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Project based Learning in Engineering Design Education: Sharing Best Practices

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Project-Based Learning in Engineering Design Education: Sharing Best Practices

Abstract

There is growing evidence of the need to prepare engineering students for the future world in which they will practice as professionals. Educational practices that over-emphasise theory alone are outdated, as it is important for students to not only gain knowledge about engineering, but also to learn how to be an engineer. Hence a transformation in teaching and learning approaches is essential to prepare students to solve complex problems in a global world. In order for students to practice as engineers, they need to have had exposure to a number of projects that offer real-world problems, along with the complexity and uncertainty of factors that influence such problems. Students need to learn how to frame a problem, identify stakeholders and their requirements, design and select concepts, test them, and so on. Learning to apply theoretical principles is much better done when given real problems and hands-on activities in projects. This form of project-based learning calls for a different mode of interaction between staff and students, and is explained in this paper. In project-based learning, teachers facilitate and guide students through the engineering design process, while students actively engage in research and problem solving activities within a team setting. The approach presented here is part of the new re-design of the engineering curriculum at Massey University in New Zealand. Some of the challenges of implementation, and best practices, are shared in this paper.

The need for a new approach

Research and new trends in engineering education clearly emphasise the importance of practical application of theory, creativity and innovation as key skills required for problem solving. The world has changed rapidly in the last decade and major changes such as globalisation, technological advances, inter-connectedness, and accessibility to information influence the way current and future generations of students learn. Educators are finding it challenging to fit in new material into a full curriculum in a timely manner. For a long time the focus in engineering education was mainly on disciplinary knowledge only, but recently there has been a significant shift in focus to include more design thinking and professional practice elements, as highlighted by professional industry bodies. Interaction with industry professionals indicates that they require engineering graduates to be able to think critically, analyse problems, create innovative solutions and communicate effectively. The Institution of Professional Engineers New Zealand (IPENZ) have stated that *"There is a need for professional engineering graduates who are "rounded" and not just technical boffins -many of the existing graduates do not have strong "soft" skills. Graduates entering industry have technical knowledge that is largely theoretical, and industry needs to invest considerably to close off the knowledge gap between principles as taught and codified knowledge as used in industry[1]."* The US Accreditation Board for Engineering and Technology (ABET) have said that-"*students should develop higher order thinking skills of analyses, synthesis and evaluation[2]."* Students have felt that sometimes they do not see the relevance of what they are taught to real-life practice. Hence there is a need to transform the way 21st century students are educated and prepared for their future professional work.

Project-based learning (PBL) is a successful approach that addresses some of these challenges and needs. Project-based learning is a comprehensive approach to teaching and learning that is designed to engage students in the investigation of authentic problems. Students become active learners and participate in hands-on activities, while lecturers provide guidance to students during their project work. The PBL method of learning and teaching thus requires a new mindset and a change in role for both students and teachers. The author and her colleagues have found that this method increases student motivation, and allows them to apply their theoretical knowledge in an interactive environment, where they discuss concepts with each other and also with staff. Students learn to research and define the problem clearly, explore the solution space for more than a single solution, and learn to iterate and improve their designs to arrive at an appropriate solution that meets the objectives. Students learn the key skills of problem solving progressively, starting with simpler applications through to more complex problem solving.

Based on a review of the literature, experience in project-based teaching, and feedback from employers, staff and students, a number of specific recommendations are made in the following sections. These best practices and criteria for project selection outlined in this paper are relevant to many engineering disciplines and can be applied to most subjects across the curriculum.

Introduction to Project-based learning

Massey University has run project-based learning (PBL) courses in the product development engineering degree for several years, and has recently expanded this method to include the engineering disciplines of electronics and computing, mechatronics, chemical engineering and food technology. The Bachelor of Engineering curriculum in these disciplines has been re-designed to include PBL courses across the four years (eight semesters), starting from the first year (Figure 1). The PBL courses in Figure 1 form the 'project spine' column on the left, and are integrated with fundamental and technical knowledge of the disciplines. There are two PBL courses (15 credits each) in each year (one in each semester) of the new Bachelor of Engineering degrees. Each PBL course runs for fourteen weeks and has a minimum of six contact hours per week. The PBL courses are integrated with the fundamental knowledge courses, and staff from all the courses in each year get together to plan and discuss the projects and the assessment schedules.

