The Virtual Design Workshop
An Online Adaptive Resource for Teaching Design in Engineering

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Abstract: Design education aims to develop in students the confidence to apply engineering fundamentals to the design of products and systems. This can only be achieved through intensive education and exposure to real-life engineering problems. One of the pressing issues in teaching engineering design is the resources- and labour-intensive nature of the subject. In practice, when developing a design, engineers are dependent on the situation at hand, so goals, problems and constraints are often ill defined and may change as the problem continues to unfold, providing no single ideal solution. Assumptions and estimations are required before each analysis step, and the results need to be evaluated against the desired functional output. Often, many analysis iterations are needed before a suitable solution is found. When teaching, providing the same scenario requires that tutorial guidance must adapt to the particular solution of each individual student. Conventional online tutorials help to combat some issues, but they are not able to track student progress in detail, nor are they able to provide customisable feedback for individual students. The aim of the research is to develop software tools that can address key problems in engineering design education and provide students with a more effective and enriching educational experience. This paper discusses a response to the issues in design education in engineering, in the form of adaptive tutorials, and puts forward the preliminary analysis of their success in helping students overcome the limitations of current design education.

1 INTRODUCTION

Design is an essential component of any engineering discipline, a combination of technical expertise and creativity. Good design is vital in creating objects and spaces that work. Design is widely considered to be at the core of engineering and it is well established that "…engineering programs should graduate engineers who can design effective solutions to meet social needs…" (Dym et al., 2005). Engineering science education tends to focus on developing skillsets within students, which allow them to solve particular problems in particular ways. The skills and knowledge build hierarchically on what was previously learnt. Often many previously learned concepts and capabilities need to be employed in order overcome the challenges in the problem to find a solution. It misleadingly implies that there is an ideal approach to the problem and an ideal solution. In reality, few true engineering problems fit this model. In practice, when developing a design, engineers are dependent on the situation at hand, so goals, problems and constraints are often ill defined and may change as the problem continues to unfold (Lemons et al., 2010). There is no single ideal solution in this situation. Assumptions and estimations are required before each analysis step, and the results need to be evaluated against the desired functional output. Often, many analysis iterations are required before a suitable solution is found. Although engineers often have general guidelines for the design process, there is no consensus regarding one correct procedure to follow in order to reach a solution (Lemons et al., 2010).

Students are often uncomfortable with the notion that there is no correct answer, as the majority of their prior learning has been assessed with examinations and quizzes where there are definitively correct answers (Goldsmith et al., 2010). Many initiatives have been taken to identify the reasons for poor student engagement with engineering design and to find ways to address the problem, both by individual teachers and, increasingly, by the community of engineering academics. The problem may lie in graduate

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students' capability to find solutions to previously unseen problems. A theoretical position on this capability and threshold concepts has been proposed in a recent paper by (Baillie et al., 2013). Numerous efforts have also been made to better integrate design into engineering curricula (Carroll, 1997; Kartam, 1998; Kurfess, 2003) and prepare graduate engineers for the industry (Todd et al., 1995). Ultimately, engineering design seeks to find a technical solution that best satisfies a particular set of requirements. This design process takes into account a range of factors, including economics, buildability, sustainability, technical performance and safety, but it is largely driven by the requirements of the problem space.

2 BACKGROUND

Despite incorporating long-practiced teaching and learning approaches for engineering design courses, current methodologies still suffer from inherent shortcomings. Design courses are resource intensive. With each passing year, there is a trend toward resources to teach becoming more limited despite increasing student enrolments, making authentic design experiences difficult to achieve (Dougherty & Parfitt, 2009). This is further exacerbated by the inability to provide feedback to such a large number of students in a timely and efficient manner. Traditional design teaching (workshops, studios, laboratories, etc.) does not translate well spatially or temporally. The interactivity of design teaching requires students to be located in the same time and place as the teacher. This limits opportunities for distance education (MOOCs) and also limits a student's capability to learn at an individual pace. Furthermore, it can be difficult to evaluate student performance in complex design assignments due to the variability of student responses. This problem is exacerbated when students work in teams, as accurate evaluation based on individual effort is difficult to implement (Dutson et al., 1997). Design courses require lecturers to put extra time into devising suitable projects for students, looking for suitable industry-sponsored projects, and coordinating the course itself (Todd et al., 1995; Wilczynski & Douglas, 1995). Faculty members have limited professional and industrial experience in design disciplines (Dutson et al., 1997). The reason for this could be today's increased focus on research output. An increasing proportion of faculty staff are recruited directly upon the completion of a fruitful post-doctoral period – staff with little, if any, professional industrial design experience.

