Problem Solving and Creativity in Engineering: conclusions of a three year PBL project involving Reusable Learning Objects and Robots

Jonathan Adams, The University of Northampton, UK jonathan.adams@northampton.ac.uk,
Stefan Kaczmarczyk, The University of Northampton, UK stefan.kaczmarczyk@northampton.ac.uk,
Phil Picton, The University of Northampton, UK phil.picton@northampton.ac.uk,
Peter Demian, Loughborough University, UK P.Demian@lboro.ac.uk

Abstract: *Problem solving and creativity within the sciences and engineering are highlighted in current UK and European benchmark and policy statements as essential capacities. What these statements fail to do, however, is offer guidance on how these skills might be fostered, let alone how they might be assessed.*
This paper presents the conclusions of a three year research project to develop a dedicated problem solving and creative thinking module for first year engineering undergraduates. The project has been funded through two project grants from the UK Higher Education Academy Engineering Subject Centre. In the module, Instructional Design and Problem Based Learning (PBL) techniques have been used with Lego Mindstorm NXT robots in order to develop creative problem solving skills in a practical setting. Focus for the module has been on developing process skills and techniques as opposed to the simple methodical solving of routine problems. Cognitive abilities and problem solving process skills have been developed and mediated through the use of Reusable Learning Objects (RLOs) within a Virtual Learning Environment (VLE). Separate RLOs have also been used to develop skills at using the robots.
The research project has been additionally informed by a parallel interview project investigating the perceptions of novice and professional engineers towards problem solving and creativity within engineering. In total, fifty-three semi-structured interviews have been undertaken with engineering undergraduates and academics at three UK universities, alongside those with practicing professional engineers. Analysis of the interviews has been in the form of a phenomenographic study in order to form outcome spaces for comparison and comment.
Student feedback through on-line questionnaires, focus groups, classroom-based observation and interviews indicates that the module, and its means of delivery, has been successful in improving creative problems solving skills. It also highlights the value of developing cognitive and process skills within a practical and motivational environment.

***Index Terms* —** Creativity, Phenomenography, Problem Based Learning, Problem Solving,

INTRODUCTION

Problem solving ability and creative potential are highlighted as essential abilities for both novice undergraduate engineers and qualified engineering professionals in UK benchmark statements [1, 2].

> "The creative way of approaching all engineering challenges is being seen increasingly as a 'way of thinking' which is generic across all disciplines. […] They [engineering undergraduates] will want to solve problems and have strategies for being creative, innovative and overcoming difficulties by employing their knowledge in a flexible manner." [1].

Additionally, creativity within science, technology, engineering, and mathematics (STEM subjects) is identified, both explicitly and implicitly, as an important driver in recent UK reviews relating to economic prosperity and Government science and innovation policies [3, 4].

Similarly in Europe, problem solving and creativity are presented as important competencies in the requirements for European Engineer (Eur. Ing.) designation:

> "Engineers aware of their professional responsibilities should strive to achieve competence such as […] an ability to apply theoretical and practical methods to the analysis and solution of engineering problems […] an awareness of continuous technical change and the cultivation of an attitude to seek innovation and creativity within the engineering profession" [5].

What these statements fail to do, however, is to offer guidance on how problem solving and creativity might be fostered and taught, let alone how they might be assessed. It is against a backdrop of benchmark statements and policies that educators must devise and implement strategies for developing, enhancing and assessing creativity and problem solving skills within the sciences and engineering.

OTHER RESEARCH

Strategies for teaching problem solving and for the development of creativity can be found in numerous texts and research publications [6-9]. Wankat and Oreovicz [10] suggest, however, that while engineering education focuses heavily on problem solving skills, lecturers and professors continue to concentrate on teaching subject content rather than showing the processes involved in problem solving. Houghton [11] proposes that problem solving is 'what engineers do'.

It is possible to identify, from both anecdotal sources and more defined evidence that deficiencies continue to exist in the teaching of creative problem solving skills [12, 13], and that the traditional models and methods of teaching used in engineering education may be outdated and not provide sufficient motivation for engineering undergraduates of the 21st Century [8].

There are a host of different procedural strategies for problem solving, which have been reviewed in detail by Woods [9] . Woods' own method, which is similar to that of Polya [14] considers problem solving as a simple five stage process: 1. Define; 2. Think about it; 3. Plan; 4. Carry out plan; 5. Look back

Valuable research also exists on the characteristic differences between expert and novice problem solvers, which can inform our understanding of developing creative problem solving skills in the classroom [15, 16].

