Introduction

Many authors, who have researched creative problem solving have argued that human ability to solve ill-defined problems creatively is influenced by the following four major factors: (1) knowledge that is possessed by a problem solver, (2) cognitive processes and strategies that a problem solver uses, (3) individual cognitive abilities as well as (4) external factors that relate to cultural and social contexts (Amabile, 1983; Pretz, Naples, & Sternberg, 2003; Weisberg, 2006).

Assuming that these four factors influence creative performance the most, it can be presumed that university studies considerably enhance creative problem solving performance of engineering students. Engineering curricula have always placed significant emphasis onto the first two factors. Numerous study units that a student takes over the years of engineering degree cover significant amount of discipline knowledge. Therefore, it is expected that engineering graduates gain substantial amount of discipline knowledge at university. Also, students are expected to learn numerous effective problem solving and idea generating techniques during hundreds of hours of practical problem solving that they carry out both individually and in groups. Therefore, it has been often assumed that engineering degrees enhance student creativity 'by default'. Unfortunately, existing evidence does not fully support these expectations. It suggests that engineering educators need to put additional efforts to adequately enhance graduates' skills in creative problem solving.

Many authors have reported on the unsuccessful efforts of engineering educators in enhancing creative problem solving skills of engineering students (Adams, Kaczmarczyk, Picton, & Demian, 2011; I. Belski, 2011; I. Belski, Baglin, & Harlim, 2013; Daly, Mosyjowski, & Seifert, 2014; Douglas, Koro-Ljungberg, McNeill, Malcolm, & Therriault, 2012; Steiner et al., 2011; Woods et al., 1997). Researchers usually agree that engineering degrees help students to acquire satisfactory volumes of discipline knowledge. Students also gain adequate skills to solve educational problems that are well-defined and are isomorphic with the problems considered during study. At the same time, most of the programs do not appropriately equip engineering graduates with efficient methods of creative problem solving that are required for solving ill-defined problems. One of the main reasons for inability of engineering programs to develop adequate creativity skills in their graduates relates to poor planning and execution of activities that are focused on cultivating student skills in divergent thinking.

The term of divergent thinking was coined by Guilford (1950). He posited that in order to create new ideas a person has to diverge from the old. Divergent thinking skills are related to human's ability to produce multiple novel ideas. Convergent thinking, on the other hand, identifies the individual's ability of logical analysis and, therefore, her/his ability to choose the most suitable concept from a set of ideas under consideration. Both divergent and convergent thinking are of importance in engineering profession. The former is responsible for a diverse number of design/solution options and underpins creativity; the latter supports the ability of engineers to choose the best solution idea under given constraints.

Daly, Mosyjowski and Seifert (2014) have recently analysed pedagogical approaches to enhance creativity skills of engineering students that were planned in seven engineering units at a Midwestern public university as well as the outcomes of the implementation of these plans. They have discovered that the activities to enhance student skills in convergent thinking were well represented in these engineering units' plans and have been achieved overall. At the same time, the development of divergent thinking skills that are the most important in engineering creativity had not been properly planned by the academics in charge of the abovementioned seven units. Therefore Daly et al. concluded that the intentions related to enhancement of the divergent thinking skills of engineering students were unlikely to result in fostering creativity of the students enrolled into these seven units.

Conclusions presented by Steiner et al. (2011) who analysed the data from the survey of 320 engineering students from three engineering schools of the Royal Melbourne Institute of Technology (RMIT) support the hypothesis of insufficient development of divergent thinking skills in engineering programs and indicate the need for teaching divergent thinking explicitly. Firstly, Steiner et al. reported that the problem solving self-efficacy of the graduates were lower than that of the freshmen. This basically means that the four years of a degree have not prepared engineering graduates to tackling ill-defied problems (students did not see themselves ready and able). Secondly, when student responses to the survey question "What methods and approaches used by your RMIT teachers improved your engineering problem solving skills the most?" were grouped into categories, it has been discovered that only 6% of graduating students found useful the regular problem solving drills "at a low to mid-level of difficulty through which solution patterns could be learned" (Steiner et al., 2011, p. 394). At the same time, nearly 40% of graduates praised learning problem solving methods explicitly as well as being guided by academics in solving 'difficult' tasks – the activities that are the key for development of divergent thinking skills. In essence, engineering students that took part in the study of Steiner et al. thought that engineering 'drill and practice' with isomorphic problems (that are likely to enhance their convergent thinking skills) were inefficient for proper development of their problem solving skills. Survey results showed the need for teaching formal methods of problem solving and idea generation that could properly develop student skills in divergent thinking.

