Developing engineering design expertise though reflection

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***Abstract**: The three key elements of engineering design expertise - framing, systemic thinking and the conscious application of first principles - have been shown to be difficult to acquire by both students and practicing professionals. Because of this, it is of value to investigate how framing, systemic thinking and the application of first principles can be better developed in engineering students which will in turn develop better graduate design engineers. This paper reports on a project to do this in two mechanical engineering design subjects. Students were introduced to one or all of the three key elements of engineering design expertise, encouraged to apply them in a design project and practice questions throughout the semester of study. Finally, students were examined on their framing ability and their ability to apply first principles. It was found that only around 15% to 20% had a developed framing ability. Further, the ability to apply first principles appeared to be bimodal some students could apply them almost completely, some could not apply them at all and only a few could apply them partially. This suggests that skills related to engineering design expertise can only be learned by some students or that the current education system (including earlier schooling) has not developed sufficient related skills in the majority of students. This requires further research.*

Introduction

Engineering design expertise was first identified and defined (to the authors' knowledge) by Cross and Clayburn Cross (Cross and Clayburn Cross 1998). It was based on the examination of two expert design engineers and was later reiterated by Cross (2003) when another designer was examined. The key characteristics of this definition were systemic thinking, framing and the application of first principles (Cross and Clayburn Cross 1998). This definition was given further support when it was demonstrated how it fits with other explanations (Suh 1990), (Pahl and Beitz 1995), (Koen 1985), (Kroll, Condoor et al. 2001), (French 1999) of engineering design expertise (Lewis 2006).

Given the number of papers that support this definition of engineering design expertise it was thought that methods to enhance the engineering students' abilities in the areas of systemic thinking (where all aspects of the design are considered concurrently), framing (where a problem is redefined so that it can be solved effectively) and the application of first principles (the application of basic science and engineering fundamentals to ensure that a design is optimum) should be investigated and developed.

It was felt that while it was possible to assess the ability to apply first principles and framing within traditional assessment, it was not possible to assess systemic thinking. Further, none of these are a process that can be taught solely in a traditional lecture format. Rather, they are a way of thinking or a form of cognition that needs to be developed over time. Framing in particular is said to be a difficult for students and engineers to develop (Cross and Clayburn Cross 1998).

Due to these issues, it was decided to try to develop the ability to apply first principles and the ability to frame by providing a series of related tasks to students throughout the semester of a design subject. Students would attempt these in their own time, discuss them with fellow students and go over issues encountered in class. The students were then encouraged to reflect upon the experience and use this to develop these two abilities. Students were made aware that they would be examined on their ability to apply these methods to a situation that they had not yet encountered in the final exam.

The application of first principles was covered in a Machine Design subject. This is a student's first introduction into the application of scientific theory learned in other subjects to the design of relatively simple mechanical systems. Framing was covered in the subject Mechanical Systems Design. This subject introduces students to methods and theory related to the design and development of complete systems from an initial concept. Both of these subjects were taught to mechanical engineering, robotics and mechatronics and product design engineering students. Students were typically in their third or fourth year of study (depending upon the subject and the specific course schedule of the individual student); and could have been single or double degree.

Method of Investigation

To evaluate the effectiveness of this reflective approach to developing key skills in engineering design expertise the grades of the pertinent questions from the exams, the official university student feedback surveys and the reflections of the lecturers and the tutors were considered and analysed. The analysis focused on looking at student comments to find insights into explaining how the efforts to improve engineering design expertise resulted in the marks for the respective questions. It was assumed that the marks provide a sufficient indication of the respective skill level of a student.

The First Principles Question on the exam was as follows:

Consider the basic centrifugal clutch shown below.

