# A COMPARATIVE EVALUATION OF APTITUDE IN PROBLEM SOLVING IN ENGINEERING EDUCATION

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**ABSTRACT**
Engineering education has been criticised for focusing solely on the science of engineering, to the detriment of preparing students for the practice of engineering. Graduates are considered by many in industry to be ill-prepared for real world problem solving and to have limited experience in applying their engineering knowledge to product outcomes. Instruction in design is uncommon, and where existing, follows a linear and predictable process that does not afford students opportunity for experimentation and exploration. However new engineering education pedagogy seeks to address these issues through early integration of design and project based learning into the curricula.
This paper describes the initial findings of a comparative evaluation exercise conducted to measure relative aptitude in problem solving by two disciplines of final year engineering students and thus validate the impact of new engineering curricula. The evaluated students were from a typical Mechanical Engineering course and from the less conventional Product Design Engineering program which integrates industrial design studies into mechanical engineering curricula. Students' problem solving methods were observed, the design outcomes were evaluated and participants surveyed. These exercises challenged the student's problem framing and solving abilities and required the application of engineering science and design acumen to achieve a creative solution for either an open-ended or constrained problem. The early findings of this ongoing investigation are examined here, and the benefits of developing a creative design focus within an engineering curriculum are clearly evident.

*Keywords: Product design engineering, wicked problems, open-ended problems, engineering education*

## 1 BACKGROUND

"It is implicit that creativity is integral to design innovation, and that design and the fostering of creativity should be the cornerstone of engineering pedagogy" [1]. Unfortunately, most engineering curricula focuses solely on a theory-based engineering science approach neglecting creativity and the development of design acumen and problem solving aptitude. To be adequately prepared for the challenges of 21st century practice, graduates must be innovative, adaptable and creative designers; this will only be achieved through extensive experience in design, problem framing and solving and the creative process. Students must be challenged to move beyond the technical aspects of the problem [2] and develop creativity through new non-linear, unstructured and flexible approaches to problem solving and idea generation [3]. However, the creative process involves having unusual ideas, tolerating the unconventional and seeing unexpected implications [4]. This makes open-ended problem solving particularly challenging for engineering students who are more comfortable when working within defined parameters, specific steps and often pre-determined results. Traditional engineering assignments, which tend to be left-brained [5], can stifle creativity and result in graduate engineers who are inclined to fixate on prior solutions, thus limiting their contribution to innovation.
If we are to graduate creative engineers and innovative problem solvers, then curricula must integrate and develop design acumen, creative methodologies and experience with 'wicked problems' [6] throughout the learning process.

## 2 INTRODUCTION

HES5350 Product Design is an elective subject offered to all student disciplines within the engineering faculty at Swinburne University of Technology. The content and delivery of this unit, which results from collaboration between design and engineering lecturers, aims to impart an understanding of the product design cycle and an appreciation of design principles in engineering and nature and the ability to creatively design quality products for a sustainable environment.

As both Product Design Engineering (PDE) and Mechanical Engineering (ME) students attempt the subject in the final semester of their fourth (and final) year, the unit provides a unique opportunity to compare differing approaches to problem solving. Specific projects, which required creative and user-centred solutions, facilitated a comparative evaluation that measured the aptitude of the individual disciplines when faced with either open-ended or constrained problems.

Product Design Engineering is a unique engineering pedagogy as it incorporates ‘designerly ways’ [7] into engineering curricula through integration of industrial design and mechanical engineering curricula. This multidisciplinary program derives 60 per cent of its engineering content from the standard mechanical engineering curriculum; therefore a comparative evaluation of student abilities between PDE and ME should highlight the contribution that the inclusion of design thinking and design aptitude has made to the traditional engineering curriculum. It was hoped that the evaluation results would provide evidence of the success of the unique and innovative product design engineering curricula, in producing more creative and adaptable engineers who are comfortable with poorly defined problems and the development of unprecedented solutions.

## 3 THE COMPARATIVE EVALUATION

The unit challenged final year engineering students to complete a three-week design project; either addressing an open-ended or ‘wicked’ problem or designing to a highly constrained brief. Students did not require specific design skills (to ensure that the ME students are not disadvantaged), but required creative problem solving ability, the application of engineering knowledge combined with an appreciation of the needs of the intended user and their environment. Projects were distributed randomly and where possible, students were engaged on different problems to their closest peers.

