Engineering Creativity – How To Measure It?

Iouri Belski[a]
Royal Melbourne Institute of Technology[a]
Corresponding Author Email: iouri.belski@rmit.edu.au

SESSION S2: Educating The Edisons Of The 21st Century

CONTEXT Scholars have been interested in sources of creativity and the ways to enhance it for centuries. The domain of human creativity has been extensively researched for over 100 years. Nonetheless, the researchers have neither agreed on the definition of creativity nor on the proper methodologies to measure it (Lubart & Besançon, 2016; Simonton, 2016). Some scholars suggested that creativity means different things in different domains (Baer, 2016; Weisberg, 2006) and argued that the definitions and the means to measure creativity need to be domain specific.

PURPOSE Establishing the definition of engineering creativity and devising the criteria and the means to assess it is of utmost importance for the development of engineers for the 21st Century. Unless engineering educators are able to accurately measure creativity skills of their students, they will be unable to establish ways to nurture creativity skills.

APPROACH Research literature relevant to creativity in the domain of technology is reviewed in order to establish how creativity is defined and how it is measured in engineering. Legal grounds of patentability and patent authorship are analysed. Findings are systematised and reflected upon.

RESULTS The following definition of creativity for the engineering profession is proposed: "*Engineering creativity is the **ability** to generate novel solution ideas for open-ended problems, ideas that are not obvious to experts in a particular engineering discipline and that are considered by them as potentially useful*".

Based on the definition, it is proposed to measure engineering creativity by engaging subjects in generating ideas for open-ended problems and counting (i) the number of independent ideas proposed by the subject as well as (ii) the breadth of these ideas. It has been posited that the eight dimensions of MATCEMIB (Mechanical, Acoustic, Thermal, Chemical, Electric, Magnetic, Intermolecular and Biological) is the most suitable means to 'count' the breadth of ideas.

CONCLUSIONS In order for engineering education to judge on successes of their programs in enhancing students' creativity skills and to establish which teaching methods are the most efficient for the purpose, (1) suitable definition of engineering creativity that is agreed upon by engineering educators as well as (2) reliable means to measure engineering creativity is needed. This paper proposes both a suitable definition of engineering creativity and suggests the measures for creativity assessment that are adequate for the engineering profession.

KEYWORDS Creativity, engineering creativity, assessment, problem solving, engineering, engineering education.

Introduction: creativity is domain specific

Both Pablo Picasso and Nikola Tesla are known as extremely creative individuals. The former created art innovations, the latter – engineering marvels. Could the creations of Picasso be measured by the same gauge as developments of Tesla? Over many years creativity scholars tried to define and measure creativity as a general skill. It was expected that this general creativity skill is identical in all areas of human activities and, therefore, transfers from one domain to another. As a result, numerous tests that 'measured' the level of this general creativity were developed. Cropley mentioned that by the end of the last Century at least 255 instruments to assess creativity were in existence (Cropley, 2000). Thys, Sabbe and De Hert (2014) reviewed research publications on creativity tests over the last six decades. They analysed 121 publications and discovered 111 measures of creativity used by the authors. Thys et al. categorised the instruments into four groups in accordance with the 4P model of creativity that was proposed by Rhodes more than 50 years ago (Rhodes, 1961). These model subdivided creativity into four Ps (facets): (i) creative Person, (ii) creative Process, (iii) creative Product and (iv) creative Press (conditions).

The popularity of the 4P model amongst creativity scholars resulted in development of instruments to assess each of the four facets of creativity. As a result, only a minority of the instruments to measure creativity directly tested subjects' performance (Belski, Hourani, Valentine, & Belski, 2014; Sarkar & Chakrabarti, 2011). Instead the instruments engaged subjects in surveys, self-reports or relied on psychometric tools, nominations by experts, supervisor evaluation and peer judgement (Carpenter, 2016).

Over the last two decades more and more scholars posited that creativity is domain-specific (Baer, 2015) and that being creative in one domain does not inevitably make a person creative in another domain (even if this second domain is adjacent to the first) (Baer, 2012; Weisberg, 2006). The domain specificity of creativity is also supported by publications that demonstrated domain specificity of creativity training and discovered negligible transfer of the creativity training gains to other knowledge domains (Baer, 2016). These findings question a utility of any universal instrument of creativity measurement. They advocate for the need of a special instrument that would enable to accurately assess creativity for the engineering profession.