Teaching of the problem solving process in the classroom can be achieved in a number of ways. One example is Thinking Aloud in Pairs Problem Solving (TAPPS), where problem solving process skills are developed through the interaction of the problem solver and a listener [17, 18]. Other strategies for developing discrete stages of the process include the use of brainstorming techniques for idea and solution generation, Gantt charts for planning and implementation and evaluative checklists for evaluation and reflection [19]. There are many more techniques. Another important, and well recognised, method for developing problem solving skills in the classroom is the use of Problem Based Learning (PBL) exercises.

In PBL the handling of a problem drives the whole learning of the student [20-22]. It must be noted, however, that Problem Based Learning is distinctly different from Problem Solving Learning, with the former being used to develop processes in a wider context rather than products in a confined environment [23].

PBL exercises are considered a 'component method' under the umbrella of Instructional Design [24]. Componential methods can be done in different ways, and are made up of different components (or features). So, for a PBL activity these components might include: setting the problem scenario, forming the teams, providing support, allowing reflection on individual performance etc.

Instructional Design and Learning Design Theories are therefore design-orientated, and can be considered as one approach to the operationalisation of cognitive education and strategies. They are concerned with developing guidelines for which instructional methods and models to use in which situation or context [24-28].

From an educational perspective, current models or simulations developed as part of Instructional Design or Learning Design (including those that utilise PBL exercises) readily lend themselves to the application of Learning Objects [25, 27, 29].

Learning Objects, and in particular their reusability in different contexts, is a relatively new concept in teaching and learning, and application and research in this area is growing rapidly [30]. One working definition is:

> "Learning Objects are defined [here] as any entity, digital or non-digital which can be used, re-used or referenced during technology supported learning. Examples of Learning Objects include multimedia content, instructional content, learning objectives, instructional software and software tools, and persons, organisations or events referenced during technology supported learning." [31]

Two metaphors presented by Wiley [32] liken Learning Objects in a simplistic model to pieces of Lego and in a more developed model as an atom. Whilst Learning Objects are generally employed as 'content chunks', learning theorists are pushing for their use and re-use in case-based problem solving scenarios, such as those developed for PBL [33]. It is this potential for the use of Reusable Learning Objects in the context of mediating problem solving and developing creative process skills within a PBL context that offers potential and forms part of the originality of this research study.

This paper describes the second cycle of a three year action research project to develop a creative problem solving module for first year engineering undergraduates. The work has involved two cycles of action research over two academic years, and has been kindly funded by initial and continuation funding from The Engineering Subject Centre at Loughborough University. Findings from the first cycle have already been disseminated at a number of conferences [34-36].

The development of module content and delivery has been informed not only by themes identified within the literature but also by a parallel project involving a series of interviews to identify the perceptions of engineering students, academics and professionals. The purpose of the interviews was to investigate the perceptions of, and characteristic similarities and differences between expert and novice engineering problem solvers. Early findings from the interviews have been presented at a number of conferences, and final analysis is now complete. [37-39].

METHODOLOGY

Two main research methods have been applied in this study: action research and interviews. The action research has involved first year engineering undergraduates at The University of Northampton in order to develop a dedicated creative problem solving module.

Action research has been chosen as the main research methodology due to its suitability for researching 'social practices' – such as the development of problem solving and creative thinking skills [40]. Each cycle of action research has involved the processes of planning, acting, observation and reflecting. It is acknowledged that this process is a recursive spiral, and that more than one iteration of the process is required for the process to be effective. Two cycles of action research over two consecutive academic years have been undertaken in this study, and this report describes the second cycle. The work has already continued into a third cycle.

