First year engineering students' problem solving in different scenarios

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CONTEXT Engineers solve problems as an integral part of their work environment. Solving problems (e.g. defining problems, analysing problems, interpreting information, transferring concepts), has been determined as a significant generic engineering competencies that engineers graduating in Australia require. To do so successfully, they must consider a range of choices taking into account all appropriate factors before reaching a final decision. First year engineering students bring with them a dearth of engineering experience to their studies and make decisions based on limited knowledge and approaches to problem solution. This paper investigates the experience of utilising alternative scenarios using 'new' thinking approaches on the development of different methods to solving a materials selection problem of engineering components. Student thinking is often limited in scale to one "size" and when exposed to "unlimited" inputs, outcomes may be significantly different.

PURPOSE This research aims to answer the question "how does a change in approaches to thinking in solving engineering problems influence a first year student's decision making process." We are trying to understand how students think when exposed to situations which they would not normally consider (or unusual or out of the ordinary).

APPROACH At the end of their first year studies in materials engineering, students were presented with a problem of selecting a material and manufacturing process for an engineering component. They were given a minimalist brief and had to rely on their previous knowledge. Once they arrived at their solution (often a closed format) they were then asked to consider alternative scenarios where the selection process allowed them unlimited resources and time, or extremely limited resources and time. An online survey requiring verbal answers was established to determine students' approach to their decision making based on their thinking process. The results were analysed according to aggregation of similar verbal responses, to determine changes in thinking as a result of open ended scenarios

RESULTS Analysis of results has indicated that first year students' answers to the open ended questions resulted in vastly different approaches to problem solution. Where resources were unlimited, seemingly "unrealistic" solutions were proposed in terms of time, finances and engineering capabilities; and where very limited resources were proposed, very simple or less complex engineering solutions were proposed.

CONCLUSIONS When students are presented with an engineering problem at first they proposed a closed form (standard) solution. However, when allowed to expand their approach, where their resources are either unlimited or extremely limited, either "unusual" or simple proposals are developed. By extending the student thinking to the extremes, they are challenged in their thinking and decision making processes. These results may indicate how students can approach decision making processes later in their engineering career.

KEYWORDS Thinking, problems, competencies.

Introduction

Engineers solve all sorts of problems, often needing to create elegant solutions while working within various limitations. Every potential answer an engineer devises for a problem must be weighed against the realities of the physical world, available materials, and a finite budget (Lawlor, 2014; National Academy of Engineering, 2004). It takes creativity to move successfully from problem to solution, all while navigating a mesh of limitations (Cropley, 2016; Felder, 1987). Engineers Australia, as well as international engineering bodies, has developed a set of competencies (i.e. defining problems, analysing problems, interpreting information and transferring concepts), which every engineering graduate must attain as a problem solver (King, 2008; Male, Bush, & Chapman, 2009; National Academy of Engineering, 2004). First year engineering students bring with them a dearth of engineering experience to their studies and make decisions based on limited knowledge and approaches to problem solving. Creative problem solving may be difficult for these students' entering their first year of engineering studies, where their high school studies have been rigidly structured and problem-solving is well defined according to specific criteria. Students often see engineering problem solving as a systematic and dispassionate process of applying impartial scientific principles or truths, overlooking the human dimension in engineering problem solving and for which not all the information is available.

Learning how to approach and solve problems, which relate to real world situations, is an integral part of an engineering students' education. Systematic engineering problem solving has been the subject of a number of textbooks, e.g. (Carmichael, 2013; Cropley, 2016) and introduced as formal courses in for example, a number of Australian engineering institutions (UNSW, 2017; USQ, 2016; Victoria University, 2016). Structured engineering problem-solving teaching seem to follow a well-defined formulaic approach, but not always allowing any room for creativity, originality, or inventiveness. Jonassen *et al* (2006) highlighted the problems in the workplace as being significantly different from that found in the classroom and often requires different thinking. Similarly, a structured education approach (e.g. the teaching of solution strategies "problem" subjects) often results in problems with well-defined solutions, involving a number of well-defined steps as summarized by Carmichael (2013) and Cropley (2016); identification of a need; problem definition; search; constraints; criteria; alternative solutions; analysis; decision; specification; and communication often resulting in one solution, constrained within well-defined boundaries.

