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Educating a Creative Engineer: Learning from Engineering Professionals

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Abstract

The rapid growth of engineering knowledge has resulted in continuous expansion of novel technologies and materials that can be used in designing new products and processed. Computer- and web-based technologies allowed engineers to significantly shorten the development of novel artefacts. These advances intensified the competition between engineering companies and shortened the lifespans of the majority of engineering products. As a result, practicing engineers are now expected to deliver creative designs to markets much more swiftly than ever before. This paper presents the results of a survey that intended to establish the ways and the means of enhancing engineering creativity that suit the engineering industry of the 21st Century. This study engaged 46 engineering experts from the major international corporations who utilised numerous creativity techniques including TRIZ in their day-to-day engineering work. It had been found that the surveyed engineering experts think that in the current Information age (i) knowledge beyond engineering profession is more important for creativity than the discipline knowledge; (ii) learning creativity methods and problem solving heuristics is more important than acquiring additional discipline knowledge; (iii) the problem solving stage of identifying and understanding a problem is the key to a creative solution.

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Keywords: Engineering creativity; TRIZ; idea generation; problem solving; problem understanding; knowledge; creativity technique.

1. Introduction

Engineering profession is often associated with extensive problem solving. Therefore the ability to solve problems creatively has been identified as one of the imperative competencies for graduating students by engineering associations worldwide [1-3]. It has been reported that the traditional methods of teaching engineering students do not necessarily succeed in enhancing their problem solving and creativity skills [4-7]. It was also reported that significant differences exist in problem solving approaches of engineering experts and novices and that these differences need to be taken into account whilst developing and improving engineering curricula [8].

Over the last 10 years of the Information age engineering profession has been changing considerably. The following are just three major reasons behind these changes:

- explosion of engineering knowledge-base that forced engineering practitioners to significantly shrink their fields of expertise and to specialise only in very narrow areas of technology;
- expanding opportunities offered by the constantly refined old technologies as well as by new technologies and new materials that resulted in significantly shortened life spans of novel artefacts and enlarged pressure on companies to offer new products to their customers perpetually;
- numerous resources associated with the growing computing power as well as with the mind-blowing internet speeds that impacted practically every area of product development.

As a result of the changes brought by the Information age, the ability to propose novel ideas quickly became one of the key expectations of the engineering profession. Therefore, skills in creative problem solving have become more important for engineering professionals and engineering graduates than

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ever before. In turn, the changes to the engineering profession brought about by the Information age have put a demand on universities to modify the ways they educate future engineers and upskill the existing engineering workforce.

Although creativity has been investigated extensively over the last 50 years, there are still significant differences between researches in the definition of creativity [9]. Engineering experts are in a better agreement and usually define engineering creativity as ability to propose novel ideas that can be implemented with beneficial outcomes for the consumers.

Creativity researchers do not fully agree on the sources and prerequisites of creative performance. Some investigators suggested that creative performance in many domains requires gaining substantial domain knowledge [10, 11]. Others advocated the importance of at least 10 year of extensive professional practice for attaining creative performance [12]. It was also put forward that the knowledge beyond the profession as well as proficiency with effective creativity techniques is required for generating novel ideas [13]. Research reports on differences between problem solving strategies deployed by novices and experts indicate that the conclusions drawn by investigators who researched with well-defined problems do not necessarily translate to the domain of ill-defined problems that are at core of the engineering profession [14, 15]. Moreover, very few authors have discussed the sources of the effectiveness of ideation techniques (including the Theory of Inventive Problem Solving (TRIZ)) in engineering creativity based on the existing research findings in human cognitive architecture [16, 17]. In other words, over 50 years of research have left numerous grey areas in awareness of the sources and the means of creative performance. Further investigations of creative performance in knowledge-rich domains like engineering that seems the 'greyest' of all are urgently needed in order to guide engineering educators in meeting the requirements of engineering industry in the 21st Century.

This paper will present the first results from the analysis of a web-based survey of practicing engineers that was aimed to establish what works and what does not work in a day-to-day creative practice of engineering experts who already operate in the age of Information. The authors wished to identify the 'hidden' sources of engineering creativity for the Information age. This paper reflects on the survey findings and on the implication of these findings onto engineering education.