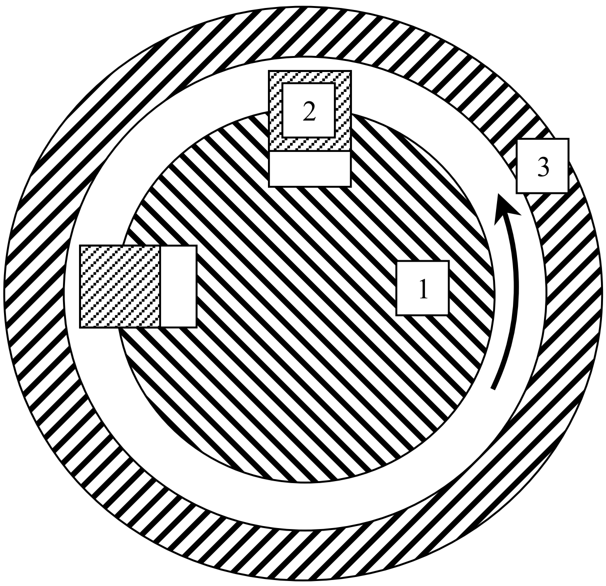

Figure 1: Centrifugal clutch

The inner shaft (1) rotates at a speed n. This causes the weights (2), each of mass m, to be pushed against the inside surface of the outer shaft (3) at a radius of R. The weights then apply a tangent force against the outer shaft due to the friction μ between each weight and the outer shaft.

We wish to know how the torque that is transmitted (from the inner shaft to the outer shaft) is dependent upon the rotational speed.

Analyse the above system to find the relationship between the rotational speed and the transmitted torque. Comment upon your findings.

Answer

In short, after analysing the system, students were expected to realise that the torque that could be transmitted was dependent upon the centripetal force multiplied by the friction between 2 and 3, and the radius of the inside of 3. Applying theory and mathematics to the system should then have resulted in the following formula: $T = n\,\mu\,m\,\omega^2\,R$. The *n* is for the number of weights (2); it was expected that students would realise that it was worth considering the effects of different numbers of weights.

The Framing Question on the exam was as follows:

A water products company wants to design a product or system that can take advantage of the current water shortages and desire to save water by harvesting rainwater. The issue is that rainwater has no pressure so it can't provide the same flow as the mains (or regular) water supply. Also, sometimes the rainwater tank will be empty and the only supply is the mains. Finally, end users will not want to have to use different systems to get their water; they like using their current taps.

Think about this problem and frame it in accordance with the framing process that was covered in the first lecture.

Answer

This is a problem that has already been solved by an Australian company. Davey water products makes a flow activated device that powers a pump connected to a rainwater tank Rainbank, which inspired this question. The device is placed in line with the water mains. When water starts to flow, the pump will turn on as long as the switching mechanism detects water in the rainwater tank. Thus, once a tap is turned the pump will force rain water against mains pressure and the rainwater will be used in the house. If however, there is no rainwater, then main water will freely flow through. Students were expected to describe a similar system and note that the valve and switch mechanism needs to be designed. If they were able to come up with a viable alternative, then that was of course accepted too.

Results

The results from the two final exam questions, the official university student feedback surveys and the reflections of the lecturers and the tutors are presented here.

Marks

The marks for the First Principles question on the final exam can be seen in Figure 2. The marks for the framing question on the final exam can be seen in Figure 3. While these are discussed in the next section, it is clear that in both questions, there were two groupings of student marks. The first was around the top end (near to full marks) and the other either around the bottom end (near to no marks) for the first principles and the 'pass' level for framing.