For the second cycle a PBL approach using an Instructional Design model has been adopted and developed for the module [24]. This is illustrated in Figure 1 below:

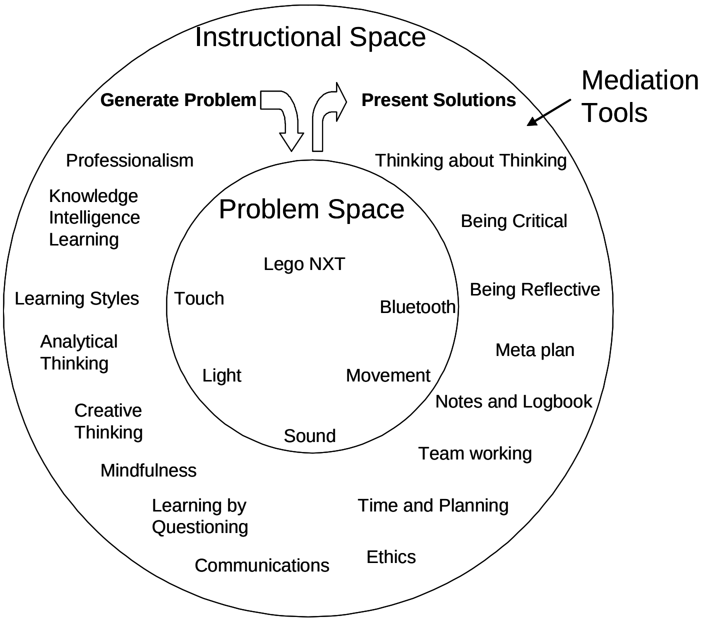

Figure 1
Instructional Design PBL Model using Learning Objects

In the model learners operate in two domains (termed 'spaces') during the creative problem solving process. In the 'problem space' they work directly on the problem, and enter the 'instructional space' when they encounter a skills or knowledge deficiency. The instructional space also provides tools to mediate the problem solving process. Instructional content in each of the spaces is provided using Reusable Learning Objects (RLOs) [32, 33].

In the project, the problem space is represented by a problem that the students have generated themselves, and have attempted to solve using Lego Mindstorm NXT robots. Within this space are also instructional items relating to the basic features and functions of the robots, along with practice activities. Items in the instructional space are related to developing both cognitive skills and abilities and also skills and techniques that are relevant to the typical stages of the problem solving process: define, think about it, plan, carry out plan, look back (reflect) [9].

RLO content has been informed by the first cycle of action research, previous published research, and findings of the interviews comparing professionals with novices. Each title in Figure 1 represents a separate RLO. Additional RLOs have also been made available to introduce the module, and to set the rules for generating the problem space. RLOs have been created in a software authoring tool called Lectora (from Trivantis Corp.). Each RLO is a self-contained learning unit, and typically consists of 10-12 screen-readable pages containing text and diagrams. Lectora also allows for the integration of audio and video content, as well as on-line and off-line testing, although this has not been done in the study. RLOs can be produced in various formats, including SCORM[1] (for integration into a VLE), zipped HTML format, and as a self-executable file. In the project various formats have been used, and RLOs made available within the

[1] SCORM or Shareable Content Object Reference Model is a standard for developing, packaging, delivering and sharing electronic learning content for use in a Managed or Virtual Learning Environment. It was developed by Advanced Distributed Learning (ADL - http://www.adlnet.org).

University of Northampton Blackboard-based VLE (NILE), on a memory stick and also in weekly emails to students. Typical screen shots of typical RLOs are shown in Figure 2 and Figure 3.

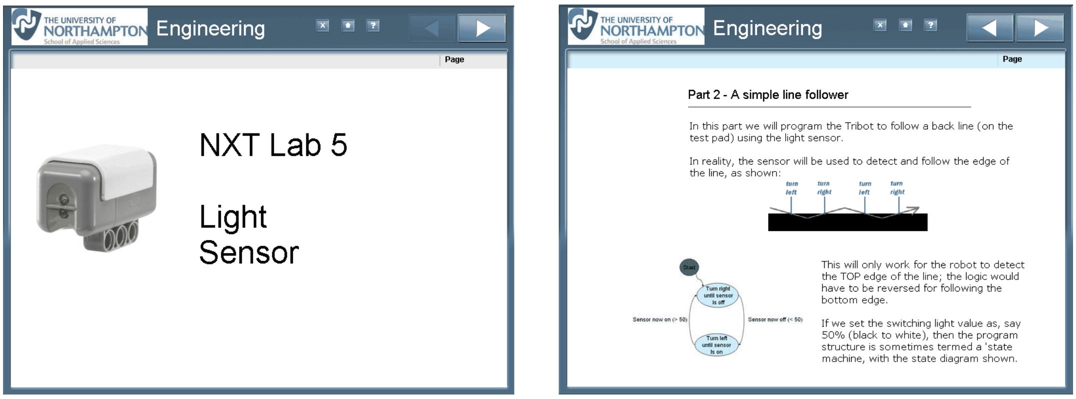

Figure 2
Typical RLO (NXT Light Sensor)