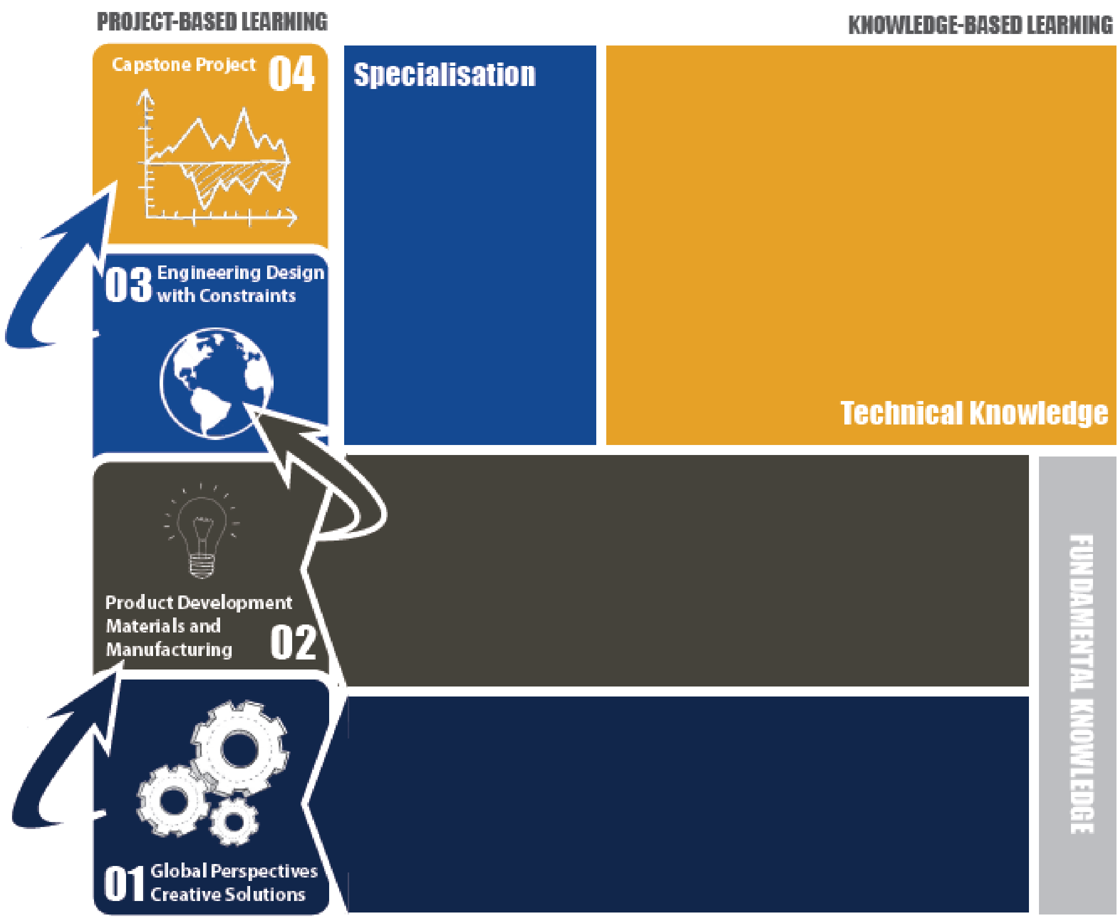

Figure 1: The new re-designed engineering curriculum

The central focus of each PBL course is a project based around a theme such as global perspectives, creative future solutions, consumer product design, and manufacturing (Table 1). International projects are included for first year engineering students as part of their Global Perspectives course, through the Engineers without Borders (EWB) organization. The projects expose students to the design process, problem definition, contextual understanding and systems thinking approaches. Students learn to work in teams, and to plan and carry out different tasks that are required during a project. They come to understand their own and their team-mates strengths and skills. Students are expected to draw information from a variety of sources and be able to filter and summarize the relevant points. They are also expected to communicate to different audiences in oral, visual and written forms.