2. Materials and methods

2.1. Survey of Engineering Experts

The authors were specifically interested in the opinions of engineering experts who have developed creative products and also have extensively used ideation heuristics in their day-to-day work. In order to collect opinions from such practitioners this study targeted engineers from companies that have been on the Thomson Reuters list of '100 Global Innovators' for at least two years [18]. The authors planned to analyse the opinions of engineers who designed new products (processes) as well as engineers and scientists who worked in Research and Development. It was anticipated that engineers who's job is to develop novel artefacts use creativity methodologies more expensively than engineers outside of product development. Therefore, the former will be able to better comprehend the importance of ideation heuristics (including TRIZ) for the engineering profession of the 21st Century than the latter. In addition, the developers of novel artefacts will be able to offer more valuable insights on the 'hidden' sources of engineering creativity that may be deployed in engineering education.

In order to investigate the role of creativity techniques and the effectiveness of TRIZ in generating novel solutions during day-to-day engineering development work, as well as the role of knowledge in engineering creativity, survey specifically targeted the participants that (i) were engaged in various activities relevant to engineering product development that required generation of novel solution ideas; (ii) were highly educated; (iii) were familiar with numerous creativity techniques including TRIZ and (iv) had at least five year of practical experience in engineering profession.

Survey of engineering experts was conducted in the second half of 2014. It was web-based and utilised the Qualtrics survey software. A number of representatives from the divisions of international corporations that were on the Thomson Reuters list (many of them have successfully employed TRIZ in product development) were contacted and were asked to distribute an invitation to participate in the survey to their engineering personnel involved in design and development. Participation in a survey was voluntary. Any participant could withdraw from the survey at any time during responding to the survey questions. Survey participants could move to the next question without answering the preceding question.

2.2. Methodology

Survey consisted of seven main sections. It was opened by the letter of invitation that explained the goals of the research and also contained the link to the ethics approval.

The section of General Information collected data relevant to each individual participant. It expected a participant to share information on her/his field of engineering practice, work area, gender, age, education as well as the years in profession.

The section on the Creativity Techniques collected information on the ideation methodologies utilised by the participant in day-to-day work as well as on a perceived level of expertise with these techniques. It also asked a participant to respond to 10 statements relevant to the participant's skills in problem solving.

The section on the Problem Solving Process consisted of six statements. It collected information on the most likely approaches that the participant deploys to solve problems.

The section on the Stages of Problem Solving contained 15 statements. It was intended to investigate the opinions of the participants on the importance of different stages of problem solving.

The section on Knowledge and Skills collected information on the influence of knowledge, practical experience as well as of ideation techniques for the creative outcomes in engineering profession. It contained eight statements.

The final section of the survey asked a participant to comment on the skills and knowledge that are vital for engineering creativity. Participants were also requested to suggest changes to engineering curricula that university educators need to consider in order to enhance the creativity skills of engineering graduates more effectively.

3. Results

3.1. The Participants

Forty six engineering experts from a number of major international corporations, who participated in the survey, fully fitted the targeted criteria. Survey responses of these 46 engineers and scientists have been considered by this study. Forty two participants identified themselves as male, four – as female. Nearly 65% of the respondents worked in Design, Research and Research & Development. Manufacturing engineers represented 18% of the surveyed.

Table 1 depicts general information on these 46 participants: the distribution of their age, their qualifications, engineering branch they represented as well as the level of proficiency with the creativity techniques they attained. As shown in Table 1, the majority of the survey participants were highly educated: 39% achieved PhD, 30% - Master degrees. Nearly everyone completed their Bachelor degrees 10 or more years ago. Seventy percent of the respondents were over 40 years of age. Most of them have been practicing engineers for over 10 years. Eighty six percent of respondents operated in fields of Mechanical and Electrical engineering. Over 90% of them have used creativity techniques in their day-to-day work on a regular basis. Nearly 70% of the respondents considered their expertise with the well-known creativity techniques as significant.

Table 1. General information on the survey participants: Age, Qualifications, Engineering Branch and Level of proficiency with creativity techniques.

Age (%)	Degree (%)	Branch (%)	Level (%)
			Novice (8)
31-40 (30)	Bachelor (25)	Chemical (11)	Basic (24)
41-50 (40)	Master (30)	Civil (2)	Medium (30)
51-60 (23)	PhD (39)	Electrical (43)	Advanced (19)
> 60 (7)	Other (7)	Mechanical (43)	Expert (19)

3.2. Use of the Creativity Techniques

Only one participant stated that he does not use any well-known creativity technique in day-to-day work. The rest of the participants indicated that they utilise at least one creativity technique regularly. Sixty nine percent of the respondents to the statement "Please list the creativity techniques you use regularly" mentioned various tool of TRIZ. Brainstorming and Brainwriting were listed by 34% of the participants. The Six Thinking Hats occupied the third position – it was mentioned by almost 14% of survey participants. Some respondents listed Mind Mapping (9%), SWOT Analysis (9%) and Root-Cause Analysis (6%). Nearly 29% of them named other ideation methods that also included individually developed techniques. For example, one of the respondents stated that his ideation approach is to "Ask children … for directions to address a problem".