Measuring creativity in engineering

Owens' battery of tests

Engineers have been trying to develop creativity assessment instruments for a long time. Owens, Schumacher and Clark, who proposed a battery of tests to measure creativity in machine design over 60 years ago (Owens, Schumacher, & Clark, 1957) mentioned that some earlier tests were developed by Harris and Simberg from General Motors. These tests were devised to increase "*the supply of potential talent* [to industry] *either through appropriate training or through the discovery of conditions optimally conducive to the problem-solving process*" (p.297). Owens *et al.* did not define engineering creativity explicitly and stated that they were exploring "*a problem-solving, goal-oriented, utilitarian sort of ingenuity…"* (p. 301).

The battery of test developed by Owens *et al.* consisted of four components: two survey instruments and two completion type tests. The Personal Inventory component (PI) contained 197 items that covered interests, personal experiences, opinions, etc. The Personal History form (PH) was made of 48 questions that were related to personal background. Scoring of the PI component and the PH form were similar. It was related to the number of responses that were typical to that of the creative engineer. The Power Source Apparatus test (PSA) engaged a subject in sketching as many intervening mechanisms as possible for the given power source and the motion sequence. The PSA performance was evaluated by the absolute number of solutions and the number of 'workable' solutions proposed. The Application of Mechanisms test (AMT) required a subject to suggest as many types of mechanisms as possible that a given (sketched) mechanism can be a part of. The AMT performance was measured by a number of suggested mechanisms.

Owens *et al.* validated their battery tests by engaging 295 engineers from 31 industrial firms. Creativity skills of the participating engineers were established on the basis of two criteria. The first criterion was related to the creativity level that a work supervisor (chief engineer) assigned to each individual engineer from his company that participated in the experiment. The second was a number of the US Patens that an individual subject was the (co) inventor of. The number of patents was established by means of the PI component that directly asked subjects to report their US Patents.

Twelve years later Owens reported on the longitudinal outcomes of creativity assessment using the above-mentioned battery of tests (Owens, 1969). He compared actual achievement of 938 engineers in 1964 that, being students of mechanical engineering, completed the battery of tests in 1955. He also used the outcomes of tests on mental ability and scholastic aptitude that were administered by the American Council on Education (ACE) in 1953. One hundred and sixty seven engineers that participated in the 1964 study completed the ACE tests as college freshmen in 1953.

Owens' 1964 evaluation comprised two inventories: the Life History Questionnaire (LHQ) that consisted of 181 items related to the subject's experience and demographics; and the Job Environment Survey (JES) that was expected to assess the "research climate" and consisted of 80 questions. As in the study of 1957, Owens' main criterion of creativity was the number of patents and patent disclosures reported by the participant. The number of workable solutions proposed by a subject in the PSA test as well as the number of overall solutions suggested by the subject were found to predict the creativity level achieved by an engineer much more accurately than AMT and the tests of mental ability and scholastic aptitude.

Purdue Creativity Test

Another test to evaluate engineering creativity was proposed by Harris. This test is also known as the Purdue Creativity Test (PCT) (Harris, 1960). Harris defined creativity in engineering as "*the ability to produce a number of original ideas when confronted with problematic situation*" (p. 254). Harris assumed that creative engineers (i) are able to produce more ideas, (ii) can change their frame of reference easier and quicker, (iii) more able to produce uncommon ideas and (iv) better able to visualise in space.

The PCT instrument utilised three types of questions. The first type expected a subject to list as many uses for a pictured object as possible. The second type asked of possible usages of two objects pictured together. The third expected a participant to suggest as many possible options of an object that was presented in another picture. The PCT measured creativity with the Creativity Score that was a sum of scores for Fluency (number of different ideas), Flexibility (score based on the number of different categories of solution ideas) and Originality (score based on the weighting of the different categories). The PCT was developed through analysis of responses of 345 students at Purdue University. The Creativity Score was validated by 64 product development engineers from the automotive industry. Harris found that the Originality score highly correlated with the Flexibility score and suggested that the former can be dropped from the test altogether.