A number of recent studies have been devoted to successes of teaching the Theory of Inventive Problem Solving (TRIZ) to engineering students in order to enhance their skills in creative problem solving (Becattini & Cascini, 2013; I. Belski, 2009, 2015; Berdonosov, 2013; Busov, 2010; Dumas & Schmidt, 2015; Livotov, 2013). Moreover, it has been reported that even a simple TRIZ tool of Substance-Field Analysis (I. Belski, 2007) as well as the Random Word technique (de Bono, 1990) can improve the outcomes of students' idea generation and may be useful for enhancing skills in divergent thinking.

In their experiment, Belski et al. (2014) involved undergraduate engineering students of the first year in generating ideas for a real knowledge-rich, ill-defined problem. Students from a control group generated solution ideas in silence for 16 minutes. Students in one experimental group were shown eight random words for two minutes each. Students in another experimental group were shown the names of the eight fields of Substance-Field Analysis (MATCEMIB: Mechanical, Acoustic, Thermal, Chemical, Electrical, Magnetic, Intermolecular, Biological) for two minutes per field. Exposure to both eight random words and the eight fields of MATCEMIB assisted the students from the experimental groups to generate statistically significantly more independent solution ideas compared to the students from the control group (Belski et al., 2014). It has been suggested, that teaching the ideation tools similar to Random Word and Substance-Field Analysis that require only a few hours to learn may help engineering educators in enhancing students' skills in creative problem solving. It was, though, unclear whether the results obtained by Belski et al. (2014) are only RMIT-specific or they can be generalised to other cohorts of students.

This paper investigates whether exposure to random words and eight fields of MATCEMIB influences students from different universities and different background in a similar way it influenced the students involved in the Australian study. This study presents the first results from universities in Czech Republic, Finland and Russian Federation that engaged the first year students in the same experiment and compares them with the results obtained at RMIT.

Ideation Heuristics Deployed

In order to replicate the results of RMIT study (I. Belski et al., 2014), student from all participating universities were shown words that belong to two simple heuristics: (a) the Random Word technique, proposed by Edward de Bono (de Bono, 1990) and (b) the systematised Substance Field Analysis (Su-Field Analysis) (I. Belski, 2007).

Systematised Substance-Field Analysis (Su-Field Analysis)

Substance-Field Analysis (Su-Field Analysis) is a procedure that systematised the application of the classical TRIZ Substance-Field Analysis with the 76 Standard Solutions (I. Belski, 2007). Su-Field Analysis represents technical systems as a set of interconnected components – a set of substances interacting with each other by means of fields, which, in turn, are generated by the substances. Both substances and fields are sketched as circles. Su-Field Analysis allows representing different technical systems in a similar way – by means of circle-substances and circle-fields. Such generalisation allows a user to model different systems in a uniform way and to apply similar rules to resolve problems that look dissimilar, but are fundamentally alike. Su-Field Analysis consists of 5 Steps and utilises 5 Model Solutions. The 5 Model Solutions represent five general solution "recipes". In order to generate ideas, a practitioner reformulates a general model solution into the problem-specific model solution and then searches through the eight fields of MATCEMIB (Mechanical, Acoustic, Thermal, Chemical, Electric, Magnetic, Intermolecular, Biological) for solution ideas that are 'suggested' by the problem-specific model solution. It has been reported that Su-Field Analysis boosted the number of ideas generated during problem solving sessions at university (I. Belski & Belski, 2013), in industry (Dobrusskin, Belski, & Belski, 2014) as well as whilst conducting failure analysis (A. Belski, Belski, Chong, & Kwok, 2013).

Belski and Belski (2013) propounded that the effectiveness of Su-Field Analysis stems from its ability to effectively guide a user in a manual search of her/his long term memory data base. The authors pointed out that the fields of MATCEMIB actually 'cover' most of the principles of operation that can be deployed in engineering design. Therefore, Belski and Belski argued that when a problem solver is reminded of the fields of MATCEMIB, she/he is able to suggest ideas that cover more diverse solutions relevant to engineering. In other words, it is likely that learning to consider ideas suggested by the eight fields of MATCEMIB may trigger diverse ideas and, in turn, enhance divergent thinking skills of students.

