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OTSM-TRIZ Network of Problems for evaluating the design skills of engineering students

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Abstract

This paper aims at exploring the opportunities coming from the application of the OTSM-TRIZ Network of Problems as a means for mapping the design steps of engineering students coping with design problems. Both the design rationale and the design protocol can be analyzed to support the evaluation of the overall outcomes of students downwards a course on systematic design, considering both the ideas they generate and the process they follow for the ideation. The paper proposes a few improvements for the OTSM-TRIZ Network of Problems, so as to adapt it for such a purpose. Some demonstrations of the applicability of the proposed method are presented by means of two different design problems faced by groups of students having homogeneous levels of expertise and engineering skills. The results, got through a research method here detailed, highlight that the proposed approach allows the evaluators/analysts to carry out the time-demanding protocol studies with significant savings in time. Moreover, this model allows the definition of appropriate metrics to carry out homogenous and more objective evaluations among students.

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Keywords: OTSM-TRIZ Network of Problems; Design Rationale; Protocol Analysis; Design Skills; Engineering students evaluation;

1. On the need of assessing the outcomes of engineering students in design

The assessment of students' performances, at the end of an engineering course, represents a critical issue from different perspectives. From the one hand, the final goal of such a process is to assign appropriate evaluations to students, so as to give them a meaningful feedback about the criticalities and the

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strengths emerged in their learning process. On the other hand, from the teaching side, the evaluation process constitutes the chance for also understanding what should be reorganized in the future, in order to improve the overall structure of the course. In other words, the evaluation process is one of the key elements to recognize the lacks both in the students understanding and in the way the topics are organized and presented to the class. According to this viewpoint, a proper assessment of students' outcomes after a course on systematic design is even more challenging because of two main reasons. First, it is necessary to highlight how the students are good in generating valuable engineering solutions capable to answer the needs of the society. Second, it is also essential to properly capture the reasoning that leads the students to produce ideas from an initial assignment, so as to verify that this is not the result of just personal talent, but the natural consequence of a structured path, from the identification of design requirements, to the definition of a solution suitable to attain the initial goals. Therefore, the design proposal developed by the students shouldn't just be judged according to "what" it is. Equally, crucial aspects to be taken into account concern the design rationale or "why" the design proposal has been generated with the provided features and characteristics and the sequence of steps resulting in the final design proposal, the so-called design history, that shows "how" the ideation process took place [1]. With a different perspective, the capturing of the design history is a critical aspect even in the analysis of design protocols [2].

According to these premises, this paper aims at presenting a preliminary investigation of the OTSM-TRIZ Network of Problems as an instrument to map the design history and the protocols of students coping with a design problem. The final goal of the research is to develop suitable means for supporting the evaluation of students' skills in systematically tackling design problems and ideating good design proposals. The next chapter examines relevant literature contributions to better clarify the context of the work. In details, it briefly summarizes the relevant issues in the evaluation of Engineering skills in engineering students, as well as the techniques to map Design Rationale and Design Protocols. A specific section at the end of chapter two is focused on the OTSM-TRIZ Network of Problem and on the latest advancements proposed by the authors in making its structure repeatable. Chapter 3, in turn, presents the original proposal of the authors for mapping the design processes of students with an enriched version of the OTSM-TRIZ Network of Problems, together with the description of the research method adopted to verify its applicability in a real context. Chapter 4 shows the application of the proposal on two different case studies, in order to provide the relevant elements to be discusses in the last chapter. The authors conclude the paper by summarizing the main results of this research activity and drawing potential further applications, as well as opportunities for improvements.

Nomenclature

ABET	Accreditation Board for Engineering and Technology
FBS	Function-Behaviour-Structure
IBIS	Issue-Based Information System
IDEF6	Design Rational Capture Method of the Integrated Computer-Aided Manufacturing DEFinition
NoP	Network of Problems
PBL	Project Based Learning
Pb	Problem
PS	Partial Solution
PFN	Problem Flow Network

2. Literature Review

As mentioned in the introduction, the evaluation of “*what*” is a design proposal should not be separately considered from “*how*” and “*why*” (or “*why not*”) the final idea has been developed in that way. The following subsections will first analyze the objectives to be achieved for the skills of engineering students, emphasizing the ones that are particularly relevant for systematically develop new concepts. Then, the methods to capture design rationale and to carry out design protocol analysis will be framed in this context, so as to conclude with a critical review of the current status of development of the OTSM-TRIZ NoP, showing that there are good opportunities to use it in different situations than the initial situation analysis of a design problem.