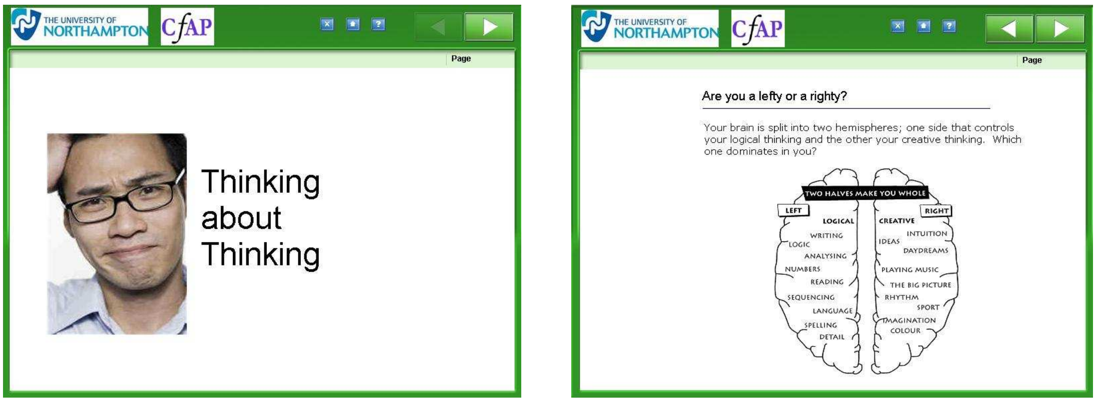

Figure 3
Typical RLO (Thinking about Thinking)

SCORM compliant RLOs (which were integrated into the VLE) were enabled with tracking and performance reporting information for inclusion into the VLEs electronic record-keeping Gradebook.

Students were provided with the opportunity of 22 timetabled one-hour class contact sessions (autumn and spring terms) in which they could access the Lego Mindstorm NXT robots and also the VLE. Access to the VLE (and RLOs) was also available outside this time, although access to the Lego robots was restricted. Ten first year engineering students regularly attended the sessions and undertook the robot problem, although the VLE (and RLOs) were also made available to undergraduate engineering students across all three years (a total of 97 students had access). Attendance was on a voluntary basis due to the module not being currently credit bearing, although students were encouraged to attend by being given a memory stick.

Students were provided with guidance (ground rules) in the form of RLOs on how to devise their own problem in order to generate the problem space. They were also required to devise some judging criteria. Metaplan was used to devise the common problem for all students (working in sub-groups) to solve. Metaplan is usually used as a problem-solving tool, but in this case was used to generate and agree the problem.

The problem generated by students was to identify and retrieve coloured ‘tags’ to the corner of a bounded area within a 10 minute period. The winning team was the one who retrieved the most tags, with the runners-up those who retrieved the next many. As an incentive small prizes were awarded to the winners and runners-up. Programming of the Lego robots was done using the visual Lego NXT-G software supplied with the robots.

Throughout the process of solving the problem students were expected to keep an engineer’s log book. Guidance for this was provided in an RLO.

In addition to the action research, a substantial study involving fifty-three semi-structured interviews has been carried out with engineering undergraduates, academics and professional engineers. The purpose of the interviews was to investigate characteristic similarities and differences between the perceptions of experts and novices to problem solving and creativity in engineering. Findings from the interviews have been used to influence the development of the action research cycles. In the interviews participants were asked three open-ended questions: "Q1: what qualities do you think make a good engineering problem solver?", "Q2: what do you understand by 'creativity' in relationship to engineering?" and "Q3: how do you think that these skills can be improved in undergraduate engineers?"

The interviews were undertaken over the period January 2007 to March 2009 and involved first-year students and academics at The University of Northampton (general engineering), Loughborough University (electrical engineering and civil engineering) and the University of Birmingham (electrical engineering). A number of practicing professional engineers from a range of industries (including lift manufacture, general manufacturing, motorsport, aerospace and electronics) were also interviewed.