Two particularly effective educational frameworks already integrated into engineering design education are "project-based learning" and "problem-based learning". Generally, project-based learning is directed at the application of knowledge in projects, whereas problem-based learning involves the acquisition of knowledge and skills in the process of solving previously unseen problems (Heywood, 2005; Perrenet et al., 2000). These two approaches are similar in that they focus on student learning rather than teaching (Kolmos, 1996). They are also similar to providing students with many worked out problems and their solutions, another effective means of improving problem solving (Sweller & Cooper, 1985). However, current project/problem/studio-based learning (PBL) and teaching methods have proven very costly to run. This cost arises because typical hands-on projects or design assignments in physical laboratories, workshops and studios require space, logistics, equipment, time and money, which are traditionally limited resources. Consequently, the extent to which these teaching methods can be utilised is restricted, often to cornerstone design courses (e.g. ENGG1000 at UNSW). With ever increasing enrolment numbers, the sustainability of even these major hands-on courses is under threat. PBL curricula are also difficult to scale to very large classes or to move online (MOOC) due to the substantial requirement for students to physically attend laboratories and work on projects collaboratively. There thus exists a need for complementary tools to augment existing design education in the online space. These tools need to replicate, as closely as possible, authentic design experiences and surround students in the design ethos. A number of software solutions are currently on the market for the purpose of teaching design-based engineering subjects.

Gibson et al. (2002) evaluated a software package, Design Builder, based on its content, operational measures, technical ability and feedback and assessment. They found that Design Builder scored extremely well under all the headings, in particular scoring above 90% in its Feedback and Assessment section, concluding that the program has achieved its goals in teaching students. The article (Gibson et al., 2002) goes on to recommend that Design Builder be adopted as an aid in teaching engineering design at the undergraduate level. One of the main benefits of Design Builder, and its potential success as an aid in teaching the concepts of design, is the ability to easily portray the practical application of the problem before design can commence. The software also allows students some control over specific variables of their design, allowing them to see first hand the effects of practical applications of the design. However, the limited control does not allow students to effectively evaluate the different characteristics of design of the system, and therefore does not provide feedback on all aspects of system design.

An additional software package (unnamed) that can aid in learning, allows the student to explore elements of shaft design (Álvarez-Caldas et al., 2007). The software provides the student design with a high degree of control, allowing changes to the overall structure and also the specific variables of design. This is an advantage to learning, as students are given the opportunity to see what effect specific variables and elements have on the overall design of a shaft and can be provided with detailed feedback relating to each of the elements.

The objective of the Heat Exchanger package (Tan & Fok, 2006) is to educate the student in heat exchanger design, and to "…bridge the gap between theoretical consideration and engineering practice…" (Tan & Fok, 2006) The software allows the students to become acquainted with heat exchanger designs through thermo-hydraulic analysis, and to understand the fabrication, costing and maintenance aspects of the design through its mechanical drawings. The program provides the student with control over specific variables that influence the overall design and also provides a customized overview of the design, however, it lacks the mechanical design capabilities for the students to understand the practical engineering application of the final design (Tan & Fok, 2006). Furthermore, other limitations of the Heat Exchanger software are that feedback is not instantaneous, and an academic is not easily able to see the progress of the students.

