadd, 2011)

3.2.5 Size-Time-Cost operator

The Size-Time-Cost (STC) operator can be used for overcoming psychological barriers. It is in the form of a simple matrix (Table 1) where the three parameters (size, time and cost) can assume two opposite values: zero and infinite (Gadd, 2011).

Table 1. Size-Time-Cost operator

	INFINITE	ZERO
SIZE	1	2
TIME	3	4
COST	5	6

For example, considering Cell number one of Table 1, the questions to be formulated is "What can be done to solve the problem if the size of the system is increased to infinite?". Similarly, in Cell number six, the question to be formulated is "What can be done to solve the problem if the costs of the system must be reduced to zero?".

3.3 Methodological approach used in this work

Currently, there is not a standardized guideline for the selection of TRIZ tools according to the problems to be faced (Fiorineschi *et al*., 2018). Therefore, to build a repeatable methodological approach, some

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trials have been performed initially, to identify the most suited TRIZ tools for the considered case. To that purpose, many different options have been explored to face the problems listed in Section 2, according to some of the most diffused TRIZ textbooks (e.g. Salamatov (1999); Gadd (2011); Altshuller (1984)). Nevertheless, for the considered application (see Section 4), only a subset of tools appeared to be suitable (i.e. the tools presented in Subsection 3.2). As a result, the framework shown in Figure 3 has been formulated, in order to exploit the previously introduced subset of TRIZ tools. As shown by Figure 3 and Table 2, it is an algorithmic process made of three main modules: contradiction modelling, brainstorming guided with SO, and brainstorming guided with STC.

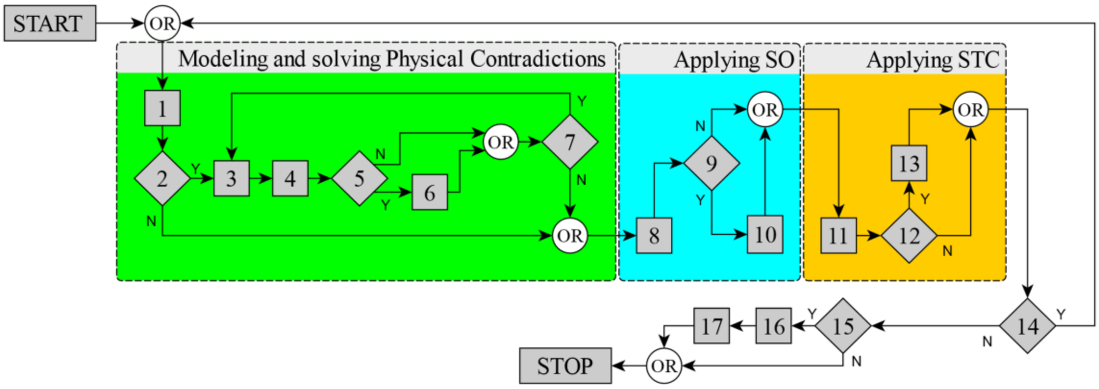

Figure 3. Framework proposed to exploit TRIZ tools for generating hints (see Table 2 for steps' descriptions)

Table 2. Description of the steps shown in Figure 3

STEP	Description
1	Identify the problems to be solved
2	Is it possible to formulate a contradiction?
3	Model the contradiction
4	Apply SP and IP to solve the contradiction
5	Any hint generated?
6	Store hints generated from the resolution of the contradiction
7	Is it possible to formulate other contradictions from the same problem?
8	Guided brainstorming with the System Operator
9	Any hint generated?
10	Store hints generated with SO
11	Guided brainstorming with the STC operator
12	Any hint generated?
13	Store hints generated with STC
14	There are other problems to be solved?
15	Any hint generated in the entire process?
16	Extract potential suggestions for course improvements (according to available resources)

In the specific case, the six problems listed in Section 2 constitute the outcome of Step 1. Then, the set of problems is analysed and (if necessary) reformulated to extract the contradictions to be solved (Step 2). In particular, Steps from 3 to 7 come from ARIZ, i.e. the Russian acronym for "Algorithm for Solving Inventive Problems", while the application of SO and STC tools does not differ from the normal procedure (see Section 3.2). The peculiarity of the proposed approach is the non-standard nature of the problems to be faced, since it is non-standard to applying TRIZ to improve the teaching and/or learning process of design methods.

After the application of TRIZ tools (Steps from 1 to 13), if hints have been generated, feasible suggestions (if any), are extracted according to the available didactical resources (e.g. course time, teaching staff, economical resources, etc.). To perform this last step, many selection procedures can be used, from unstructured ones, to well acknowledged structured procedures (e.g. selection matrices (Pugh, 1991)).

