Teaching Engineering Creativity at Tertiary Institutions

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Abstract: *In this paper results of 20 years of experimenting by the author in teaching engineering creativity in Australia and overseas are discussed. Teaching approaches and materials are presented and problems and difficulties encountered with these approaches are analysed.*

Keywords: *engineering creativity, tertiary institutions, teaching*

Introduction

Engineering creativity is a topic that continues to generate hot discussion and polarise points of view. Confusion is often caused by a lack of understanding and ability to differentiate the following:

- Thinking and intelligence.
- Creative thinking and creativity.
- Problem-based teaching and systematic teaching of problem solving methodologies.
- Is it possible to teach engineering creativity?
- How does one encourage creativity?

There are clear answers to these questions and they will be discussed in the following sections.

There is a large variety of problem solving methods, such as, the 'Try-and-see' approach, the 'Checklist' method" the 'Morphological Box' method, the 'Ideal Final Result' analysis, the 'I wish' method', the 'Ah-Ha' method, the 'Smart Little People Modelling' method, the 'Brainstorming' method, 'Synectics', and, finally, the 'Theory of Inventive Problem Solving' (TRIZ) and the 'Ideation / TRIZ' methodology. When one is asked, "What problem solving methods do you know?" a typical answer is "Brainstorming", and sometimes Lateral Thinking is mentioned. It is not surprising because many tertiary sector educators are unaware of the variety of problem solving methods available.

When the Institution of Engineers, Australia introduced the list of 10 generic skills (one of them was "Ability to undertake problem identification, formulation and solution") all universities immediately responded by including in study guides and unit outlines expressions such as, "Creative thinking is encouraged through problem-based learning, brainstorming sessions, etc.). But how many universities in Australia systematically teach engineering creativity? To the knowledge of the author of this paper, there are only two or three. Many engineers and educators mistakenly think that any discussion is brainstorming, when there are strict rules of Brainstorming session preparation and supervision. Another delusion is their use of problem-based teaching and encouraging group discussions it is teaching engineering creativity.

On the contrary, in the United States about 30 universities systematically teach the Ideation / TRIZ methodology in engineering units and some have even introduced elective units based on the Ideation / TRIZ methodology.

In the early 80's the Ministry of Tertiary Education of the former USSR introduced at university level a core unit "Fundamentals of engineering creativity". Students were systematically taught problem solving methods and under supervision of leading academics participated in research. It was common for students' names to appear in research publications and patent applications. At the same time Genrich Altshuller, the founder of classical TRIZ, published his first books [1], making the theory available for engineers, researchers and educators. The author of this paper who was at that time working at the Azov State Technical University (Mariupol City, Ukraine), started experimenting with systematic teaching of engineering creativity, and developing curriculum, and teaching and learning resources. After immigrating to Australia in 1992 he continued the development of materials for teaching TRIZ and other problem solving methods and introduced systematic teaching of engineering creativity at Monash University in 1995 and at the Queensland University of Technology in 1999. His exercise book on solving problems with TRIZ [2] was published in the USA in 1999, and then translated into Japanese and published in Japan in 2000 [3]. Results of these experiments, and teaching and learning materials will be discussed below.

Is it Possible to Teach Engineering Creativity?

The importance of this issue has been well recognised. For example, during the World Innovation and Strategy Conference (WISC98), Sydney, Australia [4], new sessions were introduced, such as "TRIZ and Other Techniques", "Product and Process Innovation", "Innovation in Education", "Organisational Creativity and Learning" and "Innovation network". During conference discussions many speakers, especially from industry, insisted that creativity couldn't be taught; creativity is something that some gifted people acquire at birth (If you want to be creative, carefully chose your parents). Other speakers (e.g. Belski, and Kosse, [4] pages 194 and 239 respectively) gave examples of how problem-solving tools can be effectively used to support creative thinking.