Table 1: Project-based courses and examples

Project Based Courses – Engineering Practice		
Semester	**Project Theme**	**Project Examples**
Semester 1	Global Perspectives	Solar cooker for a Vietnamese village; sustainable roof for huts in East Timor; water filtration system for Nepal.
Semester 2	Creative Solutions – Future Focus	Futuristic kitchen; futuristic transportation concepts for year 2070.
Semester 3	Product Development	Design of a wheelchair accessory; medical pill dispenser for the elderly; new breakfast cereal and packaging.
Semester 4	Product Manufacturing	Manufacturing of a coil winding machine.

For example, the first project (Global Perspectives) is designed to introduce students to engineering in a global context. Specific emphasis is on:

- Understanding and applying the basic design process
- Awareness of cultural, ethical, economic and social needs
- Personal and professional characteristics – critical and creative thinking
- Project planning
- Written communication

The knowledge gained in the other first year engineering/science papers is expected to be applied within the project – particularly in demonstrating the fundamental principles underpinning problem solving. Students engaged in design-based learning build their competencies in the application of engineering theory, along with communication, teamwork and time management skills. These skills are strengthened alongside their learning of the engineering principles and theory, and it has been found that students benefit most from this form of parallel learning. This has been found to also support students' motivation and interest in their field of engineering study. As a result of doing these courses, students have stated that there is an increase in their confidence in making design decisions and a better understanding of how engineering principles relate to real-world problem solving.

Criteria for project selection in PBL

The key design and professional practice concepts are learnt over time and evolve with every opportunity for applied learning through projects. The projects are first designed and selected based on the learning outcomes desired at each level. The projects must allow for open-ended problem solving and application of theory. The most important criterion is that the problem should allow for multiple solutions. A design problem usually has many solutions, and students learn to evaluate these solutions and select the most appropriate one for the situation. The projects should give students the freedom to explore the context, define boundaries, research various sources and come up with a range of alternative solutions. In other words, the project brief or aim should not narrowly specify the solution or what should be built. Projects should allow for some freedom of expression and some experimentation in order for students to select the most appropriate solution. Some projects should allow for the consideration of not only technical aspects, but also economic, socio-cultural and ethical factors.

The closer the projects are to commercial reality the better, as it trains students to handle real-world problems that they may face in their professional careers. Exposure to a number of open-ended projects ranging in focus and complexity helps with student learning and confidence[3,4]. Through project-work experiences, students learn to combine knowledge and experiences in new ways, and build a broader base of knowledge and skills to draw from, leading to innovative solutions. The project brief can be ambiguous in order to allow students to research further information, think through the situation and decide as a team the tasks, the direction and the outcomes they want to achieve.

The projects should encourage team-work. The projects usually require a number of tasks to be carried out within a tight deadline, requiring students to share the workload in order to achieve an acceptable outcome. They should require students to apply relevant theory, and encourage students to integrate the knowledge gained from all their courses. Most real-world problems and their solutions are not restricted to mono-disciplines, so students should learn to draw information from across disciplinary borders.

Example project briefs:

- Develop an environmentally friendly, durable and low-cost roof material using locally available materials. Please consider the health and safety of the family, salt from ocean breeze and strong winds affecting families in the Mekong Delta of Vietnam.
- Design and develop a water filtration system that filters the river water for use by the villagers in their households in the Mekong Delta of Vietnam.

Teaching approach and key competencies in PBL

The new approach focuses on developing key design and professional practice competencies through the project-based courses. They are: knowledge discovery, problem definition, systems thinking, professionalism, design process, communication, teamwork, decision making and action (see Appendix 1). These design and professional practice competencies are learnt through repeated applications in a variety of project scenarios each semester (Figure 2), making it familiar and easier for the students to absorb them.