2.1. Goals and approaches for improving the skills of engineering students

A well-established tendency exists in literature about engineering education paradigms that enhance the learning process of students by involving them in real industrial projects [e.g. 3]. The justification behind this approach, which goes under the name of Project Based Learning (PBL), stands in the intrinsic multidisciplinary nature of real problems and projects, so as to support students in building their own skills in a teamwork environment. The final goal of this approach is to improve both the skills directly related to engineering design, as well as those mostly concerning their permanent education in an adaptable life-long learning process. Therefore, the main challenge of PBL is to improve the skills of students to design with effectiveness and efficiency. To put in a different way, this educational approach based on the learning-by-doing model wants to both improve the students’ skill concerning the proper identification of objectives to be achieved (*know-why*) and the best way to tackle them with success (*know-how*).

In the same context, the ABET criteria for engineering programs define a set of goals to be attained for their graduate students [e.g. in 4]. The following bullet list presents a brief extract of goals for the overall students’ skills defined by ABET, an entity focused on the accreditation of engineering programs. It is not exhaustive, but it catches all the relevant issues for this paper:

- ability to design a system, component, or process to meet desired needs;
- ability to work on multidisciplinary teams;
- ability to identify, formulate, and solve engineering problems;
- ability to communicate effectively;
- the broad education necessary to understand the impact of engineering solutions in a global and societal context;
- a recognition of the need for, and ability to engage in, lifelong learning.

According to the analysis of these punctual guidelines for the definition of learning and education objectives, the need to map the design process both in terms of design outcomes, as well as process that leads to their generation, appears crucial for carrying out a meaningful evaluation of students’ skills.

To this purpose, subsection 2.2 gives a picture of what is design rationale and some methods to capture it; besides, subsection 2.3 describes what should be meant as a design protocol and the way to characterize it according to coding schemes. This analysis supports the definition of critical elements to be embedded into the original proposal of the paper, according to the current development of the NoP shown in subsection 2.4.

2.2. Methods and Models to capture Design Rationale

It has been already mentioned in the introduction that the whole set of decisions leading towards the definition of a design proposal (being it complete or partially developed) goes under the name of design rationale. This aspect is dramatically relevant for each design activity that takes place in a real context.

Indeed, its capture becomes particularly critical in both incremental and radical innovation activities. In the first case, it is particularly useful to have a clear perspective of what should be updated and improved with higher

priority. In the second case, the design rationale allows going through the past design experiences, thus supporting designers and teams in keeping track of their choices with a time perspective. This specific aspect allows the identification of past mistakes so as not to repeat them, thus recognizing best practices and reducing trial-and-error approaches to the minimum extent.

IDEF6 [1] is a modeling scheme that directly addresses these needs with a fractal structure that can be used at different organizational levels, thus mapping both the structure for the information flows in a company as well as the specific details about geometrical and functional features of artifacts.

Nevertheless, the mapping of design rationale, i.e. its representation through an appropriate model, is something that should be done while designing. Indeed, with an a-posteriori approach, it is almost impossible to keep track of all the different decisions and evaluations about design alternatives, especially because some of those decisions could be naturally taken and are, therefore, barely recognizable.

It is quite clear that this design activity deals with the analysis of different alternatives, by considering what are their advantages and their drawbacks. Moreover, it is also clear that this step-by-step process of characterization of the final design proposal deals also with the interim evaluation of their potential, so as to verify if the solution space can match the problem space. In this context, it has been widely recognized [5] that during the design process several iterations may occur between the analysis of the problem (i.e. the definition of the problem space) and the synthesis of partial solutions (i.e. the subset of variables capable of satisfying several objectives). In literature, this situation is referred as the co-evolution of problem and solution. It regards the progressive reshaping of both the spaces by defining new requirements and relaxing or even removing some of them. Issues and answers characterize this kind of dialogic discourse [6] and they follow one by another until there is a convergence towards a unique and satisfactory solution [7].

In this context, IBIS Notation [8] represents a good alternative to map the design rationale with a very simple characterization that releases from the complexity (and the comprehensiveness) of the IDEF6 models.