Survey participants assessed TRIZ tools as the most suitable for individual idea generation. In response to the statement "Please list (up to three) creativity techniques that you consider most useful for idea generation when you generate ideas individually", 51% of the survey participants listed TRIZ tools, 20% - Brainstorming or Brainwriting.

Their perception on the most effective tools for group idea generation was different to their choice of the most effective techniques for individual idea generation. Forty percent of the respondents mentioned Brainstorming or Brainwriting in response to the statement "Please list (up to three) creativity techniques that you consider most useful for idea generation when you generate ideas as a part of a team". TRIZ tools were mentioned only by 31% of the surveyed.

3.3. Importance of the Stages of Problem Solving

Survey participants were asked to assess the importance of different stages of problem solving. For simplification purposes, the problem solving process was considered as divided into four main stages [19]: (Stage 1) identifying and understanding the problem; (Stage 2) planning for solutions and generating solution ideas; (Stage 3) implementing a solution; (Stage 4) evaluating the solution.

Table 2 presents the mean values (Mean) and the standard deviation (SD) of the responses to the statements "Stage X is the most important stage of the problem-solving process". The Likert scale of 10 was used (0 – Strongly disagree, 5 – Not sure, 10 – Strongly agree).

Table 2. Opinions of the survey participants on the importance of different stages of the problem solving process.

	Stage 1	Stage 2	Stage 3	Stage 4
Mean	8.85	5.88	5.65	5.03
SD	1.52	1.73	2.25	1.90

The paired-samples t-test of the means in Table 2 revealed that the differences between the importance of Stage 1 and the importance of all other Stages of problem solving are statistically significant ($t>6.3$, $p<0.001$). Statistically significant difference has also been found between the importance of States 2 and 4 ($t=2.6$, $p<0.05$).

3.4. Knowledge, Years of Practice and Creativity Techniques

In order to assess the importance of knowledge, years of practice and creativity techniques, the participants were asked to respond to the following statements:

- "**Discipline knowledge** has been extremely useful to me in solving engineering problems creatively".
- "**Years of practice** in my profession have significantly enhanced my engineering creativity".
- "**Creativity techniques** that I have learnt over the years have significantly improved my ability to solve engineering problems creatively".
- "My **general knowledge** (from beyond my discipline) has been extremely useful to me in solving engineering problems creatively".

Table 3 presents the mean values (Mean) and the standard deviation (SD) of responses to the abovementioned statements. The Likert scale of 10 was used (0 – Strongly disagree, 5 – Not sure, 10 – Strongly agree).

Table 3. Opinions of the survey participants on the importance of Discipline knowledge, Year of practice, Creativity techniques and General knowledge.

	Discipline Knowledge	Years of Practice	Creativity Techniques	General Knowledge
Mean	7.00	7.21	7.74	8.41
SD	1.74	1.93	2.29	1.35

As shown in Table 3, general knowledge outside of a profession as well as utilisation of creativity techniques were considered as more important for achieving novel solutions than discipline knowledge and years of professional practice.

The paired-samples t-test of the means in Table 3 showed statistically significant differences between General knowledge and Discipline knowledge ($t=4.3$, $p<0.001$) as well as between General knowledge and Years of practice ($t=3.8$, $p<0.001$). Differences between all other items in Table 3 were not statistically significant.

3.5. What Knowledge and Skills to Acquire?

In order to evaluate the need to gain additional knowledge as well as the usefulness of acquiring additional creativity techniques, the participants were asked to respond to the following statements:

- "To enhance my skills in engineering creativity I need to **gain more knowledge in my own profession**".
- "To enhance my skills in engineering creativity I need to **gain more general knowledge from outside my own profession**".
- "To enhance my skills in engineering creativity I need to gain **more knowledge in mathematics**".
- "To enhance my skills in engineering creativity I need to **learn effective creativity techniques**".

Table 4 presents the mean values (Mean) and the standard deviation (SD) of responses to the abovementioned statements. The Likert scale of 10 was used (0 – Strongly disagree, 5 – Not sure, 10 – Strongly agree).

The paired-samples t-test of the means in Table 4 showed statistically significant differences between the need to gain more general knowledge versus expanding the professional knowledge ($t=4.7$, $p<0.001$). Additional general knowledge was also assessed as much more important for enhancing engineering creativity than extra knowledge in mathematics ($t=10.8$, $p<0.001$). Similarly, learning effective creativity techniques was assessed as more important than gaining extra professional knowledge ($t=3.2$, $p<0.005$), as well as more beneficial than acquiring extra knowledge in mathematics ($t=7.7$, $p<0.001$). The difference between the need to gain more general knowledge versus learning effective creativity techniques was not statistically significant.