The interviews were digitally recorded, and have been transcribed by a third party. Whilst most interviews were undertaken face-to-face, some involving academics and professional engineers were also undertaken by telephone. Overall length of audio data for all interviews is approximately 30 hours. Analysis is in the form of a phenomenographic study [41-44]

FINDINGS AND REFLECTION

Action Research

Feedback from the action research was obtained by several methods. These were the use of on-line tracking in the VLE, by on-line student questionnaires at the end of the autumn and spring terms, focus groups, classroom-based observation, and as part of the parallel interview project.

Tracking showed that the VLE site had 688 student log-ins over the two terms, and that of the 97 engineering students who had access to the site 65 (67%) had accessed the site at least once. The ten first-year students who undertook the robot task accessed the site on a regular basis. Tracking of access to the RLOs showed that all had been accessed, although the tracking proved to be unreliable due to the RLOs being also made available on a memory stick (for first year students), and as a weekly email to the whole engineering cohort. Tracking was also unreliable due to limitations of the SCORM implementation, which is discussed later.

Response rate to the on-line questionnaires was satisfactory, with 22 responses to the autumn and 12 responses to the spring questionnaire. In the questionnaires and focus groups a high proportion of students believed that problem solving skills were vital or essential for engineers (99%), whilst a slightly smaller proportion believed that creativity was important (81%). Over 85% of students rated their problem solving skills as being improved by accessing the module content, while 64% believed that their creative thinking skills had improved. Over 94% who undertook the on-line questionnaire had regularly accessed the content on the site. 98% of students thought that a separate creative problem solving module was a good idea, while 85% would recommend the RLOs on the site to other students. Of the students who also undertook the robot problem, 72% believed they were a good or excellent way for developing creative problem solving skills. Students also preferred (71% of students) the RLOs to be delivered in a VLE rather than by email or memory stick. When asked if the module would be better as an on-line simulation with no hands-on practical robot activities only 25% responded that they would prefer this. The findings reported are comparable to those from the first cycle project.

Students were also asked what they found most and least useful about the module content, and were asked to make suggestions for improvements. Several students also commented that that they had wished this module had been available when they had started their BSc Engineering studies. Here are selected comments from the questionnaires and focus groups:

Most useful:

> *"The methods you can use to solve problem and exploring different ways of getting to the right answer"*
>
> *"Taking the chance to be creative and solve problems"*
>
> *"Some of the files really helped me with problem solving in other modules on the BSc course such as creating oral presentations and writing reports etc."*

Least useful:

> *"I work full time so am unable to attend the classes as they are during working hours [part time student]"*
>
> *"Robot use because I am not in the first year"*
>
> *"This would be a lot more useful to students if they knew about it so it could be promoted better so that students are made aware of its useful content [sic]"*

Suggestions for improvements:

"More Lego robot projects and programming robots through different software"

"More access to the robots"

The second cycle of action research involved the presentation of a number of skills in order to mediate the process of creative problem solving. A central student-generated problem was achieved using Lego Mindstorm NXT robots. Feedback through questionnaires and focus groups indicates overall satisfaction with the module. A high proportion of students also believed the module had improved their creative problem solving skills in their other subjects (but this is difficult to measure objectively).

It was observed that the Lego robots served to motivate students and generated a high level of intrinsic interest; capacities that were highlighted as lacking in the interviews. The use of a student-generated problem further promoted motivation, and fostered a sense of ownership of the problem (again identified as lacking in the interviews). The robot activity also addressed a number of further issues that were identified both in the first cycle and interviews including: the need for visualisation techniques when problem solving, the desire for realistic experiential learning activities, the value of developing critical and reflective thinking skills, and the ability to work in teams.

By comparison with the use of Java-programmed Lego RCX robots used in the first cycle, the use of Lego NXT robots along with the visual NXT-G programming software enabled students to quickly undertake much more complex tasks. This ensured that the focus for the module was creative problem solving rather than simply robotics.

Although students had access to the RLOs within the VLE continually, access to the robots was limited to a timetabled one-hour weekly session. Restricted access was also available outside this time, however, several students suggested that additional access was required. An area for further investigation might be the use of a low-cost robot alternative that could be provided for students to take away. This would, however, rely on the student having access to a suitable computer, although this seems feasible.