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4 APPLYNG THE TRIZ TOOLS TO A REAL DIDACTICAL CASE

4.1 Didactical context and observed issues

The proposed framework has been applied for an engineering course focused on teaching methods for product planning and conceptual design, attended by about 20÷30 students per year, and developed along three months. The course belongs to the study programme of the degree in Mechanical Engineering of University of Florence (Italy). More precisely, within the part dedicated to conceptual design (about 30 hours), 12 hours are dedicated to a specific conceptual design method, recently developed for overcoming the flaws of classical function decomposition and morphology (Fiorineschi *et al*., 2016). According to Fiorineschi (2018), the considered method is currently taught to provide some theoretical bases to students to correctly manage abstraction levels and avoid premature leaps to concrete solutions. Frontal lessons are alternated with interactive tutorials (where the teacher collaborate with students to perform some examples) and exercises, where groups of two or three students collaborate to develop a design project that is common to the entire classroom. In the latter case, the teacher supervises students and provides an aid whenever needed. Therefore, only 5 of the 12 hours are dedicated to frontal lessons, while the remaining time is for practice. Additionally, as final exam, teams composed by two or three students are asked to perform a design project independently (from product planning to conceptual design outcomes) by following the learned procedure. A single teacher performs the didactical activity, with no other available teaching staff.

A mandatory institutional didactical evaluation is performed by each student at the end of each edition of the course, in form of anonymous questionnaire. Moreover, authors asked to compile an additional and more detailed online survey, specifically developed for the considered course. Thanks to this information, it was observed that, according to Fiorineschi (2018), students perceive the advantages of the followed method and also understand the usefulness of the theoretical fundamentals needed for its application. Nevertheless, concerning the part about conceptual design, while students appreciate (and still want more) tutorials and in-class exercises, most of them find too much onerous to follow the design method for the final design project. In particular, after the identification of errors (e.g. incorrect application of the definition of function, unclear logical passages, etc.), they revealed to feel stressed in revising the theoretical part of their work (i.e. the conceptual representations of their designs).

4.2 Applying the proposed framework

According to the proposed framework, after the identification of problems (i.e. the list of problems shown in Section 2), physical contradictions should be formulated when possible.

However, notwithstanding the presence of six potential problems to be faced, by referring on the specific course and didactical context, only two contradictions have been extracted. The first one comes from considerations about the actual difficulties perceived by students, and the need to provide them with a detailed procedural support (Guertler, 2018). According to Figure 1, the CP is the “amount of theory” to be learned (a lot or a few), while the EPs are respectively the “detail of procedural support” and the perceived “learning effort”. For the considered method, the more the amount of theory the better the procedural support but the higher the perceived learning effort and vice-versa.

The second contradiction comes from the efforts that students perceive when working on the final project. More precisely, the CP is the “Method applied in the final project” (yes or not), while the EPs are respectively the “effort perceived by students” and the “understanding level” about the method. In this case, the presence of the final project allows students to better understand how the method works in practice, but implies too much efforts. Conversely, the absence of the final project obviously reduces the effort perceived by students, but also reduces their understanding about the method. To solve contradictions, SP and IP have been applied according to standard TRIZ practice (Altshuller, 1984; Gadd, 2011). A complete description of the application of these tools is not possible in this paper, due to length limits, but a representation of the contradiction models and the obtained hints can be found at this link: https://goo.gl/kSdKZs.

4.2.1 Applying SO and STC (Steps 8-13)

Each identified problem has been faced by guided brainstorming with both SO and STC. In the first case, the problem is inserted in Cell 5 of the SO (see Figure 2), and different formulations of the

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problem have been considered according to the other eight cells. Concerning STC, for each problem, both exaggeration (toward infinite) and minimization (toward zero) have been considered for each STC dimension. Unfortunately, also in this case a complete description of the application of these tools is not possible in this paper. However, the reader can find the compiled SO and STC at this link: https://goo.gl/kSdKZs

4.2.2 Analysing hints and extracting feasible suggestions (Steps 14-16)

Many hints have been generated with the proposed approach, but some of them were not compatible with the available didactical resources (e.g. more teaching staff needed), or with the actual possibility to change the overall engineering course (e.g. by shifting the course to other periods, or modifying other ones by introducing additional arguments). All the generated hints can be found at this link https://goo.gl/kSdKZs, together with the tools used to generate them. However, by comprehensive reflections about what could be actually feasible according to the available resources, the suggestions have been screened and reduced to those listed in Table 3.