### 3.1 Issues with problem scoping

Atman et al [8] in a comparative study of freshman and senior engineering design processes found that novice students (i.e. first year) did not product quality designs even though they spent a large proportion of their time defining the problem. By contrast senior students with more developed ‘problem scoping’ aptitude, analysed and framed the problem more efficiently, enabling them to progress to better design outcomes. It was also recognised that the more experienced students had enough confidence to make assumptions which aided the analysis process. The progress of novices often stalls at the problem definition stage resulting in delays or poorly considered design solutions.

The main difficulty in teaching the diverse student cohort in this study was the lack of parity in design and problem solving abilities. It was quickly apparent that whilst the PDE students had benefited from design education practices that specifically enable progression from novice to expert, the fourth year ME students (with no direct design training) were design ‘novices’ (despite being in their final semester of study) unfamiliar with the demands of unconstrained design processes. Whilst the PDEs had well developed design acumen (after years of project based design training) and were comfortable with the uncertainty of the design challenges, the ME students lacked even the basic sketching abilities necessary to encourage creative exploration. Resultantly, the ME students required a disproportionate amount of tutoring (especially in perspective sketching) and assistance during the project.

Atman’s findings were reinforced by this research. The ME students, troubled by problem definition, failed to address the real needs of the project, focussing on the more tangible technical aspects, whilst the PDE students typically identified crucial user needs and environmental or contextual requirements, resulting in thorough framing of the problem and ultimately, successful designs.

### 3.2 Measures of comparison

The comparative evaluation projects occur within a design teaching studio environment, although project progression is not limited to in-class time. The comparisons between the problem solving aptitude of the PDE and ME students were evaluated through a variety of measures including:

- direct observation and recording of problem solving approaches
- discussions with students during the project to gain insight into their processes and difficulties
- evaluation of design solution
- anonymous reflective post-project survey

### 3.4 The student survey

The reflective survey addressed sketching /conceptualisation, problem solving and project analysis. Students evaluated their level of comfort with either open ended or constrained problems, examined the impact of their sketching abilities and provided an overall evaluation of the project. Under scrutiny was their ability to communicate ideas through drawing, familiarity with user-centred design, comfort with short lead-times, skills in critical thinking and analysis, application of engineering skills to real-world problems, and the appropriateness of their design solution and degree of innovation.

## 4 THE DESIGN CHALLENGES

The two projects enabled observation and evaluation of the difference abilities and approaches of final year engineering students confronted with a real world problem requiring a creative product solution.
Project A required a user-centred focus and a creative and divergent approach, whereas project B required a thorough technical understanding of manufacturing processes and structural engineering.
The study aimed to discover which discipline of engineering students (either PDE or ME):

- is more adept in either open-ended design or constrained problem solving
- demonstrates creative design ability in a real world context
- best applies technical knowledge to product resolution
- demonstrates understanding of user needs and environment considerations

### 4.1 Hypotheses

Some assumptions or hypotheses were made prior to the commencement of the projects.
Firstly, it was assumed that the product design engineers would perform better at the open-ended project due to their familiarity with ill-defined problems, creativity and extensive design experience.
Secondly it was expected that the PDE students with their well developed design skills (equal in the most part to that of industrial design students) would have an advantage over the ME students as their sketching abilities would lead to a more reflective design process and further enable the articulation of design conceptualisation. Accordingly, the quality of drawing was not an assessable criterion, and the MEs were taught perspective sketching to help them to explore, experiment and express their ideation.
Thirdly it was deemed important to include a project that was tightly constrained. As the engineering profession is often engaged in projects with defined parameters and restrictive specification, it was important to evaluate student effectiveness at problem solving in a more familiar environment. The constrained project required application of manufacturing and material knowledge, and did not necessarily favour either discipline, although it was an opportunity for the ME students to excel.

### 4.2 The open-ended or ‘wicked’ problem

Project A required students to design a product for use in developing nations or remote areas where communities may be located at some distance from sources of clean drinking water. In such situations, people are required to transport water long distances without vehicular support, often many times daily. Students were challenged to design a solution that enabled the movement of 80 litres of water either up and down steep rocky terrain, or across a flooded plane (preferably by a single person). A creative user-centred approach, systematic problem definition and the appropriate application of engineering principles were necessary for a successful outcome. It was implicit that students would consider user safety, in particular directional control and braking, as well as handling, refilling and pouring and other critical user needs; however these were not identified during the project briefing to allow student discovery during the problem framing stage.