Student thinking is often limited in scale to one "size" and when exposed to "unlimited" inputs, outcomes may be significantly different (McNeill 2016). Hence, the work outlined in this paper investigates the influence of students' experience of alternative solutions to problem-solving using "new" thinking approaches employing the principle of TRIZ (Altshuller, 1984). The process of problem-solving for our students is implemented according to systematic and organized steps, allowing the students to be guided to a solution. During this process, students learn to analyse, evaluate, and make conclusions, while at the same time, they apply their critical thinking skills, which may include the human aspect.

Problem-solving for engineering students

The introduction of TRIZ (Altshuller, 1984), especially in the engineering curriculum has enhanced the thinking skills of engineering students in their approach to problem-solving (Moehrle & Paetz, 2014). In their analysis of data from the introduction of TRIZ into the engineering curriculum, their results indicated that teaching students "open-ended" problem-solving skills provided them with confidence in approaching difficult or unknown problems (Moehrle & Paetz, 2014; Orloff, 2016). The students involved in these studies were all exposed to techniques of using TRIZ in different problematic scenarios by considering various scenarios, e.g. MATCEMIB (Mechanical, Acoustic, Thermal, Chemical, Electric, Magnetic, Intermolecular & Biological) as hints to problem solution (Valentine 2017).

A significant technique employed within the TRIZ approach is known as the DTC (Dimension-Time-Cost) or STC (Size-Time-Cost) method (Belski & Skiadopolous, 2017; Frenklach, 1998). In this method, the DTC/STC operator is aimed at improvements by changing: the dimensions of the system from maximum to zero; the time from infinite to zero; and the cost of the system from maximum to zero. The DTC is now commonly referred to as the STC (size, time, and cost) operator and is a simple heuristic from the TRIZ family, which is used to frame and reframe problems and to generate solution ideas. Once the students have generated a solution, they are asked to consider solutions, which involve minimizing and maximizing their proposal. The so-called STC operators under six constraints: Size = 0 & ∞; Time = 0 & ∞; Cost = 0 & ∞; and involve five steps, which are given in Table 1.

Table 1. Size-Time-Cost (STC) Operator: five Steps under six constraints (Size = 0 & ∞; Time = 0 & ∞; Cost = 0 & ∞)

Establish the Object and the means to achieve Improvement
Consider the Object under six constraints (Size = 0 & ∞; Time = 0 & ∞; Cost = 0 & ∞)
Reflect onto the task under these six conditions and propose solution ideas
Consider the means to achieve these solutions under six constraints
Reflect onto the task under these six conditions and propose solution ideas

Research Question

The research question our work aims to answer is: "how does a change in approaches to thinking in solving engineering problems influence a first year student's decision-making process". We are trying to understand how students think when exposed to situations, which they would not normally consider (thinking unconventionally, or from a new perspective).

Participants

Participants were recruited from the full cohort of freshmen (first year engineering students) studying the core subject of Engineering Materials during semester 1, 2017 at a university in the south east of Australia. An introductory course was chosen because it was assumed that students had a basic understanding of physics, chemistry, and mathematics. 110 undergraduate engineering students participated in this study (with 93 responding to the survey). The majority of participants had completed either physics (47%) or physics and chemistry (39%) in their last year of high school, as well as mathematical methods (58%) and a combination of mathematical methods and specialist mathematics (35%). A minority of students had not completed any physics (13%) or mathematics containing calculus (8%). Participants were predominantly majoring in civil engineering (41%), followed by robotics and mechatronics (24%), mechanical (18%) and telecommunications and electrical (17%). Participants primarily described themselves as first year undergraduates in their first year of studies in an engineering course (91%).

Method

Towards the end of their first year subject of materials engineering, students were presented with an open-ended problem in blended mode; i.e. although there were no face-to-face tutorial or laboratory activities associated with the activity information, students had access to online information and face-to-face consultations from their tutors. The student cohort comprised into six laboratory groups, each consisting of approximately 20 students. Students completed their laboratory activities in groups of two. The materials selection activity commenced during week 8 of the 12-week semester and was to be completed by week 11 (i.e. students had three weeks to complete the activity). It was an open-ended material selection exercise where the various student groups were provided with an engineering component and were required to determine appropriate selection of materials and manufacturing processes. The materials selection activity comprised an exercise "to select materials based on properties, manufacturing, sustainability, available time, cost, and performance." The engineering components available for selection were allied to major engineering disciplines and were both familiar and alien to the students, viz. bridge building materials; hand tools; and home construction items.