Table 1. Eight fields of MATCEMIB and some field interactions (I. Belski, 2007, p. 17)

<table>
<tr><th>Fields</th><th>Interactions Including</th></tr>
<tr><td>Mechanical</td><td>Gravitation, collisions, friction, direct contact
Vibration, resonance, shocks, waves
Gas/Fluid dynamics, wind, compression, vacuum
Mechanical treatment and processing
Deformation, mixing, additives, explosion</td></tr>
<tr><td>Acoustic</td><td>Sound, ultrasound, infrasound, cavitation</td></tr>
<tr><td>Thermal</td><td>Heating, cooling, insulation, thermal expansion
Phase/state change, endo- exo-thermic reactions
Fire, burning, heat radiation, convection</td></tr>
<tr><td>Chemical</td><td>Reactions, reactants, elements, compounds
Catalysts, inhibitors, indicators (pH)
Dissolving, crystallisation, polymerisation
Odour, taste, change in colour, pH, etc.</td></tr>
<tr><td>Electric</td><td>Electrostatic charges, conductors, insulators
Electric field, electric current
Superconductivity, electrolysis, piezo-electrics
Ionisation, electrical discharge, sparks</td></tr>
<tr><td>Magnetic</td><td>Magnetic field, forces and particles, induction
Electromagnetic waves (X-ray, Microwaves, etc.)
Optics, vision, colour/translucence change, image</td></tr>
<tr><td>Intermolecular</td><td>Subatomic (nano) particles, capillary, pores
Nuclear reactions, radiation, fusion, emission, laser
Intermolecular interaction, surface effects, evaporation</td></tr>
<tr><td>Biological</td><td>Microbes, bacteria, living organisms
Plants, fungi, cells, enzymes</td></tr>
</table>

The experiment conducted in this study was limited to exposing students to the eight fields of MATCEMIB. Each field was presented to students either alone, or together with a simplified list of interactions that illustrated the scope of actions covered by this particular field. Table 1 displays this simplified list of MATCEMIB interactions.

Random Word (RW)

Edward de Bono, suggested that Random Word "is the simplest of all creative techniques" (de Bono, 1995, p. 17). The Random Word technique prescribes a problem solver to use a random word that is not connected to the problem under consideration. De Bono advocated that the Random Word technique helps a user to generate more ideas, because humans use patterns for problem recognition and problem solving and that

> *the random word provides a new entry point and as we work back from the new entry point, we increase the chances of using patterns we would never have used if we had worked outwards from the subject area (p. 18).*

Random words can be obtained in many ways. Lists of random words that a practitioner can choose from as well as random word generators are freely available on the web. In RMIT study, random words were generated by the researchers as suggested by de Bono (1995), by using a dictionary. The following are the eight random words that were used in RMIT study: Archaism, Right angle, Lotus eater, Emitter, Ozone, Blowhole, Ball-and-socket-joint and Hanky-panky. In order to conduct experiments in Czech Republic, Finland and Russia these eight random words were translated into the student native languages.

Methodology

The first year students from Brno University of Technology (BUT), Lappeenranta University of Technology (LUT) and Komsomolsk-on-Amur State Technical University (KNASTU) participated in this study. At each participating university four tutorial groups were involved in the experiment. The following is a record of activities that tutorial groups at each university were involved in.

Students from one experimental group were shown the eight random words (the 'Random Word' group). Students from the other two experimental groups were influenced by the eight fields of MATCEMIB (the 'MATCEMIB' and 'MATCEMIB+' groups). The students from the forth group were not influenced in any way – this group represented a Control group. All students were given 16 minutes of tutorial time to individually generate as many ideas as possible for the same problem (to remove the lime build-up in pipes). This problem was used in the original RMIT study and was suggested by the Engineers Without Borders (EWD) 2014 Challenge as a possible student project for 2014.

Initially, the same Power Point slide that contained the problem statement translated into the appropriate language and a photo of a cross-section of a pipe half of which was covered with lime deposit was presented to the students for two minutes by their tutors. Figure 1a depicts the English version of the problem statement that was presented to students from all groups.

After two minutes of problem introduction that coved only the information presented in Figure 1a, all students were asked to work individually and to record as many ideas to clean the pipes from lime as possible (ideas were recorded in student own languages). The form to record ideas was distributed to the students just before the problem was presented. The form was the same for the students of all four groups. It was a copy of RMIT form that was translated into Czech and Russian for the students from BUT and KNASTU. The students from LUT used the original RMIT English version of the form.