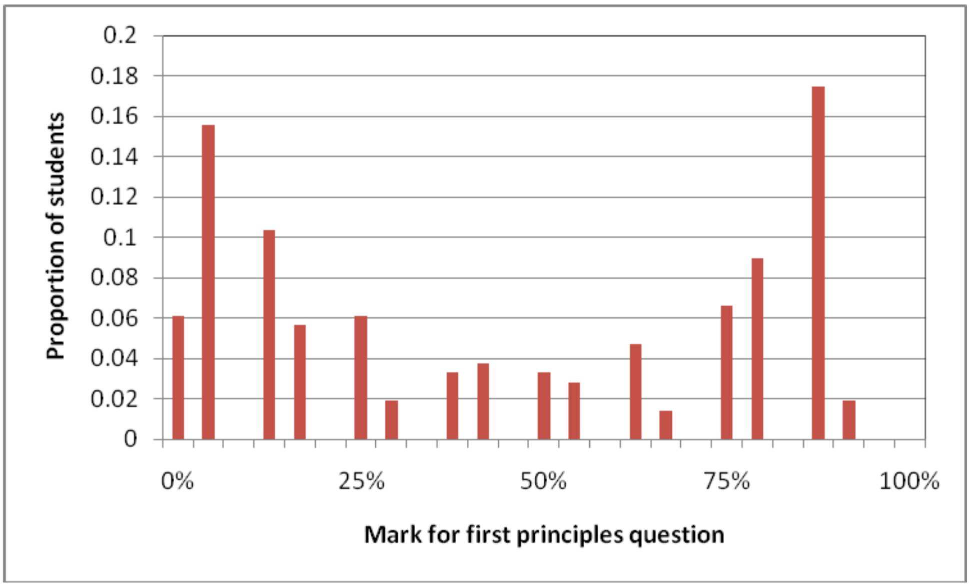

Figure 2: Marks for First Principles Exam Question

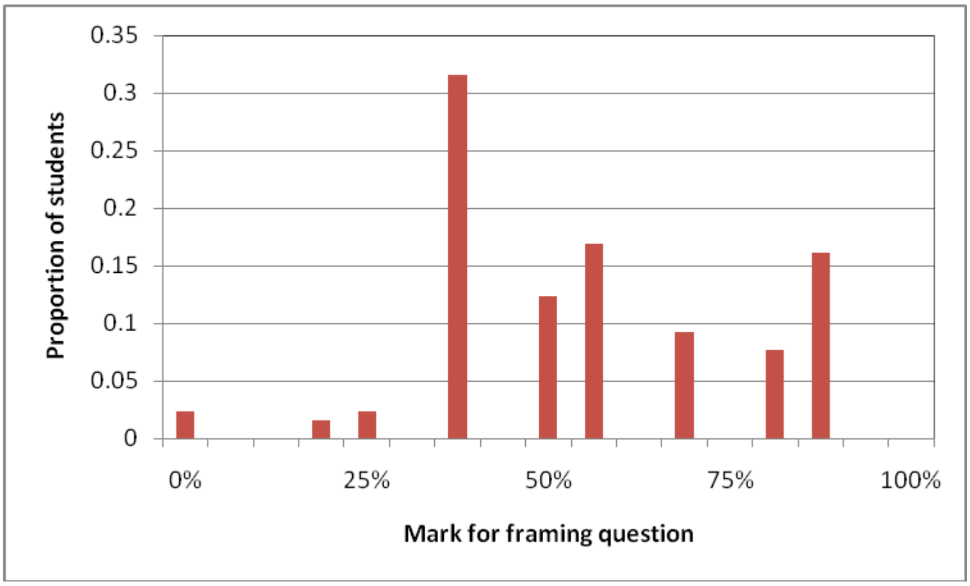

Figure 3: Marks for Framing Exam Question

Reflections of Teaching Staff

During both subjects, the teaching staff recorded their reflections on how these aspects of design expertise were being developed in students. Some of these reflections included:

- In both subjects there was a noticeable group of students who frequently expressed concern about the exam questions related to framing or first principles. Such students wanted to see more examples or get more hints to the nature of the question by having a possible topic being revealed.
- Some students were very worried about the first principles question but actually expressed relief afterwards.
- Some students needed convincing that these methods were something engineers needed. This appeared to be achieved by asking them if engineers didn't do this then who would do it for them?
- Students expressed concern about not having enough base knowledge to be able to apply first principles.
- Some students confused framing with a mission statement and reworded the framing question as a small design brief that still needed to be framed. This caused the high number of students receiving around 40%.
- Students could show some insight with framing as they wrote down what was in their head. This was not an option with the first principles question.
- There were students who were obviously digging deep and applying a lot of effort to develop their ability to apply first principles and some students appeared to enjoy having this new way of viewing design opened up for them.