The RLOs and the Instructional Design PBL model developed for the module proved a successful mechanism for delivery which could potentially be used to develop creative problem solving skills in different contexts or disciplines (i.e. the robot activities forming the 'problem space' could easily be substituted with a different activity). The RLOs were relatively easy to produce using the authoring software, and to disseminate in different formats. It is also possible to re-purpose the content of the RLO itself with use of the authoring software. Several RLOs were successfully used to rapidly develop dedicated problem solving sessions using the robots for visiting school children, and on a visit to a local primary school.

While it was possible to monitor access to each RLO, this was unreliable as the RLOs were also provided in untraceable formats (e.g. on a memory stick and by email). Problems were also encountered with the use of the SCORM object viewer within the VLE as this required a compatible Web Browser and version of Java in order to work correctly (which is not always installed on the student's computer). What was evident from tracking, however, was that students who were not undertaking the robot activity were strategic with their access to the RLOs (e.g. RLOs relating to sustainability and ethics had more accesses when students were writing project proposals, whilst the RLOs relating to writing reports and oral presentations were accessed heavily when final year students were writing-up and presenting their dissertations). One way of improving tracking might be by the inclusion of simple in-line tests built into the RLO which could be used to feed back data to the VLE. A further enhancement of the RLOs would be the inclusion of audio and video, if appropriate.

Whilst attendance for the module was voluntary, a regular cohort of first year students participated. The RLOs were also accessed, and proved useful to a large number of students in other years of their studies. Unsurprisingly, findings from the interviews indicate that the key motivation for students to do well with respect to developing (creative) problem solving skills in the academic environment is value and reward; either in the form of grades or enhancing employment opportunities. Whilst the module currently offers intrinsic reward (and some small gratuity in the form of a memory stick and task prizes) it does not presently offer academic credit. Whilst metrics (measuring creative problem solving ability) was considered, it was not investigative or implemented in the module (albeit simply using the number of tags collected in the robot task). This important area would form the basis for an entire project in itself. Academic accreditation of the module has been undertaken for the 2010/2011 academic year.

Interviews

Analysis of the frequency of occurrence of particular concepts in each interview question, alongside re-analysis of the raw interview data has been used to form three outcome spaces. This has been undertaken in a software analysis tool called Nvivo. The outcome spaces represent a composite of individual perceptions from each of the three groups of interviewees to the three fundamental interview questions. Hence, the resulting categories within each outcome space represent the composite perceptions of each group (students, academics and professional engineers). Within each category basic ordering of the concepts has been undertaken which indicates the perceived relative importance of that concept. These are shown in Figures 4, 5 and 6, with each coloured-coded rectangle representing a concept.

It is not possible within the confines of this short paper to provide a detailed analysis of the outcome spaces, or to provide the required supporting quotations. Considered here alongside each of the outcome spaces, however, is a summary of the key observations to each of the three interview questions.