For the first task of the activity (which was assessed), students were presented with the instructions and the grading rubric, and were then asked to begin their activity, which was required to be completed within seven days. Students submitted their work, which was saved in the Learning Management System (LMS). The students submitted a one page "memo" report and gave a three to five minute oral presentation substantiating their response to the selection process, similar in procedure to business presentation for an industrial company. Students submitted the memo report and oral presentation. They were then thanked for their involvement, and asked to undertake a second and related activity. At no stage were the students given any training or information in the requirements of the selection procedure.

For the second task of the activity (which was not assessed), the students were invited to voluntarily complete a survey concerned with their "thinking" approach and an examination of alternative strategies to the materials selection process, based on the STC approach (TRIZ, 2017). During this phase of the activity, each student was required to provide 'open-ended' solutions (where restrictions on size, time, and cost were removed) to the original problems in a reflective environment. Not all the students responded to the optional second task of the activity, and they were not penalised in their overall assessment.

For open-ended problem, students were briefly guided in a lecture environment on how to interact and extract information using a learning management system (Blackboard©) and the website which contained a repository of related information (TRIZ, 2017). The repository explained the STC operator procedure and approaches to obtaining a set of solutions. The students were not given any training in thinking processes, or materials selection methodology. They were required to rely on their previous knowledge obtained from the early content of the subject, their previous experiences, and their interaction with the outside world of engineering, both through the WWW and physical contact, as well as incorporating many of the competencies. Professional and personal attributes) are those required by Engineers Australia (Engineers Australia, 2017).

Survey details

The students were required to "reflect on the problem under specific conditions and propose solution ideas," following their initial submission of the engineering problem-solving task.

Table 2. Grouped Survey Questions (based on the STC approach).

Engineering material based	
Q1.1 What material would I use to construct the object if the Size of the object was infinitely small?	Q1.2 What material would I use to construct the object if the size of the object was infinitely big?
Q2.1 What material would I use to construct the object in a very short period of time?	Q2.2 What material would I use to construct the object if I had infinite time?
Q3.1 What material would I use to construct the object if I had zero budget?	Q3.2 What material would I use to construct the object if I had an infinite budget?

The survey consisted of six open-ended questions each with two parts, and was based on the students'' response to the STC questions (as given in Table 2). It is important to acknowledge that open-ended questions have a great diversity of responses (Geer, 1988).

The instructions were: "we wish to identify your thinking processes and approach to solving the materials selection assignment. The whole process will take about 10-12 minutes."

Data Analysis

Firstly, similar statements, phrases, or keywords related to the research question. During this phase were *identified*; our concerns were not with duplicate but similar terminology. The second stage focused *grouping* together similar statements, phrases or keywords related to the research question, whereas the third phase involved looking back into the data for connections amongst the groupings. The authors themselves reviewed the data in accordance with guidelines developed in agreement with the recommendations of Miles, Huberman, and Saldana (2013) and had a Cohen kappa inter-coder reliability of 90% (Cohen, 1960). The survey results were analysed according to aggregation of similar written responses, to determine changes in thinking as a result of open ended scenarios utilizing thematic text analysis where there is an occurrence or co-occurrence of words or themes (Popping, 2015). The text analysis was analysed according to the scheme developed by Montgomery and Crittenden (1977) so coding involved "locating relevant information within a larger context as well as evaluating the relative importance of two or more possible responses to arrive at a single code," based on human judgments. Linguistically similar features of responses were grouped in sections for the engineering components in order to arrive at comparable groupings.

Findings and Discussion

When students responded to the first engineering activity for realistic solutions to the materials selection problems, they all selected either one of two classes of materials for the engineering components, i.e. metals (e.g. varieties of steel, aluminium, or composites). Because of the range in qualitative responses received, similar answers, were grouped and collated.

When students were asked to reflect on their responses using the TRIZ (STC) approach (according to Table 3, Q1.1-Q2.1; Q2.1-Q2.2 and Q3.1-Q3.2 a variety of traditional (steel, aluminium and wood) and non-traditional materials (titanium, carbon nanotubes, graphene, diamond, ceramics, and gold) were selected for the various constraints. A summary of the materials chosen for bridge building, hand tools, and home construction are given in Figures 1, 2, and 3 respectively. Responses shown in Figure 1 indicate that there was not a trend for any of the STC operators whether small or infinite. For example for infinitely small, carbon nanotube/graphene was chosen, whereas for short time either wood or steel was chosen, and for zero budget, wood was chosen.