West Point Bridge Design (WPBD) is a nationwide competition organized by the United States Military Academy (USMA) (Symans, 2000; Ressler & Ressler, 2004). The competition is aimed at increasing interest in engineering among middle and high school students, by allowing them to engineer a solution to a real-world problem. The WPBD software provides the tools that students need to design and create a steel highway bridge, based on real-life parameters. This allows students to learn more about engineering design, by applying mathematics, science and technology principles to create a device that will service human needs. Students are required to use the WPBD software to design a bridge based on the specified criteria and constraints. The WPBD software allows students to graphically create a structural design, in which the student chooses the material and mechanical properties of each structural member. The student is then able to run a simulated load, determining the ability of the bridge to carry a specified load. Creating a successful design with this software is fairly simple; however, creating an optimal design at the lowest possible cost is the real challenge, thereby replicating a real-world situation (S. J. Ressler & E. K. Ressler, 2004). The target audience of this competition is limited to high school students and there is no direct educator feedback. This is strictly a design competition, so whilst it is effective in demonstrating some of the elements of design, it is not effective in teaching, or providing information to improve future design decisions. Students are required to conduct outside research that they can then use to design and test a bridge. Specifically, a survey conducted by Ressler et al. (2004) found that whilst students demonstrated a high level of perceived learning about structures, they demonstrated a relatively lower levels of learning about engineering design.

Design teaching initiatives have also been implemented by Khan Academy (*www. khanacademy.org*). One of the biggest advantages of the Khan Academy resources is its ability for students to progress at their own pace, with feedback provided as needed, ensuring individualised learning. Perhaps, the most unique thing about Khan Academy is the incredibly reach that it has. Globally, in 2012, the site was used by approximately 6 million unique students each month (Noer, 2012). Whilst the benefits of the Khan Academy cannot be denied, the setback to this mode of learning is the lack of guidance from an educator, when it is required.

The University of Pennsylvania has also undertaken an online design course. Web-based learning technologies including student generated electronic portfolios, an e-studio website and asynchronous discussion board technologies were implemented and tested throughout a multiphase research study. The study was constructed as part of curriculum improvement activities for the capstone design course sequence in the Department of Architectural Engineering. A major part of the Capstone design program is the e-studio practitioner mentorship program, providing online access to staff members who are experts in the student's field of study. The use of web-based technology has proven a success, and has provided improved course management, enhanced practice-based course content, increased visibility of student-generated projects and improved student/practitioner interaction (Dougherty & Parfitt, 2006).

One of the issues with current software-based design education is the inability to provide feedback and to engage in discussion with students. The need to address these issues are seen in such packages as Khan Academy Online, Pennsylvania Capstone Design and Udacity Online, which provide the students with a discussion forum aimed at improving learning and understanding. A proposed solution to the current issues faced in engineering design is the use of adaptive tutorials (Ben-Naim et al., 2008), where interactive instructions are adapted to student's level of understanding. Online Adaptive Tutorials (ATs), already well established in engineering science courses, promise particular benefits for design education. Similarly, they have been successfully trialed in other domains such as medicine (Velan et al., 2009). AT's have been shown to help overcome the constraints of limited resources while providing students with improved and personalised support when and where they want it. Engineering design problems present imperfect input information and have no predefined result. Each student must devise their own solution to each design problem they face. The problem factors to be analysed during the design process are difficult to specify at the outset, meaning that the tutorial guidance must adapt to the particular solution that each individual student devises. Adaptive tutorials provide a complete feedback loop to the students. They are designed so that a student is able to interact with a simulation whilst being guided, and given unique feedback based on student input into the system (Marcus et al., 2011; Prusty, et al., 2011b; Prusty, 2011; Prusty & Russell, 2011; Prusty, Ben-Naim, et al., 2011a; Ben-Naim & Prusty, 2010; Prusty, 2010). This can allow for customised student learning and real-time feedback for educators from a large group of students, thereby reducing the load on the educator and minimising course resources. The educator receives feedback on student learning via the Solution Trace Graph (STG), a visual summary of overall student performance, and can use this to update and modify instructional content as needed (Ben-Naim et al., 2009) (Figure 1).