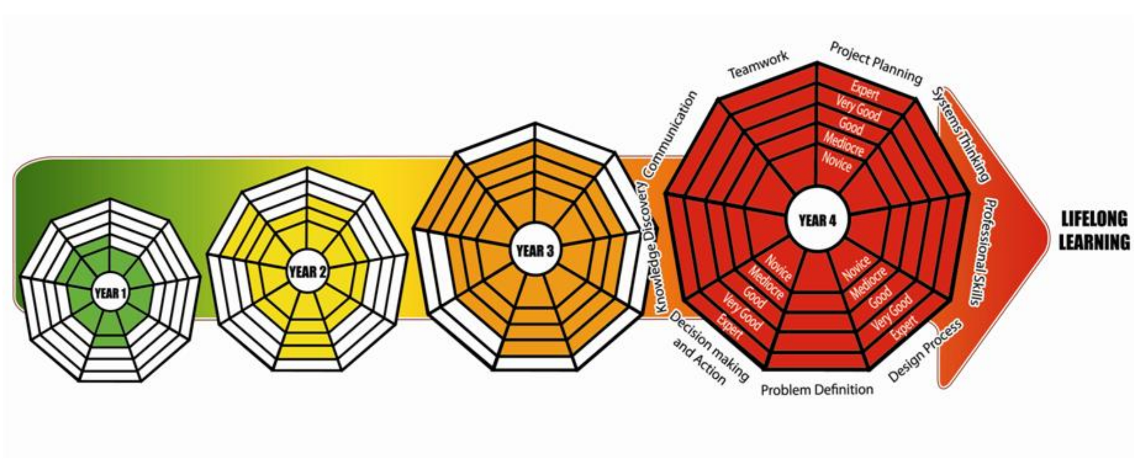

Figure 2: Progression of key competencies

Figure 2 shows that students in year one are generally at the novice level for most of the competencies. They may have never worked on a project or in a team setting. As they progress through the years, they are exposed to opportunities where they can develop their competencies. The skills and competencies are developed from initial introduction, through to application in a range of projects and contexts, in order to embed the key competencies to become habits of practice.

The teaching approach uses a scaffolding of activities, and progressive learning in order to support deep learning[5,6,7]. An example of scaffolding and progressive learning in a knowledge discovery activity would be for students to be given *selected references* to extract information from, to start with. Then in the next stage or project, they would be given the *topics* of information search, and the last stage would be for students to *identify* the information required *and source* the information themselves. More support and structure are provided in the first year, compared to later years. Online support is provided through a common website system called Stream for each paper. Stream provides information about each PBL course, the teaching schedule and weekly study plans for students (shown in the box that follows), along with a lot of other relevant information. There are staff course coordinators for every course, local to a campus, and also a global coordinator who is overall in-charge of identical courses across campuses.

What students should be doing this week

1. Learn how to gather information about the context
2. Learn about the different sources of information
3. Start to prepare your project proposal. What is a project proposal?

What students should be able to show

- Well documented background research on the context
- Clarity of the specific problem to be addressed by your project - project outcomes and deliverables
- Preparation of your project proposal

Assessment

- Project proposal

Project-based Assessments

All the assessments are related to the project, and follow the main stages of a design process. The design stages followed are the four Cs: comprehend, create, critique and communicate.

For instance, the first assignment is the project proposal which covers an understanding of the context and problem. The second assignment is the creation of design concepts, and the third is an evaluation and selection of the most appropriate solution. The fourth and last assessment is for students to communicate their solution.

Table 2 provides an example of all the assessments in a course and also shows the split between individual and team marks. This is important to ensure a fair balance and to reward those individuals who put in a lot of effort.

Table 2: Example course assessment details

	Assessment	**Team or Individual**	**Weighting** (%)
1	Project proposal	Team	10
2	Concept design assessment	Individual	10
3	Detailed design	Team	20
4	Oral presentation	Individual & Team	20 (10+10)
5	Final project report	Team	30
6	Log book & self-reflection	Individual	10

Assessment rubrics provide clear criteria of how marks are allotted in the design projects. See the example in Table 3. These are used more as guidelines and not too prescriptive. The rubrics provide students a good idea of what is expected. Assessments need to take into account the range of acceptable solutions, and judge them according to the most important criteria of appropriateness to the context of the problem, how well the problem has been investigated, understood and resolved, the clarity of the problem definition, whether the solution space has been sufficiently explored, and how creative and innovative the solution is.