The PCT and the Owens battery test were developed for selection of engineers in jobs that required novel problem solutions. Because of this practical purpose and an openly engineering focus of the tests they have not been used much by creativity scholars.

Creative Engineering Design Assessment

In the last decade another test of engineering creativity, the Creative Engineering Design Assessment (CEDA) was proposed by Charyton, Jagacinski and Merrill (2008). Charyton *et al.* advocated that the Owens' battery of tests as well as the PCT only assess divergent thinking skills and, therefore, do not adequately measure engineering creativity that demands much broader cognitive skills. CEDA was developed to evaluate creative skills of engineering designers more holistically. The author intended to assess problem finding as well as problem solving. Therefore, as posited by Charyton *et al.*, CEDA incorporates evaluation of both skills in divergent and convergent thinking and is more accurate than other measurement instruments of engineering creativity. Charyton *et al.* have utilised the 4P model of creativity but did not offer the definition of creativity explicitly. They have only indicated their view on the Process P: "*creative process is defined as using divergent thinking, convergent thinking, constraint satisfaction, problem solving and problem finding to create a design*" (p. 149).

The CEDA evaluation engages a subject in sketching designs "*that incorporate one or several three-dimensional objects, list potential users (people), and perform problem finding (generate alternative uses for their design) as well as problem solving in response to specific functional goals*" (p.148). The CEDA subjects are given 25 minutes to consider five design problems. The CEDA score is a sum of individual scores on Fluency (number of responses), Flexibility (number of response categories) and Originality (qualitative number assigned to the entire problem). It is important to note that only up to four design proposals (responses) per problem are scored. Therefore the CEDA subjects are instructed to provide not more than four designs per problem.

In 2008 Charyton *et al.* (2008) reported using CEDA to evaluate creativity of 58 engineering students and 59 students of psychology. In a follow-up study Charyton and Merrill (2009) engaged 61 first year engineering students and 21 non-engineering students in the CEDA sessions. In both studies the authors compared the CEDA scores with the outcomes of the following three instruments: (1) Creative Personality Scale (CPS) (Gough, 1979), (2) Creative Temperament Scale (CTS) (Gough, 1992), and (3) Cognitive Risk Tolerance Survey (CRT). Although the authors of both the 2008 and the 2009 studies evaluated CEDA assessment of engineering creativity as reliable, neither study found any correlation of CEDA scores with that of CPS, CTS or CRT.

Testing engineering idea generation

Over the last five years the team led by Belski reported on the outcomes of idea generation experiments that engaged over 500 engineering students from six countries (Belski et al., 2015; Belski et al., 2014; Belski, Livotov, & Mayer, 2016). All students were asked to generate as many ideas as possible for the same open-ended problem. Student performance was assessed by two criteria: (i) the Number of distinct ideas proposed and (ii) the Breadth of the proposed ideas. The former criterion was practically the same as the number of ideas in the Owens' PSA test and Fluency that were used by both PCT and CEDA. The latter criterion was similar to that of Flexibility utilised by PCT and CEDA. Breadth was defined much more formally than Flexibility. To determine Flexibility of ideas it was necessary to devise the list of response categories and to decide on the maximum number of categories for assessment. Breadth had been defined to contain eight 'dimensions' of technology, each corresponding to a specific group of technologies: Mechanical, Acoustic, Thermal, Chemical, Electric, Magnetic, Intermolecular and Biological (MATCEMIB). A student, who suggested ideas that used three of the eight dimensions, received the Breadth score of 3. Her colleague that proposed solution ideas that utilised five dimensions – the Breadth of 5. Belski *et al.* argued that the Number of distinct ideas proposed and the Breadth of these ideas can adequately assess student's divergent thinking ability (Belski et al., 2015). Belski *et al.* did not provide their definition of creativity.