Students from the Control groups were not influenced by any ideation methodology. After two minutes of problem introduction, they were allowed to think of solution ideas and to record them for 16 minutes. The slide shown in Figure 1a was presented to the students from the Control groups for the whole duration of the idea generation session.

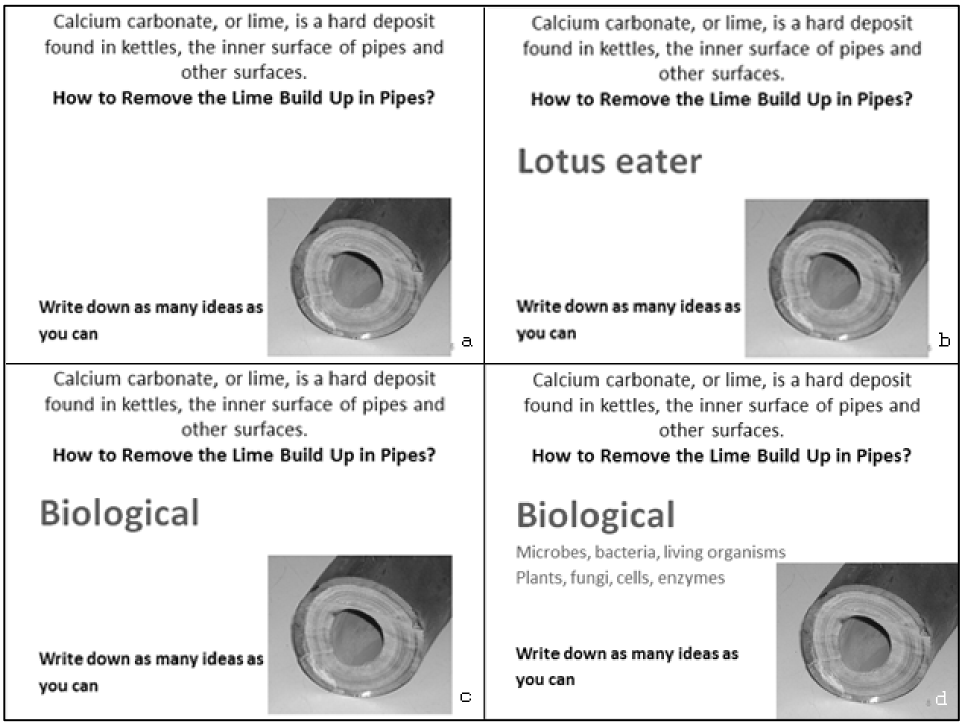

Figure 1: The English version of the Power Point slides presented to students in their own languages: a) task introductory and the Control Group; b) Random Word group; c) MATCEMIB group; d) MATCEMIB+ group.

After the two minutes of problem presentation, students from the experimental groups were told that during their idea generation session they will be shown some words. No clarifications on what these words are and what to do with them were given. Students from the Random Word groups were offered the translations of the eight random words that were used in RMIT study. Students from the MATCEMIB and MATCEMIB+ groups were offered the translations of the eight fields of MATCEMIB in the sequence presented in Table 1. Each word was shown to the students from the experimental groups for two minutes. Every two minutes a tutor changed the word on the screen and read the new word aloud. It is important to note that when a tutor of the MATCEMIB+ group changed slides every two minutes, he read aloud only the name of the field of MATCEMIB that was displayed, but did not read the words that corresponded to the field's interactions that were displayed together with the field's name.

Figure 1 depicts the English version of one of the eight Power Point slides that were shown to the students from different groups in all countries: Figure 1a – the Control groups; Figure 1b – the Random Word groups; Figure 1c – the MATCEMIB groups; Figure 1d – the MATCEMIB+ groups. Altogether the students from the experimental groups were generating and recording ideas for 16 minutes.

Results

Student ideas were evaluated by independent assessors that used the criteria developed for RMIT study. Among other items, assessors counted the number of distinct (independent) ideas proposed by each student. In order to judge how broad or 'divergent' these independent ideas were, each idea was assigned to a specific field of MATCEMIB. The ideas of student from KNASTU were evaluated by three assessors. The work of students from BUT and LUT were assessed by two assessors each. The inter-rater reliability of assessment by independent assessors was evaluated for all universities separately with SPSS by establishing the Cronbach's Alpha for the number of independent ideas proposed by each individual student. Cronbach's Alphas for all universities (including RMIT) exceeded 0.9. The Cronbach's Alpha coefficient over 0.9 suggests excellent internal consistency. Therefore, the assessment of students from all countries was evaluated as very reliable. For further analysis the number of independent ideas proposed by each individual student made by the assessors from the same country was averaged.