Table 3. Feasible suggestions for didactical improvements

N	Exploited TRIZ tools	Suggestions
1	Contradiction 1 and Separation in Time (also from SO applied on Problem 1, Cell 1 of Figure 2)	Start providing some theoretical notions before the current course. For example, definitions about creativity, fixation, abstraction and function can be provided (in this case) to first year students.
2	Contradiction 2 and Separation in Space	Perform specific investigations to understand if students with different cognitive profiles perceive different types of difficulties (e.g. with KAI test (Kirton, 1994) to identify different profiles). Results could be useful for future improvements of both teachers and method developers.
3	Contradiction 2, Separation in Time + “prior counter-action” IP.	Identify a comprehensive set of recurring errors, show examples for each of these errors and clearly explain both consequences and how to avoid them.
4	Contradiction 2, Separation in Time + “periodic-action” IP.	Students working in dyads: one student applies the method while the other doesn’t. At the end of the task the students compare their results and discuss about pros and cons of the method. An additional task is assigned, where the students invert their roles.
5	SO applied on Problem 2, Cell 8 in Figure 2. (also from STC applied on Problem 6, Cell 6 Table 1).	Tactile sense of students can be used to improve their learning experience (e.g. by means of prototypes) (Wendrich, 2017). For example, LEGO blocks and Meccano could be used to build low-fidelity prototypes of the designed products.
6	SO applied on Problem 4, Cell 7 of Figure 2	Prepare video tutorials to allow students a better understanding about how the method should be applied. In this way, it is possible to overcome time limits imposed by available didactical resources.
7	SO applied on Problem 5, Cell 6 in Figure 2.	After the end of the specific course, a social group (e.g. a Facebook or a Researchgate page) can be created to keep students in contact with the teacher, and to form a community of people talking about the method. Feedback and comments could be useful for current students, ex-students, the teacher and the method developers as well.
8	STC applied on Problem 6, Cell 2 Table 1	Prepare didactical audio/video material to provide additional support to students about theoretical notions.

5 DISCUSSIONS AND CONCLUSIONS

The objective of the work presented in this paper was to apply problem-solving tools for both improving the benefits and reducing the efforts perceived by students when learning design methods.

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Accordingly, the framework proposed in Section 3 provides algorithmic instructions to apply a subset of TRIZ tools to reach the target. In particular, the generated hints are expected to be evaluated against the available didactical resources to obtain a set of feasible suggestions. The approach developed for the purposes of this paper has been applied to a set of identified problems (Sections 2), and eight potentially feasible suggestions have been formulated. Solutions 2, 3, 4 and 7 from Table 3, will be implemented in the next edition of the course, while the other ones require more time and resources to be applied (e.g. modification of other courses). Therefore, by applying TRIZ tools according the proposed framework, the problems listed in Section 2 have been tackled from multiple perspectives, thus allowing to break psychological barriers and to find different kinds of potential solutions. Actually, other hints have been generated, but some of them were very similar, while other resulted to be not feasible for the considered context. Besides the above-mentioned results, many limits can be observed in this work, and the most impacting one is certainly the absence of information about the actual feasibility and impact of the suggestions provided in Table 3. However, this limit paves the way for future research activities. Indeed, next sessions of the course considered in Section 4 can be upgraded according to the generated suggestions. Therefore, by comparing future feedback from students with the currently available ones, it would be possible to evaluate the actual impact of the suggestions (for the specific didactical context).

Another lack of this paper is due to the impossibility to comprehensively explain how the tools have been applied. However, in this case the reader can find the required support by relying on TRIZ literature, e.g. by starting from that cited in this paper. Also the selection of tools adopted in this work is affected by non-negligible limits, since it has been performed by relying only on the experience of the authors about both TRIZ and the didactical issues concerning design methods. Therefore, it is probable that the application of the framework shown in Section 3 to other didactical contexts could allow the identification of other TRIZ tools to be potentially used for this kind of applications. Moreover, other TRIZ practitioners could suggest different tools as well.

Nevertheless, the work shown in this paper provides a "methodological approach for solving problems related to academic learning processes of design methods", i.e. focused on the didactical/academic perspective. The efforts spent for performing the work presented in this paper are expected to be well-justified thanks to both short term and long term results. Concerning the short term, the suggestions proposed for the considered didactical context (Section 4) will be taken into consideration for improving the very next session of the same course. Concerning the long term, the proposal shown in Section 3 paves the way for future research aimed at the identification of tailored didactical materials and strategies, in order to offer improved experiences for students involved in learning design methods, according to the resources available to each specific teaching staffs. By improving the didactical experiences, it is expected to better motivate students in learning and applying design methods.

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