Edward de Bono [5], a well-recognised authority on the theory of thinking, states that **thinking** is a skill that can be learned, whereas **intelligence** is an inherent capability largely determined by genes. A conference sponsored by the American Society for Engineering Education (ASEE), the National Science Foundation (NSF) and the US Department of Commerce held in the mid-60's concluded that the creative requisites of invention and innovation could be taught, but that engineering schools were not doing an adequate job.

One thing is certain, the efficiency of thinking can be significantly improved if a thinker is equipped with different problem solving tools. Methods that facilitate creative thinking can be divided into three groups:

- Methods and exercises that improve thinking (e.g. De Bono's Thinking Course).
- Methods that facilitate creative thinking when thinkers employ their own knowledge and experience (e.g. Brainstorming).
- Methodologies, such as Ideation / TRIZ, that facilitate thinking, equip thinkers with analytical and knowledge-based tools that enable them not just to solve problems, but to make scientific predictions in particular areas of engineering.

The history of the development of the Ideation / TRIZ methodology, when it flourished first in the former USSR and then in the USA, proves that creative thinking and creative problem –solving tools can be taught. The question is what can be taught and what teaching approaches can be used within the limited timeframe and overloaded programs of engineering units.

Review of Methods that Could Facilitate Thinking and Creative Problem Solving

Some approaches to thinking are known from ancient times (e.g. critical thinking); others have been developed in the 20th century. Critical thinking (from the Greek word *kriticos* which means judge) is based on the concept that if to remove "untruth", then what is left is "truth". The question can be asked as to whether successful destruction of one idea will give rise to a better one. Somebody has to suggest new solutions using problem-solving methods. Among the known methods there are very simple ones to use (e.g. the Try and see method); others, such as the Ideation / TRIZ, are comprehensive methodologies that take weeks just to learn the fundamentals and months, or even years, to master skills in using them. A review of known methods that facilitate creative thinking is given below with a brief description and analysis of advantages and limitations.

Edward De Bono is considered by many to be the leading authority in the world on direct thinking as a skill. Having background in medicine and psychology, he developed dozens of exercises and approaches for improving thinking process and originated the term "lateral thinking", which is now in the Oxford English Dictionary. Among the approaches and exercises he suggested are: PNI (positive, negative and interesting aspects of the object), APC (alternatives, possibilities choices), "L-Game", Lateral Thinking, CAF (consider all factors), CS (consequences and sequel), DRDL (dense reading and dense listening), EBS (examine both sides), OPV (other people's views), seven thinking hats, etc., [5]. De Bono's methodology is highly effective in improving thinking as a process and carrying comprehensive analysis of the object, however, it could hardly be regarded as a structured method of engineering problem solving.

The Try-and-See Method (also known as the Trial and Errors Method)

Everybody uses it, however its effectiveness is questionable unless other approaches are used simultaneously, for example the list of physical effects or analogy.

The Checklist Method

The essence of this method is in examining an object against different lists of verifying questions (checklists). Many professional inventors developed their own checklists. The author of this paper gathered several comprehensive checklists [6] that include General checklist, Problem need checklist, Fact finding/descriptive categories, Applied imagination checklist, Manipulative verbs and Searching checklist. This method can be used at early stages of design to reveal shortcomings of an existing model and often gives an insight to how it can be improved.

The Ideal Final Result Method

This method has been suggested by Altshuller as one of the tools within the Classical TRIZ, but it can also be used on its own. The essence of the method is in stating the "Ideal Final Result". There are six ways of achieving "ideality": Exclude auxiliary functions, Exclude elements, Identify self-service, Replace elements, Change the principle of operation, and

Utilise existing resources in central. This method is simple to use and often leads to good solutions.

The Morphological Box Method

This method has been suggested by the Swiss astronomer Tsvicky and includes five steps: 1. General description of the object to be investigated. 2. Revealing important characteristics and properties of the object. 3. Investigation of possible variants of obtaining each characteristic (property, function). 4. Matching these variants in a morphological matrix (box). 5. Selection and evaluation of new combinations of properties (functions).