An increasing enrolment base of students restricts the courses that can be run due to the physical space and physical equipment restrictions that come with large group sizes. Thus exists a need for complementary tools, such as adaptive tutorials to augment existing design education in the online space. These tools need to replicate, as closely as possible, authentic design experiences and surround

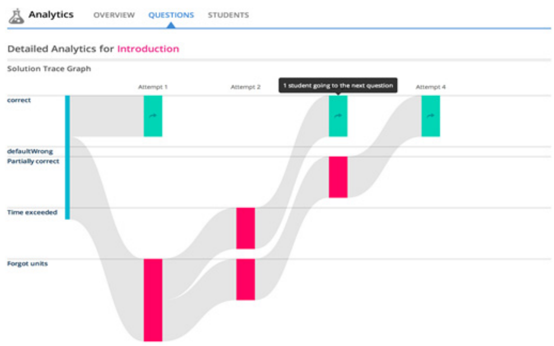

Figure 1: An example of a Solution Trace Graph.

students in the design philosophy that will ensure a future generation of engineers capable of approaching a range of different problem spaces and solutions.

2 PILOT STUDY

This pilot study used the Adaptive Tutorial system pioneered at The University of New South Wales (UNSW) (Ben-Naim et al., 2008; Prusty, et al., 2011b; Prusty et al., 2009; Prusty et al., 2013). Adaptive Tutorials (ATs) are web-based, intelligent and interactive eLearning tools, implemented on an Adaptive eLearning Platform (AeLP). ATs have been implemented since 2006 at UNSW and various other international universities in science-based education. Prusty and his colleagues (Prusty et al., 2013) have found adaptive tutorials to be effective tools in teaching science-based engineering subjects. ATs supply a valuable teaching tool with the possibility of providing a highly customised learning environment for each student (Khawaja et al., 2013). There are two features in particular that make the application of adaptive tutorials suitable to design instruction. Firstly, the visual and interactive capabilities of the AeLP offer a virtual environment with interactive tools to better engage students in engineering design. And secondly, the Adaptive Tutorial provides timely feedback, tailored to each student's actions and responses. This provides students with improved and personalised support when and where they need it – vital elements for effective design education.

The Design Adaptive Tutorial was implemented as a learning and assessment exercise to help students understand the fundamentals of design in the Solid Mechanics course offered at the second year level at the University of New South Wales (Figure 2).

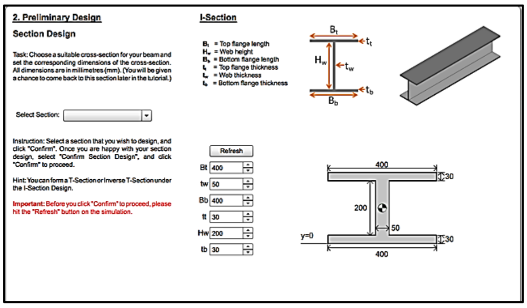

Figure 2: A screenshot from gantry beam design AT.

The tutorial was implemented for the last two years, in 2012 and 2013. Qualitative analysis of student feedback was undertaken in the form of a questionnaire based on student experience with Adaptive Tutorials in Semester 1 in 2013. In total, 304 students attempted the tutorial with an average mark of 92% scored in the tutorial material.

3 RESULTS AND DISCUSSION

A survey was given to 304 students with questions gauging the effectiveness of the adaptive tutorial in learning the concepts for the mechanical design of a gantry beam (Figure 3).

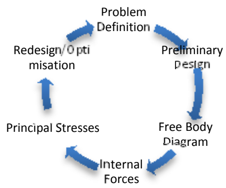

Figure 3: Design Loop for a gantry beam using Solid Mechanics fundamentals.

A number of students commented on the effectiveness of immediate feedback mechanism, as one of their most important learning resources, to the question "Do you find this Adaptive Tutorial useful to apply the fundamentals of Solid Mechanics?" Immediate feedback provided students with the ability to complete the tutorial and learn at an individual pace suitable to the student's learning needs. Table 1 documents the identified themes taken from students commenting in response to the survey question on whether the AT was useful is applying the fundamentals of Solid Mechanics.