Engineering creativity and patentability

The need of a common definition of engineering creativity

In order to measure anything accurately it is necessary to (i) explicitly define what is to be measured and (ii) establish the means and the units of measurement. The authors of the above-mentioned instruments that were developed to assess engineering creativity did not use the same definition of engineering creativity. Moreover, only Harris offered the definition explicitly: "*the ability to produce a number of original ideas when confronted with problematic situation*" (Harris, 1960, p. 254). Owens *et al.,* Charyton *et al.* as well as Belski *et al.* were not very clear with their definitions. Owens *et al.* tried to measure "*a problem-solving, goal-oriented, utilitarian sort of ingenuity…"* (Owens et al., 1957, p. 301). Charyton *et al.* focused on the creativity process and tried to assess divergent and convergent thinking as well as problem solving and problem finding skills. Belski *et al.* considered only the divergent thinking skills. Clearly, the absence of a definition of what creativity means for the engineering profession holds the development of adequate measurement instruments. What can help in establishing such distinctly engineering definition of creativity?

Engineering profession is in a unique position regarding the definition of creativity. It is one of a very few fields of human activity that has been judging the level of creativity by the formally established rules for quite some time – by means of rules of patentability. Today the question on what can be considered as novel creation in engineering and what cannot, does not seem difficult to answer. Although criteria of patentability differ a little from country to country, they offer a universal approach to the definition of creativity for the engineering domain. It needs to be noted that the validity of patentability as a criterion of engineering creativity did not change in the last 60 years. Owens *et al.* used the US Patent count as the criterion of creative engineering performance for validating his battery of tests in 1957 and in 1964.

Patentability and creativity

Patent laws usually require that, for an invention to be patentable, it must:

A. Be *novel*

B. *Involve an inventive step* (European and Australian patent laws) or *be non-obvious* (United States patent law)

C. *Be able to be made or used in an industry* (Australian patent law) or *be susceptible of industrial application* (European patent law) or *be useful* (United States patent law).

Let us consider the meaning of each of the three criteria separately.

Novelty

In accordance to the Patent Manual of Practice & Procedure (IP Australia, 2017) there is only one test for novelty:

> *"The test for determining whether an invention lacks* ***novelty*** *is the "reverse infringement test" as set out in Meyers Taylor Pty Ltd v Vicarr Industries Ltd (1977) CLR 228 at page 235; 13 ALR 605 at page 611, where Aickin J stated:*
>
> *"The basic test for anticipation or want of novelty is the same as that for infringement and generally one can properly ask oneself whether the alleged anticipation would, if the patent were valid, constitute an infringement.""*

In other words, in order for anything to be novel, an expert in the field must conclude: "I have not been able to find anything like it!"

Inventive step

As per the Patent Manual of Practice & Procedure (IP Australia, 2017) an examiner can determine lack of **inventive step** if:

“the claimed invention is one of:

- *a technical equivalent;*
- *a workshop improvement;*
- *a special inducement or obvious selection; or*
- *an obvious combination of features of common general knowledge.”*

This means that in order to satisfy the criterion of *inventive step*, the invention (i.e. solution to a problem) must not be obvious for an expert in the technological field of the invention. So an expert in the field is expected to conclude: “It is interesting!”

It is important to note that in order to pass the criterion of inventive step a solution needs to solve an open-ended problem. It is highly unlikely that a solution to a closed-ended problem in a particular engineering field will not be obvious for an expert in this domain.

Usefulness

The Patent Manual of Practice & Procedure (IP Australia, 2017) does not offer explicit guidelines on how to assess whether the proposed invention is able to be made or used in an industry. This omission implies that the criterion of usefulness is secondary to that of novelty and inventive step. The absence of explicit guidelines on assessment of usefulness may be explained by challenges in predicting what technologies and materials will be available in the future. A proposed product may be very difficult to make using the existing materials and technologies, but just in a near future some new materials and equipment may make its manufacturing simple. An expert in the field, assessing such proposal is likely to say: “It may be possible!”

After a short analysis of patentability it can be concluded that in order to be considered as a patent, a solution needs to solve an open-ended problem, must not be known before, must not be obvious to an expert in the technological field of the invention and must be evaluated by the expert as ‘possible’.