Considering the opposite end of the spectrum, when infinitely big, students chose metals (high strength), for infinite time they chose again high strength metals and for infinite budget the students selected almost equally high strength metals and carbon nanotube/graphene. It was only for infinitely small size or infinitely large budget that the section was non-standard i.e. not a steel but carbon nanotube/graphene. In the area of home building materials, responses are shown in Figure 2, which indicate that when materials selection is governed by time there was not a trend for any of the STC operators; whether small or infinite. For infinitely small size artefacts, polymers, followed closely by ceramics/glass/diamond were chosen, and for short time periods, wood, followed by ceramics/glass were chosen, whilst for zero budget, wood was clearly chosen.

Considering the opposite end of the spectrum, when infinitely big, students chose metals, when they had infinite time; they chose almost equally ceramics/glass/diamond and metals, and for infinite budget the students selected ceramics/glass/diamond followed by metals. For all STC "large" cases, it interesting to note that metals were either the highest or next to highest on the selection list. Drilling down further into this data showed that it was non-traditional metals such as titanium, which comprised most of the metals list.

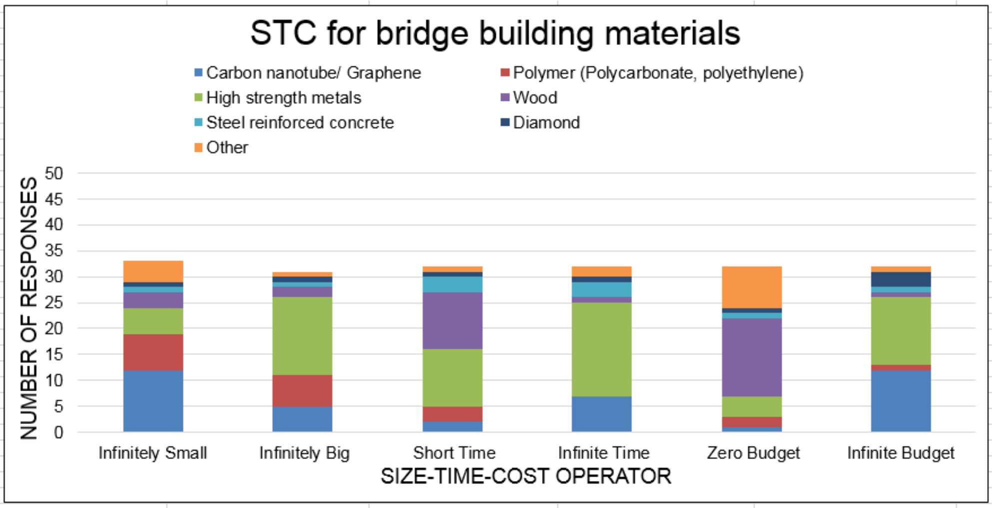

Figure 1. Materials for bridge building materials selection according to the STC approach.

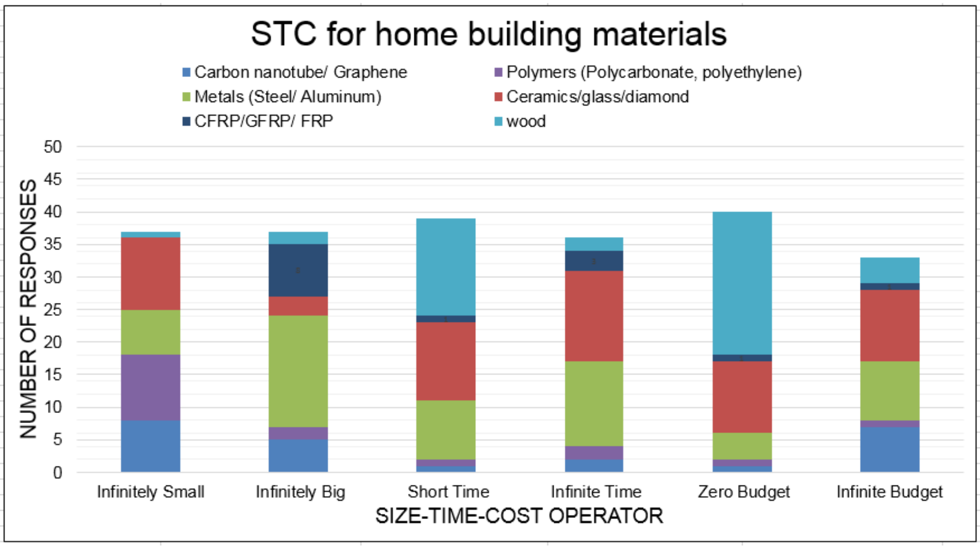

Figure 2. Materials for home building materials selection according to the STC approach.