Logbook: Students are encouraged to record their rough notes, ideas and design decisions in their logbook for each project. They also record their own reflections on learning, project meetings and evaluations of self and team members[8]. The logbooks are checked by their staff supervisors and feedback is given to students at several points during the project. Formative and summative assessments are provided in each course, instead of end-of-semester exams, as these continuous assessments provide better feedback to students on their performance early enough for them to take remedial action.

Table 3: Example rubrics for assessing a proposal

Proposal – some criteria	**Mark allocation**			
	0	1	2	3
State aim	No aim	Overall aim of what the project is expected to achieve is stated, without outcome or benefits.	Overall aim of what the project is expected to achieve is stated, including EITHER outcome OR benefits of the project.	Overall aim of what the project is expected to achieve is stated, including outcome and benefits.
Define objectives	No objectives	Some objectives are defined in specific, actionable steps.	Most objectives are defined in specific, actionable steps to achieve the overall aim.	All objectives are defined in specific, actionable steps to achieve the overall aim.
Describe scope	No scope	Scope or extent of the problem is too narrow to necessitate the generation of more than 1 solution.	Scope or extent of the problem is too narrow (lacks enough detail) to necessitate the generation of more than 3 solutions.	Scope or extent of the problem is broad enough (described in enough detail) to necessitate the generation of at least 5 solutions.
List constraints	No constraints	Factors that are not specific to the context are listed.	Fewer than 5 factors that are specific to the project and context, and create boundaries or provide direction, are listed.	At least 5 factors that are specific to the project and context, and create boundaries or provide direction, are listed.
List key stakeholders	No stakeholders	Some key people or organisations that may be involved, or have an influence on the project and its outcomes are listed.	Some key people or organisations that may be involved, or have an influence on, the project and its outcomes are listed *and* reasons for involvement are stated.	All key people or organisations that may be involved, or have an influence on the project and its outcomes are listed *and* reasons for their involvement are stated.

Example calculations on the number of tyres required and some initial sketches recorded in a logbook for a house roof (3metres x 3 metres in size) are shown in Figures 3 and 4 respectively.