Table 4. Opinions of the survey participants on the importance of acquiring more knowledge and learning effective creativity techniques.

	Need to acquire more:			
	Professional Knowledge	General Knowledge	Knowledge in Mathematics	Creativity Techniques
Mean	5.79	7.71	3.41	7.24
SD	2.11	2.01	2.27	2.55

3.6. Reflections of the Survey Participants

Survey participants were asked to reflect on the ways and the means to enhance creativity skills in engineering. The following are some responses of the survey participants to the statement "Please comment on the skills/knowledge that you see as the most vital for you to gain in order to enhance your skills in engineering creativity". The reflections are arraigned into two groups. One group of responses points to the importance of creativity techniques. The reflections from the other group argue for the need of acquiring more knowledge outside the profession.

"Using creativity techniques alone or in a team for solving problems". "Practice in TRIZ and axiomatic design". "Use a mythological approach (e.g. TRIZ) to tackle the problems." "Usage of TRIZ, de Bono techniques and other creativity tools." "More knowledge of and familiarity with problem/creativity tools".

"Understanding of concepts outside engineering, identify good ideas and adapting ideas to solve problems". "Broad experience on various technical domains". "Basic knowledge in other fields in order to generate analogies. "Generalist knowledge on many fields". "Wide general scientific knowledge". "Basic [knowledge in] science and technology in relevant and related areas. Full and analytical understanding of the processes and equipment used in industry and their strengths and weaknesses."

The following are some responses of the survey participants to the statement "Please reflect on how you generate creative ideas at work and explain what helps you to generate them":

"*Identify the right problem to solve, think about similar problems and how they are solved, adapt and combine good solutions into one". "For simple problems just structuring problem and solution ideas as mindmap already helps. For more complex problems, I like more to effectively use the creativity of a group of experts for solving." "What is really important is how the problem is described. For instance in terms of contradictions." "Talk a lot with colleagues and experts about the problems which have to be solved." "Analyse the problem and try to understand all root causes (technical, organizational, environment,...)". "Leveraging ideas from a diverse range of disciplines and then making connections between areas. I do a lot of reading on the tech industry and technical trends as well." "Discussion with people with different background is extremely helpful."*

4. Discussion and Conclusions

4.1. The Importance of Knowledge Outside the Profession

In accordance to the opinions of the engineering experts that participated in this study, the knowledge outside of the individual's professional domain plays extremely important role in attaining creative solutions in their day-to-day engineering work in the Information age. This conclusion can be drawn on the responses presented in Tables 3 and 4 as well as in the reflections of the participants exhibited in Section 3.6.

Firstly, the mean value of survey responses to the statement on the importance of General knowledge for creativity (Mean=8.41/10 in Table 3) statistically significantly exceeds the mean values that signified the importance of General knowledge (7.00/10) and Years of practice (7.21/10). Also, the fact that the standard deviation of the mean for General knowledge in Table 3 (SD=1.35) is much smaller than the standard deviations of the other three means (1.74 to 2.29) manifests the best agreement amongst the participants on the importance of General knowledge.

Secondly, the value of knowledge beyond discipline for engineering creativity is further supported by the opinions of the survey respondents on the statements related to knowledge and/or skills they need to gain in order to further enhance their creativity that are presented in Table 4. The participants really 'voted' for the superiority of acquisition of additional knowledge outside of their profession as the means to enhance creative performance (Mean=7.71/10). Neither additional discipline knowledge (5.79/10), nor extra knowledge in mathematics (3.41/10), which is often considered as the "language of engineering and science", was considered of importance for upskilling in engineering creativity. It needs to be noted, that, similarly to the standard deviation of the mean for the importance of possessing General knowledge presented in Table 3, standard deviation of the mean for the General knowledge acquisition (see Table 4) is also the smallest of all (SD=2.01). This again demonstrates the best agreement amongst survey respondents on primacy of general knowledge compared to purely professional knowledge for creative performance in engineering.

Thirdly, the reflections of the survey participants presented in Section 3.6 further support the need of expanding general knowledge to enhance engineering creativity.

The conclusion that knowledge beyond the discipline is imperative for attaining creative engineering solutions in the 21st Century supports the hypotheses of Belski and Belski on (i) detrimental influence of expertise on engineering creativity and on (ii) the necessity to identify and to utilise ideation techniques that can help a user in effectively searching her/his Long Term Memory (LTM) knowledge base [13, 16]. Moreover, Belski and Belski argued that (i) the depth and the breadth of individual knowledge that is stored in LTM determines the person's limit of ideas that she/he can propose whilst searching LTM for solutions and (ii) in order to generate creative ideas, engineering experts need to exploit the knowledge beyond their expertise (see Figure 4 in [16]). Both arguments have been indirectly supported by the responses of the engineering experts that have participated in this study.