The Morphological Box Method is useful at early stages of design and helps to find dozens (sometimes thousands) of new combinations of existing features.

The Long Period of Meditation Method (the "Ah-Ha" method)

Ah-Ha is the feeling of having an insight to a problem that has been bothering you for some time. It includes three stages: 1. Gather possible information about the object (the "sponge" stage). 2. Let your mind incubate information (the "egg" stage), and turn to other things leaving the problem alone. 3. One day the idea will come to your mind (Ah-Ha stage). Many professional inventors and scientists use this approach and can tell "success stories", for example Darwin liked showing the exact place on the walkway where the theory of evolution came to his mind. There are special exercises that can be used to improve the effectiveness of using this method, such as Daydreaming, Night-dreaming and Imagination games.

Brainstorming

Quite often people say – let's brainstorm this problem and start discussion, mistakenly thinking that this is Brainstorming. Osborn, who developed the Brainstorming method in late 1930's (www.brainstorming.co.uk), suggested strict rules that can be expressed as follows: Generate your own ideas; Pick and develop somebody's idea; Ideas can be generated in any form (serious, humorous, fantastic, etc.); No proof is required; Total ban on any critics during brainstorming sessions. Brainstorming sessions quite often result in more than 50 new ideas as a result of group thinking. Sometimes a person who generates a useful idea or an idea that leads to a useful idea has a feeling of not being recognised, and some experts think that this is a shortcoming of the method.

Synectics

Synectics is a group technique, similar to brainstorming, but where the groups are deliberately drawn from widely different backgrounds, and projection and empathy are used to obtain an alternative view of the problem. Different kinds of analogy are employed, for example, personal analogy, direct analogy, symbolic analogy, fantasy analogy, analogy with nature, and "by chance" analogy. It has some similarity with De Bono's thinking tools but with an engineering focus. Often it helps to find completely different ideas and approaches.

The Method of Smart Little People Modelling

This tool has been suggested by Altshuller as part of classical TRIZ and can also be used on its own. The essence of the method is that the required function in the model of the object is carried out by a crowd of intelligent small creatures, which, when given the order, are able to grasp, drag, pull, throw, get together, or perform any other required action. Quite often it gives insight into how the required function can be implemented in an engineering solution.

The Method of Developing an Inventor's Idea (The "I wish" Method)

This method was developed in the mid-80s in the Lithuanian Academy of Agricultural Sciences [7], by a group led by Chapiale. The algorithm includes seven steps with four different pathways within it, which are explored consecutively. The key step of the method is expressing wishes, converting them into ideas, and developing them into engineering solutions. The method includes extensive supplementary lists, in particular, 1. List of kinds of energy and energy of fields; 2. List of sensations; 3. List of different states of an object. These supplementary lists are used at certain stages of the problem solving process. The method is effective but relatively complex to use.

The Ideation / TRIZ Methodology

The letters T, R, I, Z form an English acronym for the Russian words *Teoriya Resheniya Izobretatelskih Zadach*, which, translated, mean the Theory of Inventive Problem Solving. The founder of TRIZ, Genrich Altshuller, suggested ten laws of technical system development that can be used for scientific prediction in different areas of science and engineering. He proved that inventive problems could be classified, codified and solved methodically, just like other engineering problems. When he released the TRIZ fundamentals in the early 50's, he suggested six tools that form the Classical TRIZ. They are as follows:

- The Contradiction Matrix.
  Altshuller indicated that any inventive problem contains at least two contradicting parameters. For different combinations of contradicting parameters he suggested inventive principles placed in the cells of the Contradiction Matrix. These inventive principles have been derived from real patents (more than 1 million patents have been analysed to refine and complement the Contradiction Matrix).
- Physical Contradiction.
  The essence of a physical contradiction is when a parameter contradicts to itself (e.g. to improve strength the cross-sectional area has to be bigger, to reduce weight – it has to be smaller). To resolve physical contradictions he suggested different separation principles.
- The Substance-Field Analysis (SUF).
  Altshuller suggested that in any technical system at least two substances interact through a field. To improve insufficient action, or to eliminate undesirable action another substance and/or another field can be added to the system.
- The Ideal Final Result Analysis (has been described in previous sections).
- The Smart Little People Modelling (has been described in previous sections).
- The Algorithm of Inventive Problem Solving (ARIZ), which includes all these tools and can be used for tackling highly challenging problems.

The Kishinew group of TRIZ researches led by Zlotin is the most renowned group of Altshuller's followers that contributed to further development of the TRIZ methodology. In 1991 the Ideation International Inc. was established in the United States (Zlotin is the Chief Scientist of the company). The Ideation International Inc. refined the TRIZ methodology, developed new tools, developed the Innovation Work Bench software package, and now the Ideation / TRIZ methodology in addition to Classical TRIZ includes the following new tools:

- Problem system information innovation situation questionnaire (ISQ).
- Problem formulator.
- Useful / Harmful effect analysis (SUH modelling).
- Anticipatory Failure Determination (AFD)

The Ideation / TRIZ methodology has grown into the most powerful methodology of creative solving of engineering problems. It has flourished in the USA, and TRIZ centres are established in several European countries and Japan. Unfortunately, it remains little known in

Australia. Teaching materials on the Ideation / TRIZ methodology for different user levels from beginners to advanced users can be obtained from the Ideation International Inc. (http:\\www.ideationtriz.com).

Teaching Engineering Creativity

When, in 1993, the author of this paper approached several universities in Melbourne and offered his materials for teaching engineering creativity, a typical answer was "we do not have time to teach all this". Most Australian universities still adhere to the opinion that problem-based teaching is sufficient to make students resourceful and good creative thinkers. Let's look at the problem from a different perspective. Is pushing a trainee into a swimming pool the best way of making him a good swimmer? Or it is better to teach him a swimming technique first, ie, what to do with his hands and his legs? The positive experience of leading universities proves that engineering creativity can be systematically taught without compromising the integrity of a curriculum.

The author of this paper working at Monash University and then at QUT developed arguably an optimum approach to teaching engineering creativity within a Mechanical Engineering Degree. It can be easily adapted to other areas of engineering. These teaching materials have been adopted by several universities in the USA, Singapore, Israel and Australia. Quite often the author is invited nationally and internationally to give seminars and workshops on approaches to teaching engineering creativity.

Teaching and learning approaches

In the first Mechanical Design unit "Fundamentals of Mechanical Design" taught in the second year, two weeks are devoted to systematic teaching of engineering creativity. During one lecture a review of existing problem solving methods is carried out. This lecture is followed by a tutorial and one of the exercises is a brainstorming session with an in-class assessment. Another lecture is entirely devoted to the Ideation / TRIZ methodology. Some of the problems brainstormed at the previous tutorial are solved using the Ideation / TRIZ tools to demonstrate the difference. More than 20 solved tutorial examples are available to students from the Design Web-site, as well as the course notes with detailed description of problem solving methods. The first part of the book [2] is also available to students from the Design Web-site. The IWB software is available to students at the Design Studio and computer classes. To assess skills in using the Ideation / TRIZ methodology students are given assignments including two problems. For example,

Problem 1. Using different TRIZ tools solve the following problem:

Large aircraft such as Jumbos and cargo carriers land at relatively high speeds - 200 to 280 km/h. On each landing, the undercarriage tyres lose approximately 10 kg of rubber causing them to be replaced frequently. Fig.1 below shows a typical good landing. Note the smoke (rubber being burnt) and skid marks (rubber deposited due to impact) as the aircraft lands.

Suggest methods for preventing extensive tyre wear thus increasing tyre life.