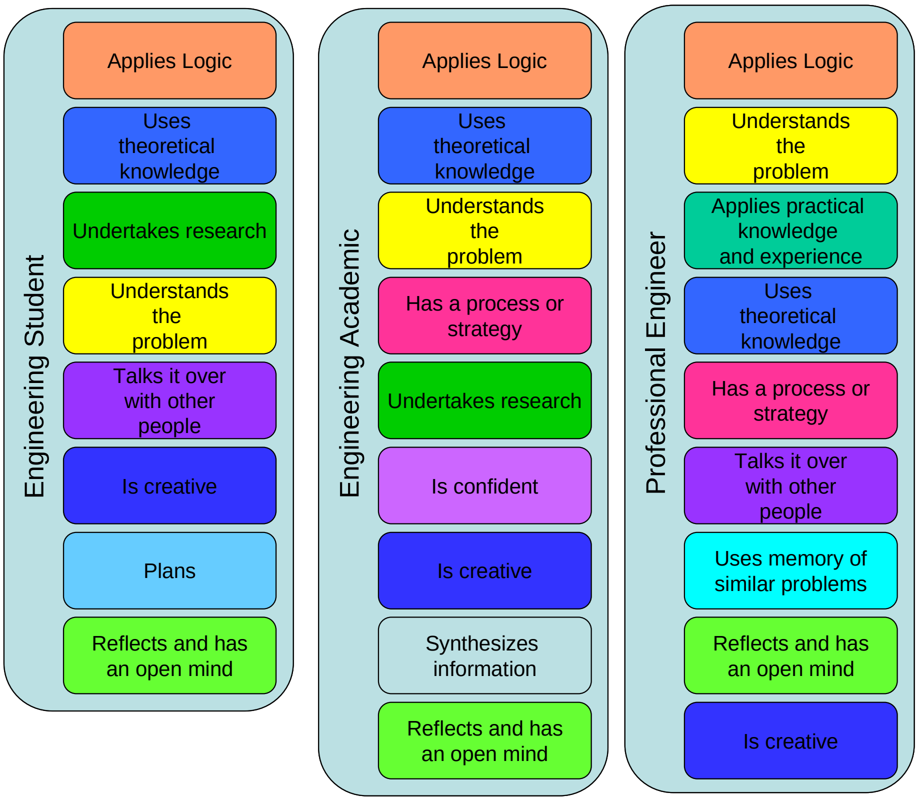

Figure 4
Outcome Space Q1 – Good Engineering Problem Solver

Findings from Question 1 confirm previous studies in that students tended to identify discrete skills appropriate to stages of a typical problem solving process rather than taking a holistic process-based approach [45-48]. Students also tended to concentrate on analysing the problem and identifying what knowledge or skills they already had. Professionals on the other hand took a broader approach by considering the problem as a whole and selecting and adapting strategies accordingly. Also evident was the dominance of the application of logical thinking within engineering [49, 50]. This clearly demonstrates the need to develop activities and instruction that develop process skills, and which also encourage creative thinking. It was also apparent that when a knowledge deficit was encountered in both students and professionals that an attempt was made to resolve this through research (information finding) or talking to other people. What is being observed here is the notion of knowledge networking, as suggested by Allen and Long [51]. In order for students to apply knowledge acquired this way effectively requires additional skills such as criticality, reasoning, synthesis and presentation. These skills are often not developed until much later in undergraduate studies (towards their dissertation), so suggesting perhaps these should be developed much sooner. It is the development of process-related and knowledge networking skills and activities to stimulate creative thinking that has been implemented in the action research.