Indeed, IBIS allows to map also hypotheses, conjectures and assumptions and not simply decisions concerning the characterization of the design proposal. On the other hand, the hierarchical relationship between problems and solutions (namely issues and answers, in IBIS jargon) is poorly supported, also for what concerns the processes of detailing solutions and decomposing problems in sub-problems.

Therefore, in reference to the different abilities pointed out by the ABET objectives, the mapping of the Design Rationale of designing students is of crucial importance because its analysis allows to better evaluate their skills in identifying and solving problems.

2.3. Analysis of Design Protocols

The analysis of design protocols is an approach aimed at understanding the behavior of people that are facing design problems or specific design tasks. This empirical method is mainly used for research purposes, with the objective of capturing the elementary steps carried out by individual or teams that advance in the ideation of a design proposal. It consists in the exploratory search for regularities or differences in the design path followed by designers having different experiences, different backgrounds, as well as different genders or age. The overall goal is to shed light on the cognitive processes characterizing the design activity, in order to identify best practices and, as a consequence, reshape the logic of design methods with new prescriptions and guidelines oriented towards an increased effectiveness and efficiency of the whole design process.

In a literature review of 2009 [9], Jiang and Yen showed the distribution of studies carried out with the protocol analysis approach. Despite from this review it does not appear evident, to address the need of comparing results of design activity, coding schemes are crucial to interpret the sequence of design steps (also called design moves). These schemes allow organizing the results according to variables and parameters in order to characterize the elementary steps described during think-aloud protocols (an individual describing his/her thoughts) or conversational ones (a team discussing on the design choices).

Consistently with what has been already stated for the Design Rationale, even the Design Protocols cannot be reliably rebuilt with an a-posteriori approach because of the potential loss of relevant information. To this purpose, such studies foresee the recordings of design activities with video and/or audio recordings, so that analysts can manage them without missing any relevant piece of knowledge emerging from the designers' behavior. To this

purpose, Jiang and Yen also showed that, regardless of the applied coding scheme, the analyses require from 10 to 100 times the duration of the protocols.

As well, also the mapping of the design protocol is relevant in evaluating the satisfaction of the ABET criteria. From its analysis, it is possible to better understand how the students are capable to work in teams, as well as to carry out with the needed fluency the cognitive processes involved in design, such as the generation and the evaluation of new ideas and the search for new knowledge.

According to the considerations of subsections 2.2 and 2.3, the authors consider that the OTSM-TRIZ Network of Problems can represent a good candidate to both map the Design Rationale and the behaviors of designers so as to put on the table further knowledge elements capable of supporting the evaluation process for a systematic design in an engineering program.

2.4. OTSM-TRIZ Network of Problems: from its origins to its current status of development

The NoP is an instrument mainly developed by Nikolai Khomenko in the framework of the OTSM-TRIZ theory with the aim of supporting designers in dealing with the initial steps of complex problems solving activity [10]. Its original version was poorly structured and its main constructs were “Problems” and “Partial Solutions”, without a specific definition about the links that should connect the nodes of such network. Nevertheless, different scholars have exploited its potential and it has been suggested as part of a framework for the development of a future generation of Computer-Aided Inventive Problem Solving tools [11]. Furthermore, it has been also applied in different case studies [e.g.: 12] and implemented as part of an algorithm for tackling inventive complex problems within the boundaries of both TRIZ and OTSM-TRIZ [13].

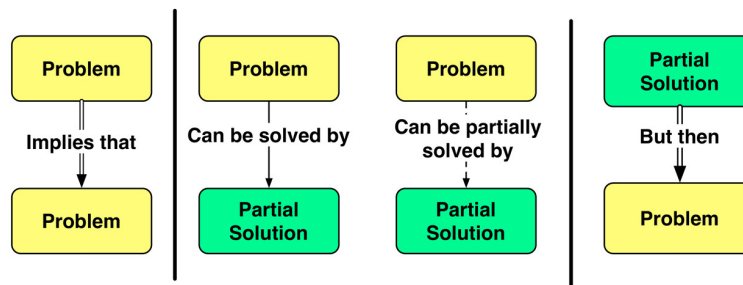


Fig. 1. Graphical Representation of the constructs of the Network of Problems according to [14] (from left): causal relationship between a couple of problems; sufficient and insufficient solving links; causal relationship between a problem and a solution

Cavallucci et al. [14] carried out the latest advancements in formally defining the main constructs of the NoP. In that paper the authors chose to release from the boundaries of OTSM-TRIZ and abandon the hierarchical structure of the network suggested by Khomenko by privileging an unordered structure that, according to their assumptions, is more capable to describe the essence of problematic situations as connections between problems and solutions that, by nature, are not hierarchically organized.