Patent authorship and creativity

The majority of legal cases on inventorship that were considered in Australia and USA specifically focused on the individual contribution to the inventive concept. In order to establish the authorship of the invention, the judges have normally tried to establish who really conceived the idea that underpins the invention. The legal case of Townsend v. Smith ("Townsend v. Smith," CCPA 1930) is usually referred to for the definition of the conception:

> *“The conception of the invention consists in the complete performance of the mental part of the inventive act. All that remains to be accomplished in order to perfect the act or instrument belongs to the department of construction, not invention. It is therefore the formation in the mind of the inventor of a definite and permanent idea of the complete and operative invention as it is thereafter to be applied in practice that constitutes an available conception within the meaning of the patent law.”*

In essence, legal practitioners consider authorship as mental act of idea generation. In other words, this legal definition of patent authorship nominates human ability to generate novel ideas (i.e. divergent thinking) as the major skill of engineering creativity. This means that the definition of engineering creativity needs to be closely related to human ability of generating ideas. Consequently, instruments of creativity measurement in engineering have to assess the skill of divergent thinking (i.e. idea generation), and not to devote much attention to evaluation of the convergent thinking skill.

Defining engineering creativity

Let us combine the findings from considerations of patentability and authorship. First of all, analysis of authorship established that a creator of an invention is a person that originally developed the idea for the invention. This implies that creativity is a human **ability** to generate solution ideas. Secondly, as per criteria of patentability, the idea needs to solve an open-ended problem, be novel, not obvious to an expert and accepted by her as possible. Consequently, engineering creativity can be defined as:

> *Engineering creativity is the **ability** to generate novel solution ideas for open-ended problems, ideas that are not obvious to experts in a particular engineering discipline and that are considered by them as potentially useful.*

Interestingly, this definition of engineering creativity can be viewed as expansion and clarification of the definition given by Harris nearly 60 years ago:

> *"the **ability** to produce a number of original ideas when confronted with problematic situation"* (Harris, 1960, p. 254).

How to measure engineering creativity?

The definition of creativity proposed by this study can be subdivided into the following three parts that can guide the design of an appropriate measurement instrument: (1) it is an ability to generate novel ideas to solve an open-ended problem, the ideas that are (2) non-obvious to an expert in the domain and (3) can be implement (today or in the future).

Ideally, an instrument to measure engineering creativity needs to assess all three parts of the creativity definition. Practically such assessment would not be realistic. Evaluation of novelty (1) would require thorough patent/publications search. Assessment of the other two parts would require engagement of experts. A pragmatic approach that can be implemented by university academics without massive investment of time and money may look similar to that used by Owens *et al.* (1957) in their PSA test or by Belski *et al.* (2015) to assess student idea generation performance.

Subjects are to be asked to record as many ideas as they can for an open-ended problem, which can be understood by them reasonably well (e.g. a problem that requires only basic knowledge of science to comprehend). The subjects' performance can be evaluated using the criteria that have been validated by Owens *et al.* (1957) and Harris (1960) as specifically suiting the engineering profession. These criteria are: (i) the number of independent ideas proposed by the subject (Fluency) and (ii) the Flexibility of these ideas. Counting the number of independent ideas seems straightforward. A measure of Flexibility is more challenging to decide upon. It is possible that the eight dimensions of MATCEMIB used by Belski *et al.* (2015) is the most suitable means to 'count' Flexibility. These eight dimensions practically cover most of the professional fields within the engineering domain, so ideas can be adequately classified. Accepting the MATCEMIB dimensions as the Flexibility measure can also eliminate the need to define sets of idea categories for every problem offered to subjects in order to assess their creativity. This will ascertain achieving higher inter-rater reliability of creativity assessments. The eight dimensions of MATCEMIB are clearly defined and would mean the same to an engineer from any part of the world. Also, the number of dimensions (breadth) seems to adequately evaluate the non-obvious nature of a solution. The higher the breadth of the proposed ideas, the broader are the operational principles that these solution ideas utilise. Expecting that an expert in any engineering domain holds expertise in two to three of the eight dimensions of MATCEMIB, the breadth of the ideas proposed by a subject would be a clear measure of whether the ideas proposed are non-obvious.

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