The vast majority of students found the tutorial to be helpful in applying fundamental principles, and 82% indicated that the tutorial was indeed useful to apply principles of Solid Mechanics (Figure 4).

Table 1: Identified themes from student comments on the usefulness of the AT to the fundamentals of Solid Mechanics.

Theme	*Comments No*
Helpful	41
Instant feedback	37
More interactive than classroom learning	29
Revision of basic concepts	15
Incorporates many necessary fundamentals	13
Shows design process in action	13
Enjoyable experience	11
Applicable to current study	9
Step by step	7
Not sure if useful to me	2

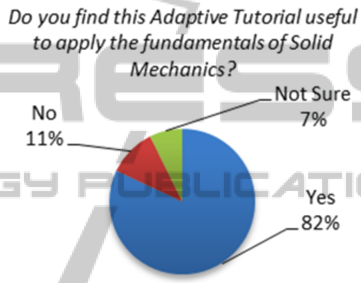

Figure 4: Applying ATs to the fundamentals of Solid Mechanics course.

More importantly, it appears that students found it easy to navigate their way through the adaptive tutorial and found the tutorials to be easy to learn

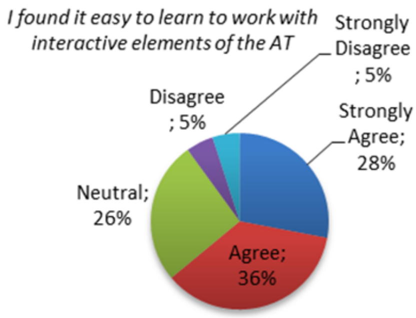

Figure 5: Ease of use of AT interactive elements.

(Figure 5). A number of students also commented on the ease with which they were able to manipulate the interactive elements of the tutorial, therefore using their limited cognitive resources to complete the tutorial as opposed to learning the tutorial interface.

A positive response was also obtained from students on the preference of using Adaptive Tutorial as a learning tool in Solid Mechanics (Figure 6). Approximately one third of the students surveyed, or 32%, strongly agreeing that Adaptive Tutorials are their preferred teaching method as opposed to traditional written assignments and 33% of students surveyed agreeing that adaptive tutorials are a preferred method of learning.

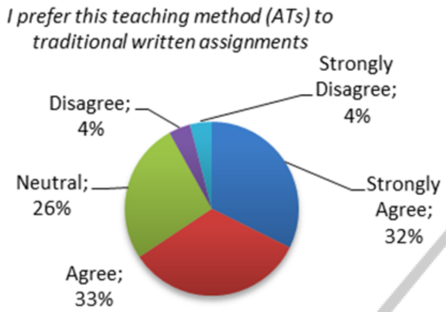

Figure 6: Preference for teaching methods.

4 CONCLUSIONS

The pilot study has indicated that adaptive tutorials could be an effective solution to design education in engineering. Adaptive tutorials enrich student knowledge with the instantaneous real-time and customised feedback, based on student input into the system. In particular, for larger groups of students, educators are able to instantly discern problems that a student might be experiencing with coursework material without the need for individual consultation via the STG, a visual summary of overall student performance. This can be used to update and modify instructional content as needed, thereby reducing the load on the educator and minimising course resources (Ben-Naim et al., 2009).

Furthermore, an increasing enrolment base of students restricts the courses that can be run due to the physical capacity and equipment restrictions that come with large group sizes. Thus exists a need for complementary tools, such as adaptive tutorials, to augment existing design education in the online space. These tools need to replicate, as closely as possible, authentic design experiences and support students with the development of design that will ensure a future generation of engineers capable of approaching a range of different problem spaces and solutions.

Leading on from the pilot, further studies will utilise not just qualitative survey data, but will also include information regarding course marks and overall course performance. The program of adaptive tutorials will also be expanded to encompass different engineering disciplines, such as Mechanical Engineering, Civil Engineering, Naval Architecture and Aerospace Engineering and also include Architectural design problems. This will aid in providing an overall picture into the effectiveness of adaptive tutorials in student understanding of fundamental design concepts in engineering.

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