Figure 1 shows the boxes concerning the NoP as presented in [14]. Moreover, Cavallucci et al. also consider as possible the connection between PSs, discouraging their use because they underlie the need of further solutions to completely solve the problem.

According to the content of Figure 1, it is clear that the NoP, at the current state of its development can just take into account real situations, as it is reasonable in the description of the initial situation. Nevertheless, the presence of hypothesis and conjectures, which are typical of the design processes aimed at the search for new solutions, is not representable within this framework, as well as the decomposition of a problem in simpler problems or the detailing of Partial Solutions described at different detail levels.

To this purpose, in Chapter 3, the authors present a new version of the Network of Problems that tries to summarize all the above mentioned aspects, so as to fully describe the steps of engineering students designing a solution capable to address a problematic situation. More in detail, the proposed model should be capable to

map all the relevant aspects that have to be considered for the evaluation of their design skills after a course on systematic design, such as:

- the capability to identify system requirements/product attributes;
- the capability to identify solution concepts suitable to attain the defined requirements;
- the capability to select the best solution(s) in a set of alternatives according to predefined criteria (satisfaction of requirements); and
- the capability to follow a meaningful sequence of logical steps along the whole design process.

3. OTSM-TRIZ Network of Problem enrichment and research method

3.1. OTSM-TRIZ Network of Problems for mapping the design moves during the development of solutions

As mentioned above, the purpose of this improved Network of Problems is not to map the problems and just the existing alternative (partial) solutions with reference to the current technology advancements as proposed by [14].

Indeed, a model conceived for mapping the behavior of designers should allow the analysts also to take into account conjectures to be proven (by experts opinion, available data, etc.), as well as the synthesis from a working principle capable to solve the problem to a solution concept enriched by, e.g., main components as well as their mutual interaction. At last, it is also necessary to embed the capability to represent the decomposition of a situation into elementary problems, as suggested as a good design practice by the different contributions in the field of systematic design (e.g: [15]).

To this purpose Figure 2 provides a graphical and textual description of the proposed improvements to be integrated in the NoP constructs proposed in [14]. Please note that the construct connecting two partial solutions has changed its meaning.

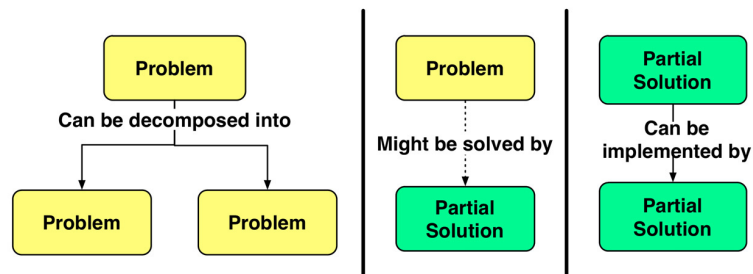


Fig. 2. Graphical Representation of the original contribution to enrich the Network of Problems so as to map the designers' moves during the different stages entailed in the development of solutions. From left to right: (a) Problem decomposition, (b) hypothesis of solution, (c) synthesis of a more general solution.

Moreover the authors suggest mapping the sequence of design moves by simply adding a label inside each node.

3.2. OTSM-TRIZ Network of Problems for mapping design moves: description of the experiment

In order to verify the effectiveness of the proposed modeling technique and to enable the repeatability of the experiment, the authors have defined in advance the procedure by which it is possible to capture the required data.

The test can be carried out with both individuals and teams. In the first case, a think aloud approach is necessary to properly catch the protocol and the rationale reducing at the minimum extent the presence of biases. On the contrary, the conversational approach is obliged for teams. In the specific case examined in this

paper, the authors carried out the experiment with three panels of 3 to 4 engineering students of the MS course on Product development and Engineering delivered by the school in Mechanical Engineering of the University of Florence. The individuals of each group are engaged in both the analysis and the synthesis of solution concepts as a team who should make decision under consensus. The authors also managed to combine the teams such that their average mark in the whole MS career is equally balanced.

To reduce the bias due to the application of a specific test case, the groups were asked to tackle two different problems, which are well known and widely used in literature for design studies. The problems are respectively available in [16] and [14] and their description has been a little adapted so as to also evaluate the students' skill of correctly identifying the requirements.