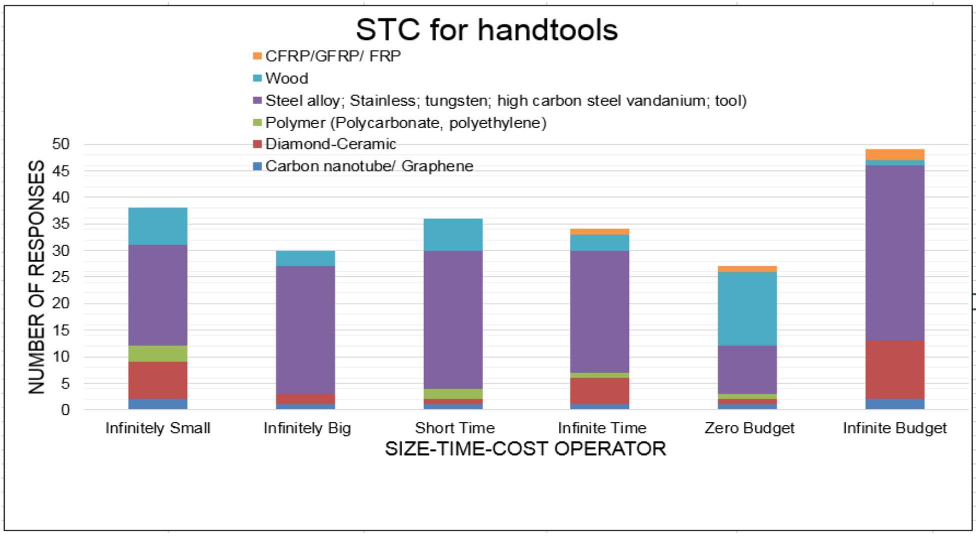

Figure 3. Materials for hand tools materials selection according to the STC approach.

Moreover, in the third area, of hand tools detailed responses are given in Figure 3. Analysis of responses for selection of materials for hand-tools also dictated by time, also show that there was a definite trend for all of the STC operators whether small or infinite. In all cases, the predominant material for selection was a metal. Again, drilling into individual data components for metals, showed that the selection was not confined to steel or aluminium, but now also included tungsten, titanium, tungsten and vanadium, exotic metals.

The results from this study are similar to those found by Wertz, Purzer, Fosmire, and Cardella (2013) for students' ability in retrieving information from the web, and importantly, similar to findings from Ashby (2015) where students were required to undertake a case study for selecting wind farm components and reflect upon their decision. The results of this work were in agreement to that of a number of authors (Belski &Skiadopolous 2017, Moehrle & Paetz,2014, and Frenklach,1998), in that allowing students to be free from traditional thinking approaches results in a significant number of unconventional/familiar solutions which may subsequently be the precursors to actual solutions. It is interesting to note that the students selection of components of the STC operator was in no way influenced by the lecturer, but was solely developed using blended/online delivery of information and relying on the students' own acknowledge and skills.

This qualitative survey does have limitations. The control experiment was that of the same cohort of students who were first asked to submit a traditional engineering solution (using a variety of information resources, web, journals, books), and after completion, reflect upon a constraint-free approach. This change in their approach to materials selection was developed (learned) by the students based on the information they received using the LMS and Edison21 (TRIZ, 2017). The students were guided to learn independently, and use the STC tool themselves when faced with a problem to solve in the future: a new achievement.

Closing remarks

Students can be exposed to a variety of problem-solving strategies based upon traditional engineering solving techniques. These techniques are all constrained by specific engineering requirements, leading to traditional solutions. However, when constraints to size, time, and cost (STC) are removed, inspired, but not always practical solutions may be developed. From these solutions, further refinement may arrive at solutions, which provide optimization of any of cost, time or size restraint. The conclusions of this activity are that giving students constraint-free activities often resulted in uncommon solutions to engineering materials selection problems, whilst keeping in mind that standard solutions were also applicable.

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