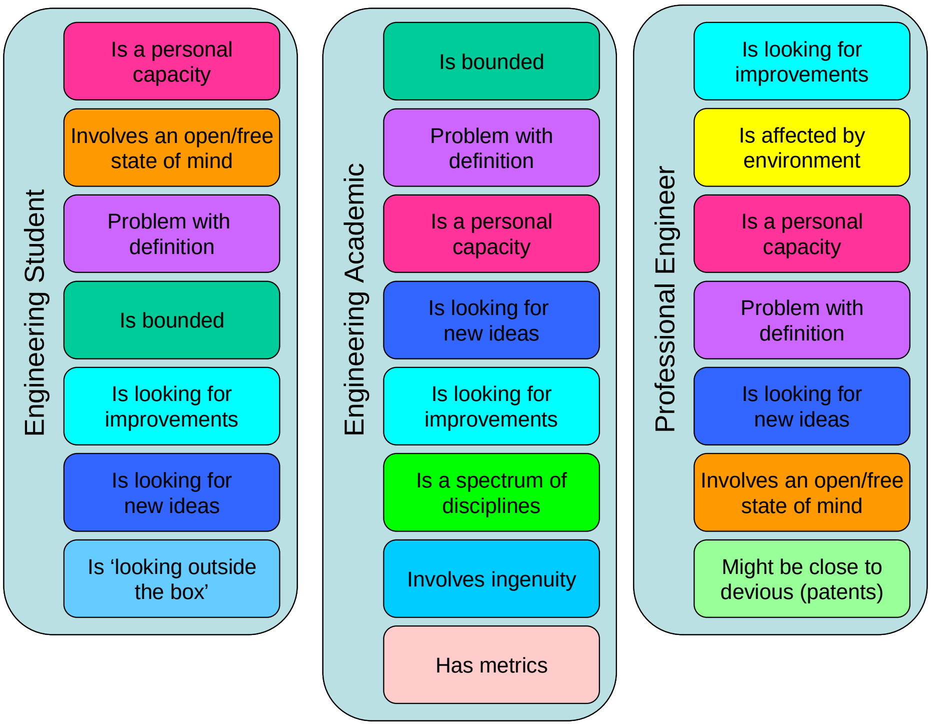

Figure 5
Outcome Space Q2 – Creativity in Engineering

In Question 2, looking at the perceptions of what creativity is in engineering, themes are largely convergent across students, academics and professionals, but with some exceptions. Two key perceptions relate to the actual use of the word creative within an engineering context, and with the belief that being creative is a personal capacity (as highlighted by Abra [52]). Whilst it was not disagreed that there was a place for creativity within engineering, this was often associated with artistic subjects such as music or art than with engineering. Other associated, but probably more tangible concepts such as innovation, ingenuity and entrepreneurship were offered in many cases as more suitable alternatives. It was also widely believed that creativity (and its associated concepts) was a personal, internalised capacity that not every person might be able to demonstrate or call upon. In nearly all cases, creativity was associated with some end product or artefact, and seldom with the process that had been undergone to come to a solution. Creativity as a process of improvement, as opposed to devising something new, was the most important perception for the professional engineer. It is, perhaps, these tensions with creativity in an engineering context that need to be overcome with engineering students, and possibly in the engineering arena as a whole, which the action research has attempted to achieve.

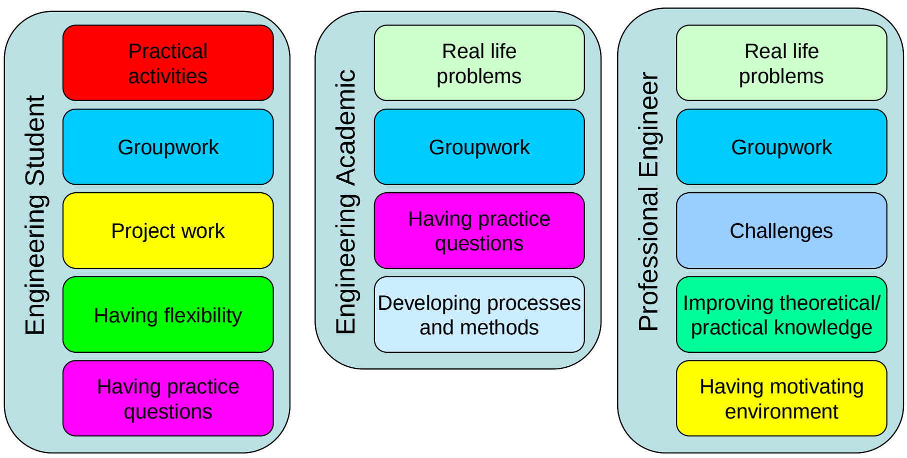

Figure 6
Outcome Space Q3 – Improving Skills

Question 3 asks for perceptions of what might be done in order to improve problem solving skills and encourage creative thinking in engineering undergraduates. Again, responses from both students and professionals were agreeable and predictable in that both practical activities and the involvement of groupwork (or teamwork) were perceived as essential commodities for improving these skills. These agree with the findings of Felder [6]. Whilst a whole range of practical activities were identified, ranging from project work and design tasks to case studies and industrial placements, the emphasis here was clearly on their applicability to real life. In addition, professional engineers identify the requirement for a stimulating and motivating environment. Indeed, it is both suitable practical activities involving groupwork and environment that have been taken forward into the activities within the action research part of this study.

CONCLUSIONS AND FURTHER WORK

Developing creative problem skills in engineering students is clearly of vital importance, as highlighted in the many benchmark and policy statements. Effective problem solving is more than simply being able to solve routine or familiar problems. It is also about recognising strategy, process and method.

This study has attempted to develop and foster creative problem solving process skills using a PBL-based Instructional Design model. RLOs have shown their potential for use as mediation tools within this context. Lego Mindstorm NXT robots, which have replaced Lego RCX robots used in the first cycle, have proved an effective and stimulating means for generating and solving problems. Student feedback has, on the whole, been positive and many students believe that their creative problem solving skills have been improved.

Both cycles of action research and the parallel interviews have highlighted a number of useful themes that have, or will be, incorporated into the module. Themes for further work include:

- Investigation of the notion of the acquisition of knowledge through Knowledge Networking, and methods for its improvement
- Development and enhancement of the PBL model using RLOs, and investigation of its potential for use in other disciplines
- Development of further RLOs and enhancement of existing RLOs to include audio, video and on-line testing
- Investigation of alternative low-cost robots and practical activities in order to enhance accessibility
- Investigation and implementation of metrics for the formative or summative assessment of creative problem solving ability

Further details about this research work along with the RLOs to download can be found at:
http://www2.northampton.ac.uk/appliedsciences/appliedscience/engineering/problem-solving

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