The students have to face the problems within a predefined time span, thus creating a situation where it is necessary to work under time pressure, so as to simulate almost-real design conditions.

For collecting the data, the students were asked to fulfill three different forms where they should annotate the time and the specific design move, which should be related to the identification of a product attribute, the generation of a solution concept and the evaluation of the solution concept. This kind of written mapping enables the analysts to reorganize the design moves according to the audio/video recordings with improved efficiency and saving time (the analysis of a design protocol normally takes from 10 to 100 times the duration of the protocol itself [9]). Moreover, audio recording taken with appropriate devices (e.g.: audio recorders as well as simple mobile phones) allow the analysts to have a clear understanding of what has happened during the design protocol and which rationale there is behind the different design choices, recapturing all the design moves actually done by the designers', removing the bias given by the sole indications given by students on the forms.

The criteria for mapping the different design moves follow:

- each product attribute, functional or geometrical requirements, as well as goal should be characterized as a Problem;
- each concept aimed at satisfying on the abovementioned attributes and requirements should be characterized as a Partial Solution;
- each of the design move should be characterized by a numerical ID to be inserted within the node;
- the different nodes should be linked consistently with the meaning of the constructs presented in subsection 2.4 and 3.1 and, especially, according to the meaning described by the team of designers, as interpreted by the analyst.

4. The Network of Problem as an instrument to capture rationale and map the protocol in design

The small sample of testers (3 groups, 10 people in total) is not sufficient to draw conclusions upon a statistical significance analysis. Nevertheless, such a sample is considered more than sufficient [e.g: 17] to carry out exploratory studies for verifying the feasibility of approaches. The outcomes of the whole testing activity have been initially examined with the forms filled by students, as presented in Table 1. Subsequently, the design protocols have been examined by listening the audio recordings and organizing the single design moves coherently with what declared at the end of subsection 3.2, without biasing the intents of designing groups. Such results are collected in Table 2.

Both in Table 1 and 2, Co-Evolution should be interpreted as the occurrence of iterations between the Problem and the Solution design space (or vice versa) that lead to a definition of a new requirement, as well as the relaxation or the removal of an existing one. In the case of Table 1, such occurrences have been evaluated by means of the timeline given by students. In Table 2, on the contrary, it has been possible to identify Co-Evolution iterations, primarily, by listening the audio recordings of designing sessions and, afterwards, according to the examination of the produced NoP.

Table 1. Details of the analyses carried out by the three groups on the two different problems. Data collected and organized according to the forms filled by students during the design activity.

Characterization of the design move	Group #1 Problem #1	Group #2 Problem #1	Group #3 Problem #1	Group #1 Problem #2	Group #2 Problem #2	Group #3 Problem #2
Attributes	15	17	9	10	16	15
Solution Concepts	18	20	7	6	12	3
Evaluation	1 Solution composed by 3 PS	4 good Solutions	2 bad Solutions	1 PS is ok, 5 no.	12	1 PS is ok, 1 PS no.
Co-evolution	0	0	0	0	0	0

Table 2. Details of the analyses carried out by the three groups on the two different problems. Data collected and organized according to the Network of Problems.

Characterization of the design move	Group #1 Problem #1	Group #2 Problem #1	Group #3 Problem #1	Group #1 Problem #2	Group #2 Problem #2	Group #3 Problem #2
Problems (Pb)	30	32	21	29	19	14
Partial Solutions (PS)	34	40	17	22	13	8
# of design moves	78	79	41	63	53	21
Co-Evolution	8	5	7	13	1	0
Pb decomposition	12	0	5	3	1	0
Synthesis of PS	11	8	4	6	4	0

The analysis of the design protocols has been organized in the shape of Network of Problems, as for Table 2 and their detailed discussion will be addressed in Chapter 5. Yet, it is important to show how the different constructs of the proposed NoP model should be applied to map the protocols and the rationale concerning a design activity. It goes beyond the purpose of this paper to give a detailed representation of all the 6 protocols and, for reason of readability, it is not possible to show a complete example of a Network of Problem collecting all the design moves. Nevertheless, for the sake of clarity, Figure 3 presents an excerpt from one of the protocols concerning the peanut-shelling machine where it is possible to notice almost all the different constructs presented in subsections 2.4 and 3.1.