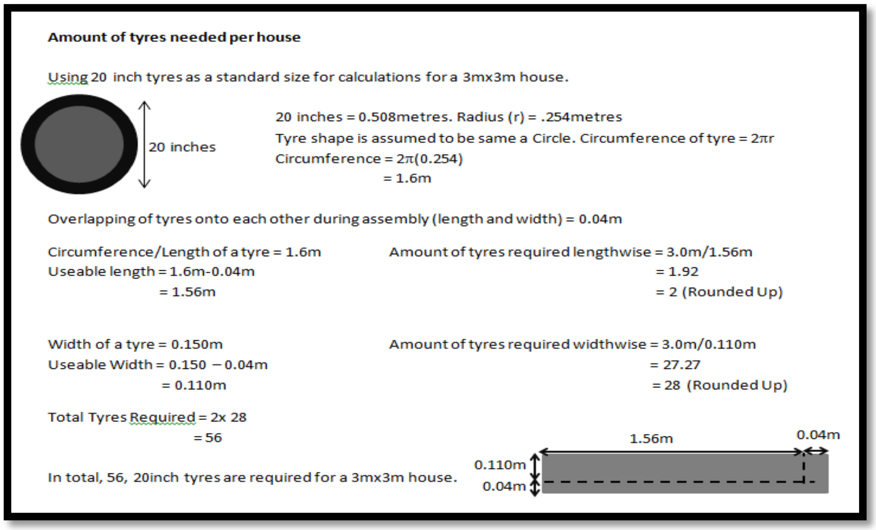

Figure 3: Example calculations in a logbook

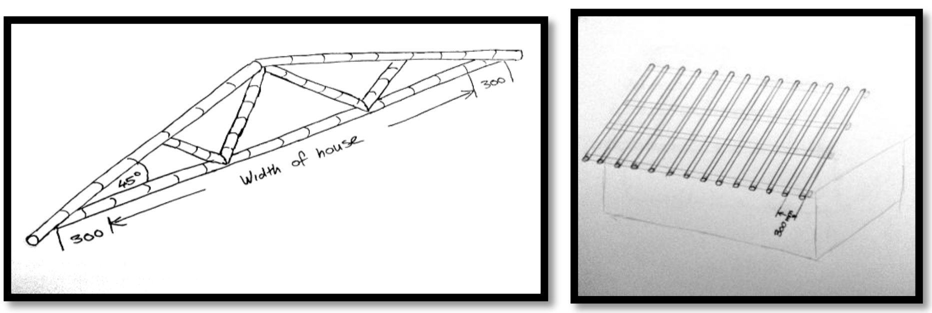

Figure 4: Example sketches in a logbook

Creativity and innovation can be assessed by the novelty of the solution, whether it represents a new combination of elements, and its patentability. Assessors also look to examine whether socio-cultural, technical, economical and sustainability factors were considered. From an academic standpoint, the design process and application of theoretical principles, and the student's learning, are important.

The assessments across all the eight papers in the first year (four courses in each semester) are mapped onto a central timetable, so that there are no scheduling clashes for students. All tests are held at the same time across campuses, and usually at the start of the day. This is so that students do not miss morning classes to study for a test later in the day.

Learning Outcomes:

Below are some of the learning outcomes expected from the PBL courses. On completion of the project-based papers, students will be able to:

1. Apply science and engineering principles to the solution of a complex engineering problem - where complexity is defined by the social, environmental and economic context.
2. Recognize the basic processes required for project management and define the key elements of the design process. Use the design process and methods to arrive at creative solutions that are relevant to the context and user needs.
3. Clearly define a problem, recognizing uncertainty and creative thinking in the approach to solving a problem and consequently discuss potential solutions and articulate final recommendations.
4. Recognize the need for enquiry and demonstrate an information survey of print and electronic literature.
5. Demonstrate one's professional ethics, responsibility and behaviour when working with one's peers.
6. Practice written, visual and oral communication styles.
7. Explain the roles and responsibilities of engineers to the solution of engineering problems within societal and cultural settings.

In the second PBL paper, students are encouraged to think about the future (approximately 20 to 30 years ahead) and design a product or process that might be used in this future scenario, based on the brief provided. Students are introduced to some key tools including freehand sketching, computer aided design, visual communications software (Photoshop), creative thinking, fore-sighting and design techniques. All of these contribute to their final project outcome - an innovative concept for the future that challenges and impresses visitors to an end-of-semester exhibition.

Implementation of PBL

The implementation of any transformational educational approach can face some resistance and requires training and understanding of the new methods, as well as the benefits. In this case some of the challenges were contextual-based. The multi-campus situation at Massey University presented the challenge of maintaining equivalence and identical learning objectives. The new approach also called for additional staffing resources for large class sizes (around 80-120 students). Students are in teams of four, and staff members are required to go around the classroom during the project work and stimulate student discussions and thinking around key concepts. The ideal ratio would be a staff member for every 20 students or so. In the present instance, a number of staff supervisors contributed, with each staff member providing guidance to around four teams. This challenge can also be addressed by employing senior students such as postgraduates or final year undergraduate students to assist alongside staff during tutorials in a classroom. An alternative is to split the class into streams and handle around 20-25 students at a time.

The PBL approach requires a different type of space compared to traditional lecturing classrooms. A more open, flat classroom with furniture that can be moved and re-configured to suit team-work is required. Tables with wheels that can seat four students are used. In an open classroom setting, staff are able to walk around the tables and provide guided instructions to students during the problem solving and design work. Materials for hands-on activities (that include cardboard, green foam, sticky tape, rulers, craft knives) are required for students to be able to quickly make simple models and prototypes.