Feedback from Student Surveys

At the end of the subjects the students completed a student satisfaction survey, similar to the surveys most students complete at universities around the country. Students appeared to be satisfied with the subject that focused on first principles (80% agree or strongly agree, n=50), but 80% also agreed or strongly agreed that it was harder than other subjects. The subject that focused on framing had a lower satisfaction (60% agree or strongly agree, n=18), but still 80% agreed or strongly agreed that the subject was harder than others.

There were numerous free response comments of varying natures on different topics from both surveys. However, there were extremes associated with the feeling of what was covered and how.

At one end were comments such as:

- Makes me want to be more clever and committed than I typically am.
- Open ended problems are a great thing keep them coming, the project was a good, open ended concept and enjoyable to partake in.

- The application of our knowledge to real world examples was fantastic. This subject kind of links other subjects together, and shows us why we needed to know all that other stuff.

At the other end were comments such as:

- More involved lectures and provide detailed information (are needed). Lecture needs to write and explain practical problems and solve examples to prepare students for tutorials. Also, the subject is confusing and the lecturer and tutors do not provide much help, which result in uncertainty in performance for the subject.
- Perhaps sometimes there could have been more detailed about the requirements of the assessment task, sometimes some of the finer details weren't know, which could have caused some slight confusion. Mainly because we haven't really done a subject like this before.
- I did find the assessments to be vague as to what was expected.

Discussion

A consideration of the marks shows something interesting. There appears to be considerable bifurcation between the students who were able to demonstrate the skills associated with engineering design expertise and those who couldn't. This is most evident in the marks shown in Figure 1, where few students showed a medium level of performance. This is also evident to some extent in Figure 2, but not as much. However, the academics involved did state that confusion over framing produced answers that resulted in a near average mark (40%). This suggests that some of the answers that correspond with Figure 2 might have received a higher mark than was deserved if a true definition of framing was used. Restating the problem is not framing, yet marks were allocated to students for writing something down even if it wasn't framing. If this is indeed true, then one would expect to see greater bifurcation in the marks shown in Figure 2.

The reason for this bifurcation might be evident in the feedback from student surveys. Positive comments seemed to centre on an enjoyment of applying knowledge to unique design problems and a desire to improve. However, negative comments focused more on the need for more details, more examples and a greater certainty in what was required for assessment. The application of first principles and framing are not processes that can be developed simply by rote (Ramsden 1992), which seems to be the learning styles of students asking for more details, more examples and greater clarity. They require instead and ability to clarify a problem that has not yet been fully defined (Cross and Clayburn Cross 1998). If those students who performed poorly in the assessment were from the same cohort who made the negative comments on the survey, then it might be that a developed rote style of learning is so detrimental to learning engineering design expertise that students using this approach will simply not be able to pass, despite the use of reflection or maybe any other method.

However, it did seem that students could overcome one learning style and adopt a more suitable one. The comments by the academics did refer to some students 'digging deep' suggesting that they were in new territory or that they were confronted with new types of problems, but that they still took on the challenge. Further, some students showed fear (suggesting that this style of learning was new to them), but then relief afterwards (suggesting they had done well). This could be viewed as evidence of students shifting from one learning mode to another when they had to.

Why some students could not take on these new challenges is unclear from the evidence at hand. However, the academics involved did state that some students felt they lacked the required fundamental knowledge to apply first principles. If this lack of base is a result of the learning style used when this base matter was taught (and students only learnt the methods associated with the theory as opposed to developing a deep understanding), then this would suggest that some students have been using a surface or rote learning approach (Ramsden 1992) so long that they were unable to use any other when required.

Conclusions and Future Work

There is evidence that some students can master skills associated with engineering design expertise when asked to apply and reflect upon them, while others cannot; there is no middle ground. The reason for this bifurcation might be related to learning style, but it is unknown if this is a result of the individual or the education system they have been in. Whether engineering design expertise could be a clear indicator of real student ability or something that is either a pass or a fail needs to be further investigated. Further, approaches and the scaffolding of activities to help students develop the associated skills of engineering design expertise requires further investigation.

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