Note that all the different nodes present at least one label in brackets, which are consistent with the position Id of that node in the sequence of the design moves by the cooperating group of designers facing the problem at hand. Where more than a number in brackets is assigned to a node, it means that the designing group considered such specific facet of the problem more than a time. The three different constructs concerning where Pb connects to PS (Sufficient solution, Insufficient solution, Hypothetical solution) are present in Figure 3. Moreover, there appear also the consequences of the application of such PS in terms of new emerging problems. The process of synthesizing a solution from an abstract to a more concrete level is represented as well as the problem decomposition.

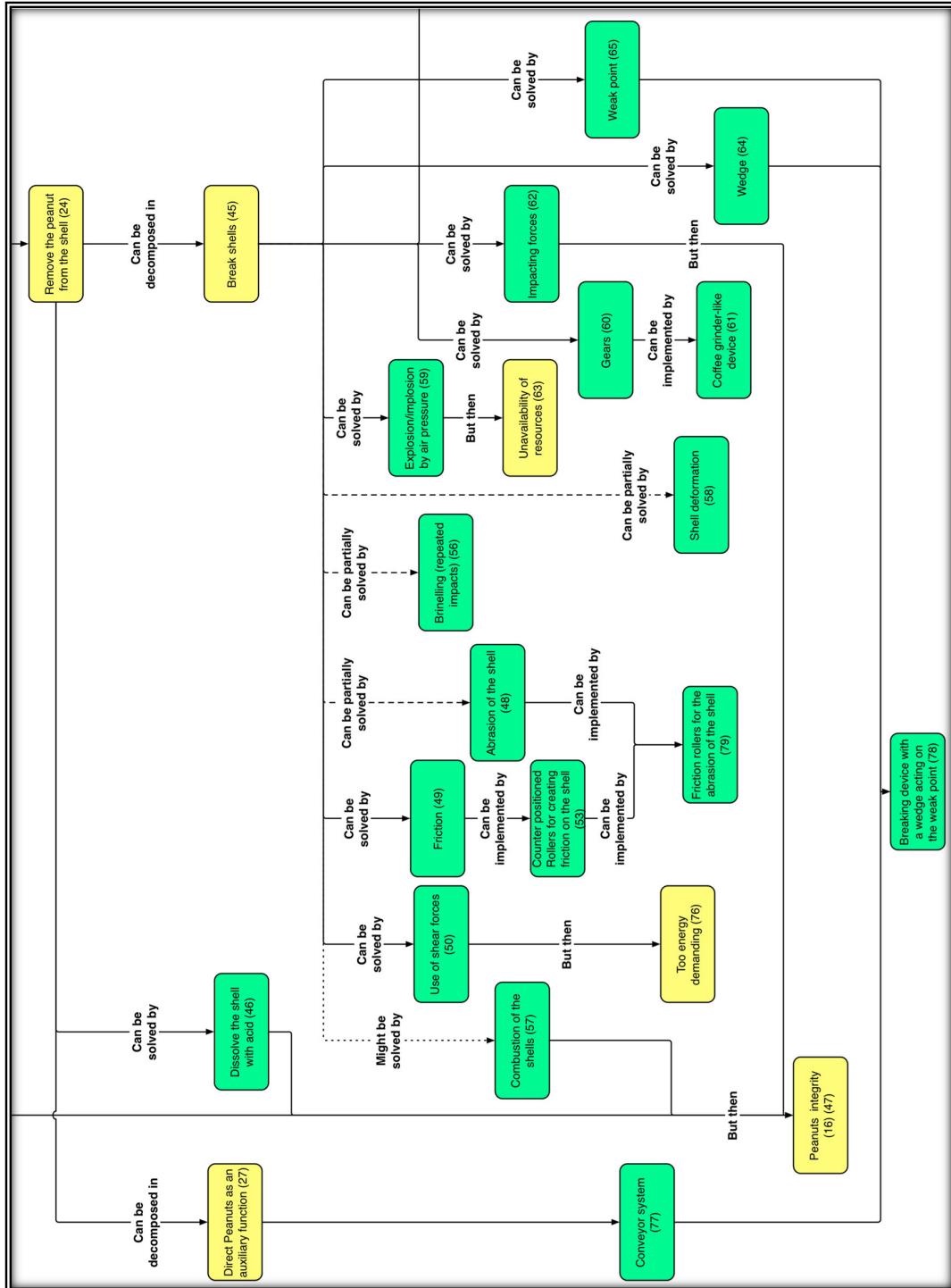


Fig. 3. Excerpt of the Network of Contradiction built upon the analysis of the design protocol carried out by Group #2.