Table 2 presents the result of all four experiments for the number of independent ideas proposed by each individual student. It also contains information on the group sizes.

Table 2. The average number of independent ideas proposed by students from four countries

Group Information	Australia			Czech Republic			Finland			Russia		
	Stud.	Mean	SD	Stud.	Mean	SD	Stud.	Mean	SD	Stud.	Mean	SD
Control	21	2.02	1.44	18	3.56	1.55	8	5.81	1.89	21	4.32	1.44
Random Word	17	3.25	1.85	16	3.78	1.64	8	5.69	1.03	24	3.29	1.79
MATCEMIB	15	3.65	2.15	17	6.50	1.76	5	9.30	2.59	20	5.65	2.64
MATCEMIB+	18	5.13	2.07	18	6.92	3.19	6	9.67	3.27	23	6.62	2.37

The differences between the numbers of independent ideas generated by students from all four countries were statistically significant for Control group vs MATCEMIB and MATCEMIB+ groups. Statistical significance was discovered for the number of ideas proposed by students from Random Word group vs MATCEMIB and MATCEMIB+ groups for student from BUT, LUT and KNASTU. While RMIT students from the Random Word group generated statistically significantly more ideas than the students from the Control group, KNASTU's Control group statistically significantly outperformed the Random Word group. The differences between all other groups of students from the same university were not statistically significant.

Table 3 reveals the 'breadth' of the ideas generated by students from different groups.

Table 3. The 'breadth' of the ideas proposed by students from four countries over the eight fields of MATCEMIB

Group	Australia	Czech Republic	Finland	Russia
Control	2.05	2.53	2.75	2.57
Random Word	2.38	2.47	3.38	2.38
MATCEMIB	3.53	5.53	5.60	4.30
MATCEMIB+	4.44	4.56	6.00	5.59

The breadth of ideas was calculated as a sum of eight terms, each equal to a fraction of students that proposed ideas that were assigned by the assessors to each field of MATCEMIB. It has been discovered that the majority of ideas proposed by students from the Control groups were of Mechanical, Chemical or Thermal nature. The students from the MATCEMIB and MATCEMIB+ groups proposed solutions that 'covered' most of the eight field of MATCEMIB. For example, the following is the spread of the ideas proposed by the students from the Control group at RMIT: 95% of students proposed Mechanical ideas; 5% - Acoustic; 14% - Thermal; 86% - Chemical; 0% - Electric; 0% - Magnetic; 0% - Intermolecular; 5% - Biological. Therefore, the breadth of ideas *B* proposed by the Control group from RMIT was equal to:

$$B = 0.95 + 0.05 + 0.14 + 0.86 + 0 + 0 + 0 + 0.05 = 2.05$$

The ideas put forward by the students from the MATCEMIB+ group at RMIT was significantly broader: 89% of students put forward Mechanical ideas; 28% - Acoustic; 78% - Thermal; 100% - Chemical; 44% - Electric; 22% - Magnetic; 28% - Intermolecular; 56% - Biological. Most of the ideas generated by the students from the Random Word groups belong to two fields: Mechanical and Chemical. The following is the spread of the ideas proposed by the students from the Random Word group at RMIT: 100% of students proposed Mechanical ideas; 6% - Acoustic; 19% - Thermal; 94% - Chemical; 0% - Electric; 6% - Magnetic; 0% - Intermolecular; 13% - Biological.

Discussion

The outcomes of the experiments conducted in Russian Federation, Finland and Czech Republic only partly support the conclusion drawn by RMIT study (I. Belski et al., 2014). The influence of the eight fields of MATCEMIB has been fully replicated. Students from the MATCEMIB and the MATCEMIB+ groups in each country proposed statistically significantly more ideas than their counterparts from the Control groups. At the same time, the eight random words shown to the students from BUT, LTU and KNASTU did not boost the numbers of ideas proposed compared to the Control groups as it happened at RMIT. On the contrary, the Control group from KNASTU statistically outperformed the Random Word group. The difference in the number of independent ideas suggested by the students from the Control groups and the Random Word groups from BUT and LTU were statistically insignificant.

The fact that the results of RMIT study on the influence of the eight fields of MATCEMIB have been replicated by three other universities in three different countries reinforce the position of Su-Field Analysis as a simple ideation heuristics that is able to effectively enhance problem solving skills of engineering students.

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