Figure 1: Boeing 747 during landing. Smoke from burning rubber tyres is clearly seen (Source: Lufthansa magazine)

Example of a solution to this problem is given below.

Problem 2. Using different TRIZ tools solve the following problem:

In space, where everything is in a state of weightlessness, astronauts are faced with problems whereby common devices work in unusual ways or do not work at all. For instance, when you use a hammer on Earth, its kickback is compensated by its weight. In space, when you hit something with a hammer, it kicks back towards your head with dangerous speed.

Modify a hammer to compensate for the kickback in space.

Example of a solution to Problem 1.

To employ the Contradiction Matrix approach, we have to identify two contradicting parameters. The parameter we are trying to improve (or maintain) is **Speed**. Deteriorating parameter is **Waste of substance**. For this pair of contradicting parameters, the Contradiction Matrix suggests the following inventive principles:

10. Prior action
- **a.** Carry out all or part of the required action in advance
- **b.** Arrange objects so they can go into action in a timely matter and from a convenient position

13. Inversion
- **a.** Instead of an action dictated by the specifications of the problem, implement an opposite action
- **b.** Make a moving part of the object or the outside environment immovable and the non-moving part movable
- **c.** Turn the object upside-down

28. Replacement of mechanical field
- **a.** Replace a mechanical system by an optical, acoustical or odour system
- **b.** Use electrical, or electromagnetic field for interaction with the object
- **c.** Replace fields (stationary with moving, fixed with changing in time)
- **d.** Use a field in conjunction with ferromagnetic particles.

So, the Contradiction Matrix suggests doing something in advance, placing an object in a favourable position, making stationary object moving and moving object stationary. Moving fields can be employed to perform the action.

I our case, the major problem comes from velocity gradient, because the runway is stationary and the tyres are moving. If we can equalize velocities (make moving object stationary) the tyres will touch the runway with zero relative velocity. An engineering solution may be to spin the tyre (preliminary action) so that linear velocity of rotation will compensate translational velocity. To drive the tyres electric motors can be used, built in the landing gear (moving magnetic field) or energy of the wind (another moving field) driving tyres by means of blade-like ribs placed on side surfaces of the tires.

Students utilise acquired problem-solving skills in the Warman Design and Build Competition of IEAust, working in teams of four. In the second Design unit "Design of Mechanical Components" students in small groups of three, carry out the first part of a project on gearbox design and continue to utilise problem-solving skills learned.

In the third Design unit "Design and Maintenance of Machinery" students carry out the second part of a group project on the development of a lubricating system for the same gearbox. One of the lectures is devoted to the Anticipatory Failure Determination followed by a tutorial on case studies of machinery failure analysis with the use of AFD. So students studying design are exposed to all Ideation / TRIZ tools and also have freedom to use other problem-solving methods as well.

These teaching approaches and systematic teaching of creative problem solving methods improved students' attitude and allowed the achievement of a high level of development of generic skills. Over the last three years failure rate in mechanical design units has been significantly lower than in other engineering units.

Conclusions

In this paper different aspects of teaching engineering creativity at tertiary institutions have been discussed. It has been demonstrated that:

- There is confusion among the engineers and educators on thinking and intelligence, creativity and creative problem solving, and whether is it possible to teach creativity.
- Effectiveness of creative thinking can be significantly improved through systematic teaching of problem-solving methodologies.
- There is a large variety of problem-solving methods.
- Review of existing problem-solving methodologies and systematic teaching of advanced methodologies, such as the Ideation/TRIZ enable students to compare and make their own judgement.
- Teaching materials and approaches used enable systematic teaching of different problem-solving methods within a limited time frame and put them to practical application through Design units and other subjects.
- Systematic teaching of creative problem solving methods improves students' attitude and allows the achievement of high level of development of generic skills, as well as contributes to the reduced failure rate in Mechanical Design units.

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