### 4.3 The constrained problem

Project B was a highly constrained problem where students designed a lightweight cafe stool which could be fabricated from a single piece of mild steel sheet. The furniture was required to support the load of a 100kg person, be suitable for outdoor use in the public domain, and address stacking and storage demands. Students were challenged to utilise sheet steel fabrication processes (such as pressing, rolling, folding, stamping) and balance structural needs with aesthetics, weight and comfort. A further requisite allowed the steel sheet to be manipulated in multiple processes, but not cut into pieces and reassembled. This highly constrained technical project required application of knowledge of material properties, manufacturing processes and structural engineering principles. Although project parameters were tightly defined limiting the breadth of conceptual exploration, students were expected to realise innovative and original (not adaptive) outcomes, appropriate for user and the cafe domain.

# 5 ANALYSIS OF PROCESS AND OUTCOMES

## 5.1 Studio observations

"Sketching enables the abstract development of a solution to an 'ill-defined problem' through the visualisation of mental imagery." [9] Unfortunately the ME students had difficulties with sketching (particularly in perspective); this limited their ideation, reflection and design progression.

In week 1 where students should have been engaged in problem framing rather than conceptualisation, the ME students (who were more problem than solution focussed) were already developing variations of the existing 'Hippo Roller', rather than pursuing unique and innovative solutions.

By week 2, all of the students were engaged in conceptualisation, with the MEs struggling with ideation due to undeveloped design and sketching skills; issues exacerbated by the short time line.

In the open-ended project:

- prior solution fixation was evident with many variations of the existing roller solution
- there was an overall lack of consideration for user environment (e.g. water and steep terrain)
- the ME students often appeared out of their depth, and uncertain how to proceed.

In the constrained project:

- students lacked understanding of metal forming processes/potential forms, however some basic engineering principles (structural triangulation) were emerging
- at this stage furniture forms involved simple folding fabrication – there was little evidence of material deformation to create (complex) curvature to gain structural strength.

By the end of the third week, all students had achieved a result, although not always an appropriate design. Results for the constrained project were much more successful with mostly unprecedented designs, whereas the open-ended project had a higher level of inconsistency and less innovative or unique solutions. Overall results were better than expected, possibly due to frequent tutoring during the project. Lecturers noted a significant improvement in confidence and design ability as the project progressed, indicating that significant learning had occurred.

## 5.2 Analysis of outcomes

The final design outcomes were evaluated by lecturers against the following criteria:

- evidence of problem framing and creative problem solving processes
- demonstrated understanding of, and response to, user needs and environment
- technical resolution of final design – manufacturability, uses of materials etc
- ability to broadly conceptualise without fixation on prior solutions
- innovative application of engineering knowledge in a real world context

### *5.2.1 Analysis of constrained project*

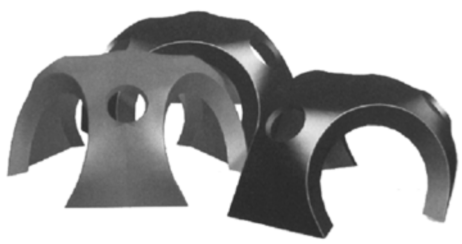
| Mechanical Engineering students | Product Design Engineering students |
|---|---|
|  |  |
| Simple 3D forms –sheet metal folding only | Complex 3D forms (including double curvature) for strength, visual appeal and comfort. |
| Solutions were mostly folded cubes representing only functional requirements | Utilised more complex manufacturing process and 'pushed' the material further. |
| Aesthetics were unrefined and consideration of user comfort and safety not demonstrated | Superior aesthetics, clever stacking solutions and more cafe friendly designs |
| Lack of technical proficiency, demonstrating only a basic knowledge of manufacturing | Designs more technically proficient including sheet cutting patterns/ waste minimisation |

*Figure 1. Constrained project – outcomes and analysis*

### 5.2.1 Analysis of open-ended project

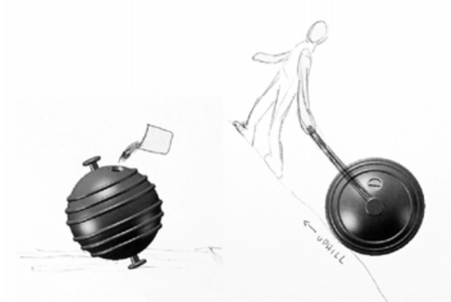
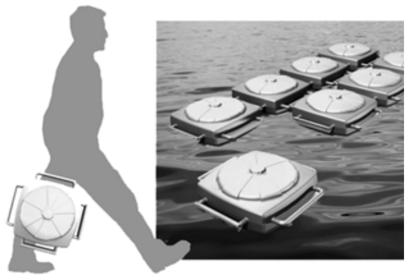
| Mechanical Engineering students | Product Design Engineering students |
|---|---|
|  |  |
| All projects poorly resolved – 50 percent of outcomes not to an acceptable standard | Well resolved/flexible solutions, multifunctional and modular designs for ease of handling |
| User safety not evident - braking and steering systems not considered or resolved | All of the PDE students had resolved braking systems for safe ascent/descent |
| Lack of innovation- universal fixation on variations of existing product | Some fixation on roller type solutions, but mostly innovative and original solutions |
| No consideration of 'flooded terrain' scenario | 50% addressed both steep and flooded terrain |
| All designs lacked technical detail/ resolution | High level of technical and manufacturing resolution and attention to detail design |
| No user consideration e.g. filling and pouring | Highly refined functionality for user needs |