The new approach calls for more hands-on activities for students. Some staff may need to change their style of teaching from giving fifty-minute PowerPoint lectures to guiding students as they solve problems. Students appreciate having relevant examples that relate theory to practical applications. For many topics, it is much better and more engaging to have the students doing things in the class. For instance, developing a list of design specifications can be done with concrete products distributed to each team to create specifications for their 'ideal' product. Students can be asked to disassemble simple objects such as a stapler (or a disposable camera, an electric fry-pan or a can opener) in class, re-design it to suit a particular context and target market, and sketch the parts. These interactive and creative exercises help students learn by doing, and are appreciated by students. Students are asked a number of questions to make them think, and make appropriate design decisions.

As part of the implementation, staff responsible for teaching the first year papers meet and discuss how they can support each other. Engineering staff contribute to a module in the Physics course (which is taught by science staff) to reinforce the application of physical principles to engineering problems. Conversely, science staff are encouraged to participate in the engineering design project review meetings.

Benefits of PBL in engineering design education

In the PBL approach, there is less emphasis on rote learning and more on understanding of and applying engineering design principles. There is less chance of plagiarism due to the frequent assessments by staff throughout the course, the close supervision of team-work, and evidence gained from logbook records of individual contributions. Since the project themes and briefs also change every semester, one cannot copy from previous or senior students.

Project-based learning helps relate theory to practical applications, enabling deep learning. Students remember their project experiences better, and are able to identify their own strengths and areas for personal development. Collaborative learning also takes place, as students learn from their own team members, and from observations of other teams.

Student evaluation and feedback

In the 2013 student survey, students have clearly said that they enjoyed the project activities, and the hands-on tasks. Three methods were employed to gather student opinions – an online survey (147 responses received), face-to-face discussions by staff from the Department of Teaching and Learning (over 300 students participated), and course feedback. Students said that the projects, Stream online support (especially, the weekly study plans), practical and applied activities, class discussions, problem solving exercises, and field trips helped with their learning. Engineering staff were appreciated for their approachability, hard work and subject knowledge. Some of the responses regarding what hindered their learning included clashing deadlines, timeliness of feedback, and not having a common architecture on Stream sites for all courses. The clashing deadlines have now been addressed by a collaborative staff workshop that resulted in a relatively even spread of assessments throughout a semester. The other two main negative responses are being addressed for courses in 2014. Overall, the students said that the PBL courses enhanced their learning, and was interesting and fun.

Conclusions

The importance of integrating practical engineering design methods through projects, alongside the learning of engineering fundamentals, has been shared in this paper. The key challenges facing staff while transforming undergraduate engineering education to incorporate more project-based learning approaches are also covered. Important criteria for selecting suitable projects and key competencies that are developed through project-based learning are discussed. Some of the best practices, assessments and examples presented here will be of interest to engineering design faculties and to those who are looking to offer active learning educational experiences to tertiary students.