4.2. The Importance of Creativity Techniques

The survey participants confirmed the effectiveness of creativity techniques for attaining novel engineering solutions. This conclusion can be drawn based on the data presented in Table 3 and Table 4 as well as on the reflections of the survey participants provided in Section 3.6. The mean values for the Creativity techniques are the second highest in both Tables 3 and 4. Also, as shown in Table 4, learning creativity techniques was assessed by engineering experts as more important for creative performance than gaining extra professional knowledge. Interestingly, the opinions of the respondents on the value of creativity techniques presented in Tables 3 and 4 were less uniform than their assessment on the importance of general knowledge and the value of the discipline knowledge for creative performance. The standard deviations for the items related to the value of Creativity techniques in engineering problem solving that are presented in Tables 3 and 4 are the highest of all (2.29 and 2.55 respectively). This is likely to indicate that not all the survey respondents were equally successful in utilisation of ideation methods and/or that the creativity techniques they used were not fully suiting the problems they tried to solve.

The latter conclusion on the inadequate suitability of some ideation methods for solving day-to-day problems is further supported by the fact that out of 69% of the participants, who have applied TRIZ regularly, only 51%, found it useful in their individual problem solving and only 31% – in group problem solving. Such discrepancy between the number of the regular TRIZ users and the number of successful TRIZ applications by its regular users suggests that TRIZ experts and TRIZ teachers need to consider changing the basic set of TRIZ tools that is taught to engineering professionals by taking into account their prior knowledge and practical experience [20].

4.3. The Importance of the Problem Definition Stage

Another interesting conclusion that can be drawn from the data depicted in Table 2 and from the reflections of the participants exhibited in Section 3.6, relates to the status of the problem solving stage of understanding a task that some authors identify as 'problem finding'. All 46 participants of this study positioned the stage of identifying and understanding the problem far above all other stages of problem solving. This conclusion supports the findings of many other researchers that reflected on the close relationship between problem finding and creativity [19, 21, 22].

4.4. Study Weaknesses

This study has a number of weaknesses that may restrict the conclusions drawn by the authors.

First of all, although sampling the participants for the survey makes the results of the survey statistically acceptable, this survey sample concentrated on the engineering experts that were likely to be 'creative' and may have not represented well 'an average' engineering expert involved in design and development of new products. Secondly, it engaged only expert engineers who were familiar with numerous creativity techniques. Thirdly, practically all survey participants were aware of TRIZ. Sixty nine percent of them have even used it for over five years. This is certainly not a norm for engineers working in design and development.

In other words, the conclusions drawn by this study may only represent opinions of the engineering experts who perform complex non-routine work that involves development of novel artefacts and solving very challenging problems. Therefore, these conclusions may be even more valuable to young engineers than the findings that would have been revealed by surveying 'average' engineers. In essence, the study findings can guide young engineers in attaining exceptional creative performance. They may also help academics to enhance engineering curricula for the needs of the 21st Century.

4.5. Conclusions

The following are some early conclusions of the study.

Engineering educators need to consider allocating more space in engineering curricula to units that are devoted to general knowledge – knowledge that is relevant to engineering profession, but is outside the scope of the main engineering specialisation of the pupils. This is likely to result in enhanced ability of engineering graduates to develop novel products and processes that utilise ideas from outside of their narrow discipline area.

Considering the importance of the problem solving stage of problem identification and understanding, as well as lower than expected satisfaction with TRIZ application by the surveyed, the authors wish to propose academics to include tools of classical TRIZ into their teaching toolboxes. Teaching these heuristics is likely to help students in acquisition of effective problem reframing and problem definition routines. The Method of Smart Little People, the Size-Time-Cost operator and the notion of the Ideal Ultimate Result (IUR) that require little prior knowledge and can be taught to practically anyone [20] seem suiting this purpose well [23].

The conclusions of the recent study that was carried out at Philips [24] suggest that the TRIZ procedure of Systematised Substance-Field Analysis [25] can be very effective in group idea generation. In the opinions of practicing engineers from Philips, the latter methodology helped them to generate numerous viable design ideas (that were patented) after they have unsuccessfully deployed the Brainstorming technique for idea generation. More research on effectiveness of Systematised Substance-Field Analysis for group idea generation is needed, but the first findings are encouraging.

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