5. Discussion and conclusions

This paper presents a research activity aimed at providing further instruments to people involved in academic institutions that should evaluate the engineering skills of students in design. After an analysis of the relevant elements in literature (Design Rationale Capture methods, Protocol Analysis techniques and the state of the art of OTSM-TRIZ NoP), it proposes an adapted version of the OTSM-TRIZ Network of Problems as a means to map both the rationale and the protocol in design, considering this issue as valuable in supporting such an evaluation process. The following subsections present a critical examination of the results and authors considerations about the potential of this technique, in terms of students' skills assessment as well as its application in different fields of technique.

5.1. Critical analysis of the outcomes from the experiments: strengths and weaknesses of the proposal

The results presented in Section 4 shows that there is a consistent difference in the outcomes provided by the students with paper forms and the analysis of the recordings of their protocols. Generally speaking, it appears as mostly evident they are not able to recognize the emergence of a co-evolving problem-solution behavior that, on the contrary, appears several times as for the analysis of the recordings and the NoPs. A potential explanation to this inconsistency can stand in the marked systematic approach towards design presented during the course. In this perspective, one can consider that students' behavior in taking notes of their design moves may be impacted by their perception of teacher's expectations.

Moreover, the three different groups show the tendency to underestimate the design moves. Indeed, the comparison between the "Steps" of Table 2 and the sum of all the occurrences for Attributes, Solution Concepts and Evaluation shows that the former almost double the steps noted on paper forms.

The paper forms allow the evaluator to immediately assess the prolificacy of groups in the three stages of the design process. This comparison can be carried out both in terms of identified attributes, and of generated solution concepts, so as to provide a preliminary indication of how the design process has been carried out. On the other hand, the goodness of ideas and the students' judgment skills require a detailed analysis of the Evaluation form. From the results collected in Table 1, it appears clear that some groups have just tried to focus on non-satisfactory outcomes of their work; other students put their efforts in identifying the good ones as well as those who have tried to summarize the best results of their work in a unique design proposal having a better potential. The NoP analysis, on the contrary, provides more fine-grained elements to carry out the evaluation. For instance, the fluency in analysis and synthesis tasks can be evaluated in terms of colors and number of nodes, but more details can be caught considering the capabilities of students to decompose problems in more elementary ones as well as in detailing solution concepts. Nevertheless, the greatest contribution of the NoP stands in the clear vision of the students' skill of understanding the impact and the feasibility of their proposals, so as to match one of the most critical ABET criteria presented in subsection 2.1.

5.2. Impact of the approach

This approach has demonstrated to give good advantages and further knowledge elements for supporting the evaluation of the students' skills in designing engineering solutions. In details, the greatest impact of this contribution stands in the mapping of the design process that is often just evaluated on the basis of poorly references presented in an unstructured way by the students in their works. Therefore, this application can have a relevant impact especially for those engineering courses where the systematic approach has a paramount weight, even if compared to the goodness and brightness of design proposals.

Moreover, it is worth to mention that the new proposal for the OTSM-TRIZ NoP can be adopted besides the evaluation of engineering students' skills, such as for mapping the design rationale and for interpreting the protocols of designing people. Especially in reference to the protocol analysis (see subsection 2.3), it is worth

mentioning that this approach allows to radically slash the time ratio between the protocol duration and the time needed for its analysis to about 1:1-2.

For what concerns the further developments of this work, the authors expect to define a metric for measuring the outcomes of students, so as to start releasing from a subjective to a more objective approach (e.g.: both the analysis- and the synthesis-related skills of students could be calculated in terms of connections between nodes), which is also capable to point out with better precision the criticalities of the learning process, both from the side of students and educators.

In this context, since experienced designers show a pronounced approach towards the co-evolution of the problem and solution, as reported by Cross 2001 [18], an appropriate metric to easily calculate the iterations between Problem and Solution spaces would ease understanding to what extent the course has impacted the experience of students in designing new solutions.

Moreover, in terms of specific coding schemes for the analysis of design protocols, it is possible to imagine that the future developments of such an approach will better support the identification of the cognitive process described by Gero and Kannengiesser in [19].

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