*Figure 2. Open-ended project – outcomes and analysis*

## 5.3 Student feedback

Students were asked to complete a retrospective survey after the project addressing sketching and conceptualisation, problem solving and overall project analysis. This reflective survey found that:

- Most ME students were satisfied with their ability to communicate their thoughts and designs; however this was not evident in the submitted work. It was clearly apparent that the ME students were hindered by an inability to articulate ideation or communicate through drawing.
- None of the ME students were comfortable with short lead times and that they were more at ease and familiar with constrained problems, rather than open-ended or ill-defined problems.
- The ME students had enjoyed the challenges, although for many design activity was unfamiliar territory. Despite a high level of engagement and enthusiasm their design inexperience was evident as was a tendency to focus more on the problem than the solution.
- As expected, the PDE students were comfortable with both types of creative problem solving activity and utilised their sketching and design skills and experience in human centred design.
- All students were challenged by the projects, but felt that the problems posed were appropriate for their skills and knowledge. There was a general indication that students valued the experience and wanted more solution-focussed and open-ended projects during their course.

# 6 CONCLUSION

The first iteration of this ongoing research appears to support the initial hypotheses. As expected, the Product Design Engineering students performed better at the open-ended problem due to their familiarity with uncertainty, experience with user-centred design and established design abilities.

Unexpected however, was how poorly the Mechanical Engineering students would perform. Whilst it was predictable that ME students would lack drawing skills and design experience, it was expected that this would affect only the quality of their communication and aesthetic design. It soon became apparent was that these students, although technically competent, were relatively inexperienced in applying their knowledge to real-world contexts. This ineptitude manifested in the early problem framing stages with poor analysis of the problem, and infrequent consideration of user needs and environment. In the open-ended project, all the PDE students had successful and well considered outcomes; however the ME students mostly failed to move beyond poorly executed iterations of an existing product. To a certain extent it had been expected that the open-ended problem may not suit the MEs, however the constrained and technical project with its application of manufacturing and material knowledge was expected to produce more even results. Unfortunately it did not. Whilst all the students produced satisfactory results for the constrained problem, once again the solutions of the PDE students were superior; aesthetically, functionally and more surprisingly, technically.

Contrary to expectations, the multidisciplinary Product Design Engineering students proved to be more adept at their engineering due to their ability to apply their science in practice. Whilst they excel at ‘wicked’ problems, in this evaluation they were found to be significantly better at problem framing and technical resolution than other student engineers, even when faced with highly technical problems. This clearly demonstrates that the inclusion of ‘designerly ways’ into the engineering curricula has not compromised the integrity of the ‘science’ of engineering; rather it has enhanced the ‘practice’.

## 7 DISCUSSION

Industry feedback suggests that many engineering graduates are ‘unsuitable’ for employment because of ‘skill deficiencies’ in creativity, problem-solving, and independent and critical thinking [4]. Fostering creativity may not be occurring or may be ineffective and it is apparent that we do not teach the language of design, preferring instead the language of mathematics [10].

The initial findings of this ongoing comparative evaluation of the problem solving skills of engineering students (whilst derived from a relatively small sample group) support the positions of both Fox and Cross who have identified that there is ‘an educational justification for design’ as a means to develop cognitive skills and real-world problem solving abilities [11],[12].

It is apparent that sketching and design activities, and experience in the practice of engineering can be a motivating factor in engineering learning developing more creative and adaptive design engineers. Creative engineers are “driven to seek uniqueness, have unusual ideas, tolerate the unconventional and seek unexpected implications” [4]. Engineering curricula must develop creativity and design aptitude, if we are to graduate engineers who are more than just technically competent. Open ended design problems “force students to think creatively and ultimately foster in them an appreciation for developing creative solutions” [13], become comfortable with divergent thinking processes and develop ideational fluency. Experience with ill-defined design problems (that are not amenable to the techniques of science and engineering), is invaluable in engineering education. It is essential that students develop flexible and divergent dichotomies and eliminate tendency to fixate on existing solutions; this may require a new teaching approach for engineering design.

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