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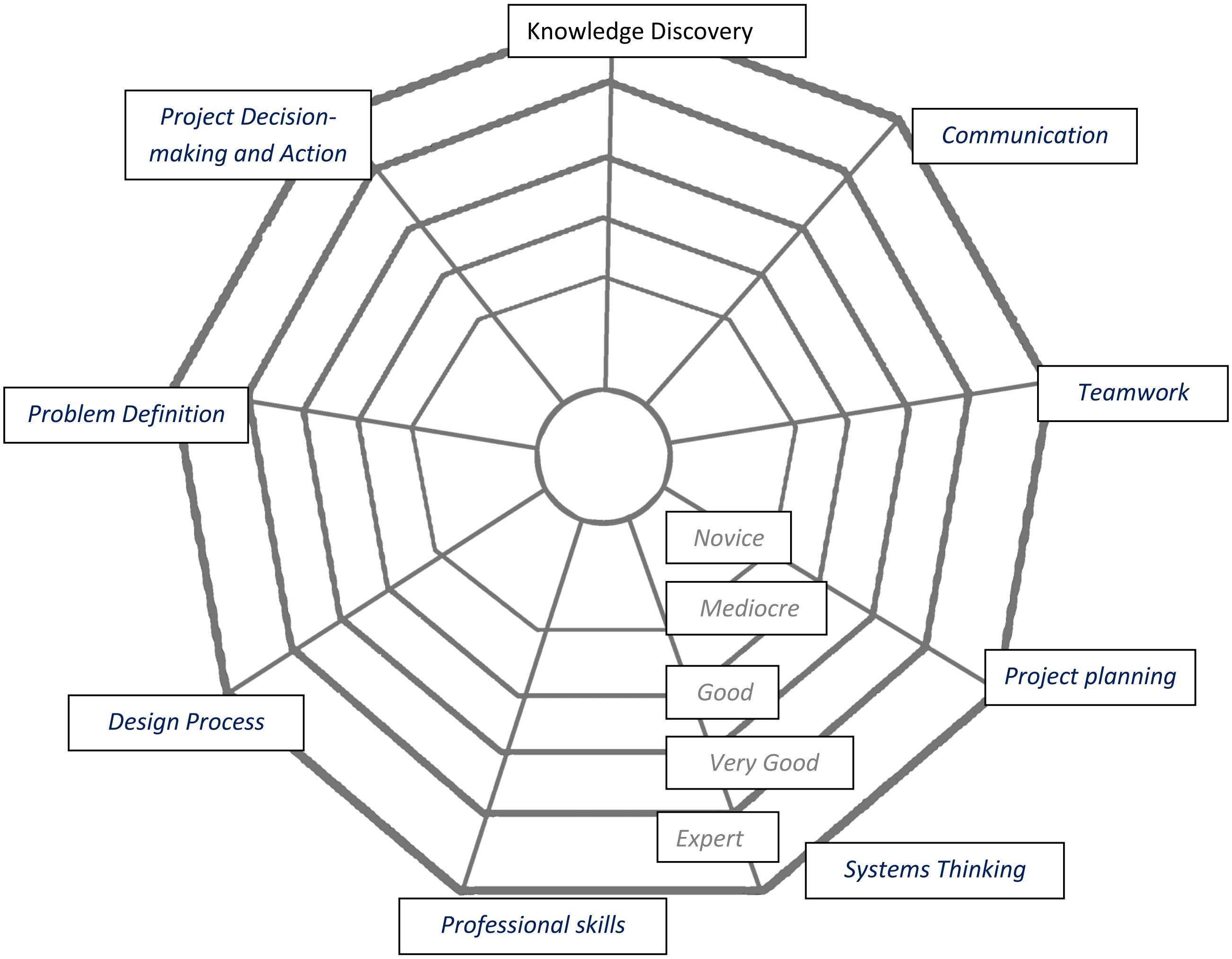
Appendix 1: Spider chart showing Key Competencies



The key competencies are at the heart of <u>engineering problem solving</u>.

1. **Systems Thinking**: thinking holistically about a problem/opportunity
2. **Problem Definition**: identifying and defining a problem/opportunity
3. **Communication**: oral presentations, written and visual (multi-media/graphical) communications, appropriate to various audiences
4. **Teamwork**: effective teams, leadership, cooperation for common goal
5. **Project Planning**: time management, proposal, task scheduling
6. **Project Decision-making** and **Action**: having to make choices, balancing the information available against the cost of acquisition and consequences of the decision, and acting on the results.
7. **Knowledge Discovery**: Sourcing and filtering information from various media, people and so on.

8. **Design Process**: methods of divergent and convergent thinking, creative and critical thinking.
9. **Professional Skills**: integrity, accountability, responsibility, willingness to initiate, learn and take risks, knowing one's strengths, positive attitude, sensitivity to other contexts, and such like.

Rating scale:

Novice: To have little experience or no exposure

Mediocre: To be able to participate and contribute to

Good: To be able to understand, explain and apply competently

Very Good: To be skilled in the practice or implementation of

Expert/Excellent: To be able to lead effectively or innovate in

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